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Enhancing Distribution Grid Resilience via Multi-Autonomous Microgrid Islanding

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Abstract. The ability of power systems to withstand and recover from natural events, like storms, earthquakes and floods is referred to as resilience. These events may not happen often. They can cause damage to infrastructure and disrupt the supply of electricity. That's why it's crucial to consider resilience when planning and operating networks. In this paper we present a method to enhance the resilience of distribution networks these are the parts of the system for delivering power to end users. Our approach involves dividing the distribution network into subnetworks called microgrids. Each microgrid operates independently. Includes sources of generation loads (consumers) and storage devices. These microgrids can function as part of the grid. Operate autonomously in what we call island mode during major disturbances. In situations they can isolate themselves from the grid and use their internal resources to continue providing electricity specifically for critical needs. To assess how well our approach performs we introduce a measure called a resilience indicator. This indicator evaluates how effectively users electricity demands are met during and after a disturbance occurs. It can be calculated individually for each microgrid or holistically, for the distribution network by considering how these microgrids interact with each other. Our research demonstrates that the method we propose can improve the reliability of the power distribution network. We achieved this by comparing the results obtained from our approach with those, from a network that does not use microgrids. Our paper adds to the existing knowledge, on the resilience of power systems by introducing a technique centered around creating multiple independent microgrids.

Key words. Resilience, Electrical power systems, Microgrids, Islanding and Extreme natural events.

1. Introduction

One of the current indicators of technological development in different countries is the robustness of the power system. The need for electrical energy has become extremely important for humanity in recent years due to the diversity of systems and fields that supply electrical energy to provide adequate services to customers [1]. Power systems often suffer from a variety of failures caused by network equipment failures, electrical failures, sabotage, and human error. Most of the common disturbances that can affect the power grid are addressed and planned for as part of planning studies or defense plan preparation [1]. Traditional disasters can be prevented by calculating maximum losses through planning considerations and reliability calculations, so extreme events with low probability (referred to as high-impact low-probability events) cause more damage [2]. Earthquakes, floods, snowstorms, ants, sabotage, human error, and cyber-attacks are examples of critical events [2]. These types of events result in long-term energy losses and large economic losses due to property damage, causing more damage on the power system equipment front [3]. Therefore, resilience research is re-emerging to assess, classify, and improve electricity. Power the system for these types of events [3]. The various scientists who work on the topic of resilience enhancement have agreed on the three crucial actions to take: modeling of the extreme events studied, classification of the type of resilience to be studied, measurement and evaluation of resilience-by-resilience indices, and finally, the appropriate improvement technique [2-4]. Resilience is a wide concept used in a variety of contexts and disciplines, including economics, psychology, meteorology, and technical fields [4-5]. The United Nations suggested a generic definition of resilience in 2009. "Resilience is the capacity of a system to cope with a disturbance and get back to its original or stable state." It may be applied at any level, including climate change, natural catastrophes, health crises, and societal conflicts. It enables us to overcome challenges, adapt to new conditions, and build a brighter future [4-5]. Our main contribution in this study is to present a resilience evaluation tool for microgrids, power grids, and electrical energy systems in general. On the other hand, we suggest an approach for increasing resilience via autonomous multi-microgrid network islands. This section introduces the notion of resilience in power systems, classifies several types of resilience research, and concludes with resilience curves and

markers [4-5]. The remaining sections of this paper are organized as follows:
Section 2 explains the resilience of electric power systems, as well as their classifications and different study frameworks and the extreme events that cause the degradation of resilience, as well as their modeling and simulation methods, Section 3 will present the different measures and evaluation of resilience rates of distribution power systems and microgrids, presented in the literature, as well as the measure proposed in this paper for microgrids and distribution systems, Section 4 investigates the improvement and correction techniques of the resilience índices, Section 5 an application on the IEEE test networks and finally the Section 6 concludes with a conclusion and future research perspectives.

2. Electric power systems resilence:

There is no standard definition of power system resilience, so scientists can provide a variety of definitions. In [6] and [7-9], resilience is the ability of a system to anticipate, resist, or absorb rare and frightening events, adapt to their consequences, and quickly return to an acceptable level after such events.

A. *Classification of the resilience of electric power systems*

To help comprehension and discussion, the concept of resilience includes long and short-term qualities that may be explored in two categories based on when the events occur [10], resilience can be classified into two domains: planning and operation. Resilience planning is considered a long-term task. It aims to make distribution (RD) and transmission networks more robust and intelligent by preparing ahead of time to mitigate HILP events on the power grid.

B. Faults and causes of resilience degradation

The events that cause a system's resilience to degrade, on the other hand, are those that cannot be foreseen or understood in terms of when and where they will occur, as well as the harm they may inflict, and are known as "high impact and low probability events," or "HILP." Such catastrophes include natural climatic disasters such as floods, earthquakes, hurricanes, and snowstorms, as well as man-made sabotage such as cyberattacks. Extreme disasters have serious effects for power system resilience, such as long-term outages, destruction of essential power system equipment, cascade failures, and power outages [11]. The acquired data and meteorological statistics may be highly valuable in modeling severe natural events and constructing a meteorological profile. They can be derived from measurements taken at meteorological stations, In actuality, the propagation of the defect or occurrence in question is a significant issue in the modeling of severe events; in [11], the authors offered an overview of the modeling of the replication of extreme events:

1) Hurricanes:

To predict hurricane-related events, it's important to include hurricane features such as occurrence, direction, angle of propagation, speed, center pressure, speed fading rate, and wind radius [11]. A hurricane model was built using the Poisson distribution function, as shown below :

$$P(h) = \frac{\exp(-\lambda)\times\lambda^{h}}{h!} \qquad (1)$$

The probability distribution function (P) indicates the yearly occurrence of hurricanes, whereas λ and h represent the average number and number of storms each year, respectively.

2) Windstorms:

Windstorms are regularly replicated using extreme wind simulators based on actual data and measurements that account for windstorm occurrence throughout the year [11].

3) Flooding:

Estimating the impact on several components of a system of electricity at different sizes using historical flood data.

3. Measurement and evaluation of resilience:

Until present, no resilience measuring approach has been established as a standardised and officially acknowledged method. This has prompted academics to offer numerous evaluation criteria and classifications for the proposed approaches. Some have also converted existing reliability measurements into resilience metrics, while others have created new classical metrics. These strategies are categorized as quantitative or qualitative. Quantitative approaches, such as statistical analysis methods [16], graph theory-based analysis methods [17], and fuzzy logic model methods [18]. In the following sections, we will offer various literature-based methodologies, either resilience metrics or reliability metrics, for quantifying the resilience rates of electrical networks.
In [5], the IEEE reliability measures LOLE (loss of load expectations), SAIFI (system average interruption frequency index), and SAIDI (system average interruption duration index) were modified to the resilience evaluation metrics against HILP occurrences and characterized as:

$$SAIFI = \frac{Total\ number\ of\ customers\ interrupted}{total\ number\ of\ customers\ served} \qquad (2)$$

$$SAIDI = \frac{Total\ customers\ storm\ interrupted\ minuts}{total\ number\ of\ customers\ served} \qquad (3)$$

Article [12] presents another measure that is derived from the literature and is predicated on the state transition of electrical energy systems. Figure 1 [30] clearly depicts the transition stages, with So representing the network's stable operating state prior to the incident, Sd representing the network's degraded operating condition after the event, and Sf representing the network's stable operating state following the restoration. The system performance P(t) is evaluated during the event and is defined by the system state transition points P(to), P(td), and P(tf), where ej represents the fault event. R1 measures resilience as the time-dependent ratio of recovery to loss. The resilience metric R1 has a value range of 0 to 1 both before and after a disturbance occurs. R1=1 indicates that the system is entirely robust, whereas R1=0 indicates that it is not resilient.

$$R1 = \frac{P(t_f|e^j)-P(t_d|e^j)}{P(t_0|e^j)-P(t_d|e^j)} \quad (4)$$

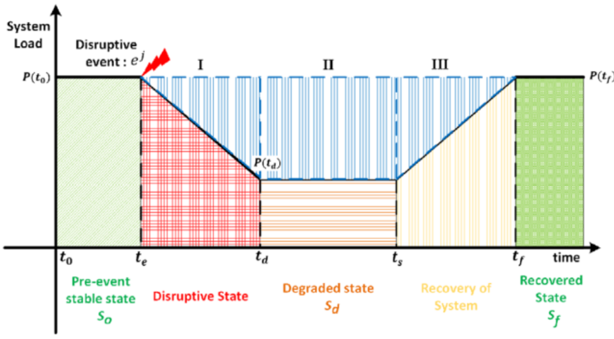

Fig. 1. Resilience curve representing network operation states.

The undistributed power planned, the demand that was denied power, the generators that were put out of service as a result of the event, as well as the duration of the last one and the time required to restore the system to operation, are the first electrical parameters evaluated for the damage suffered by a system in question during an extremely violent event. Furthermore, measurements that focus on a single parameter may not adequately reflect the system's current state or level of resilience. As a result, A combined measure has been proposed in paper [29] to as closely approximate the system's status as possible following a disruptive event. The measurement value ranges from 0 to 100 (% of 100) and is presented as follows:

$$R2 = \frac{Rp+Rt}{2} \quad (5)$$

The first element, Rp, is equivalent to the evaluation of power served to the customer and the rate of customers who will be without power supply; or we must take into account the initial state of the system's resilience, Rpint, which may be 100% if the network operates perfectly, or less than 100% if the system investigated previously encountered problems, like the loss of a generator or a transmission line.

$$Rp(i) = Rpint - \sum_{i=1}^{N} Ploss(i) \quad (6)$$

The penalty concept is used for the second part of this measure, which corresponds to the outage time between the end of the event and the system's restoration of service, rather than its original condition, so that resilience decreases by a percentage as the outage time increases. The penalty rate as a function of outage time is represented in the following two-line matrix:

$$P = \begin{bmatrix} 3 & 5 & 10 & \ldots & 71 & 72 \\ 0 & 10 & 20 & \ldots & 100 & 100 \end{bmatrix} \quad (7)$$

Where p is the penalty equal to the outage period in percentage, taking into account the system's initial total resilience Rtint, which would be up for the most of the time at 100% if no fault occurred earlier, otherwise Rt would be as follows:

$$Rt(i) = Rtint - P(j) \quad (8)$$

C. The measure proposed for microgrids and distribution systems:

As the first contribution to this paper, we present a resilience assessment metric that can be applied to microgrids, multi-microgrid systems, and distribution networks with any desired network performance, whereas existing metrics are either specific or general, resulting in approximate and less accurate results. The metric is expressed as follows:

$$R_{MGn} = \frac{(P_{dt}-P_{loss})+(P_{dct}-P_{dcloss})}{(P_{dt}-P_{dct})}\% - R_{\tau c}\% \quad (9)$$

R_{MG}: microgrid resilience
P_{DT}: total demanded performance
P_{tloss}: total lost performance
P_{dct}: total critical demanded performance
P_{dcloss} total lost demanded performance

$$R_{tc} = \begin{bmatrix} 1 & 2 & 3 & \ldots & 71 & 72 \\ 0 & 1 & 1 & \ldots & 99 & 100 \end{bmatrix} \% \quad (10)$$

R_{TC}: means the penalty applied to the network over the time that critical loads are out of service and deprived of power, or over the time that the network does not supply critical loads and they are out of service, or over the time that the network resilience rate degrades.
The resilience of the global distribution system or multi-microgrid system is:

$$R_{SD} = R_{MMG} = \sum_{i=1}^{N} R_{MGn} \quad (11)$$

When n is the number of the microgrids and R_{SD} is the resilience of distribution systems
R_{MMG}: is the resilience of multi-microgrid systems.

4. Techniques to improve the resilience of electric power systems:

There are several approaches for making a conventional power system more secure, including production redispatching, shunt injections, switching operations control, and transformer regulation [13–14]. These solutions are beneficial, but they are insufficient for ensuring power system stability. In general, there are several techniques for developing resilience, referred to as "resilience resources." These techniques might be operational or include planned activities. Many operational strategies may also be employed to build resilience. Examples include real-time outage alerts, fault location and isolation, service restoration, risk assessment and management, innovative defense and oversight schemes, priority setting and disaster assessment, on-site production unit setup, DG islanding and restructuring, demand-side management, and demand response [15]. As well as practical tools in terms of resilience are also used such as the use of micro-grids, unitary commitment based on resilience, transmission line switching and defensive islanding.

A. Reconfiguration-based methods:

Electrical network reconfiguration is researched and applied in reality, typically as an automatic or operator-assisted process for rerouting or restoring power following or during a network event. Transmission switching, or network reconfiguration, has traditionally been employed to transfer power over wide geographical areas. The electrical system has been reconfigured to reroute power in distribution networks that are typically routed radially, allowing for the installation of alternate networks via movable circuit breakers. Planned reconfiguration operations can take anything from a few minutes to a few hours, whereas automatic restoration can take as little as a few seconds or minutes. The majority of the research and implementation of reconfiguration algorithms were carried out for real-time.

B. Resilience-based unit commitment :

Some mathematical models for resilience-based generation resource planning have been developed thus far. These models are built on several algorithms, such as decentralized [17] and preventative [18], that plan production and storage resources to increase power system resilience by covering a specific level of uncertainty connected to HILP occurrences and renewable resources. Furthermore, certain unit commitment models were not originally developed for resilience but can be modified to this goal.

C. Defensive islanding :

Defensive islanding is another excellent approach for increasing the transmission system's resilience. Defensive islanding is an adaptive algorithm that reduces the impact of unanticipated catastrophic occurrences [20], [21], and [22]. By solving a graph cut issue, this approach separates the more susceptible components of a power system. Self-sufficient islands are developed in this manner, increasing resilience.

D. Improving resilience using micro-grids:

During major disruptions, the purpose is to restore service to the loads as quickly as feasible. Traditionally, restoration is carried out from the top down, beginning with generation, then the transmission network, and lastly the distribution network. Only until the distribution network has been restored will the loads be serviced. As a result, the duration of the disturbance to vital loads is extended. When a microgrid has a disruption or outage, it instantly initiates local self-restoration to conserve as much load as possible. At the same time, service restoration starts at the transmission layer and moves on to the distribution network. The recovery process will be speedier this manner because of the parallel method of the process, an upward process from the distribution level and a downward process from the transmission network side [23] and [24].

5. Case study :

In this part, we will apply the technique suggested in this study to a modified IEEE 33 test network that we created earlier in [31]. The position and size of PQ type DGs were optimized using a Genetic Algorithm, and the optimal sequence of tie switches was discovered using Particle Swarm Optimization. The following figures and tables show the position and size of the DGs, as well as the tie switches:

Table 1. position and size of DGs.

DGs	Integration bus	P (MW)	Q (MVAR)
DG1	22	0.506	0.22
DG2	29	1.012	0.6
DG3	15	1.25	0.53
DG4	25	1.32	0.6

Table 2. Optimized sequence of tie switches.

Tie switch	From bus	To bus
S1	20	16
S2	17	27
S3	4	12
S4	30	24

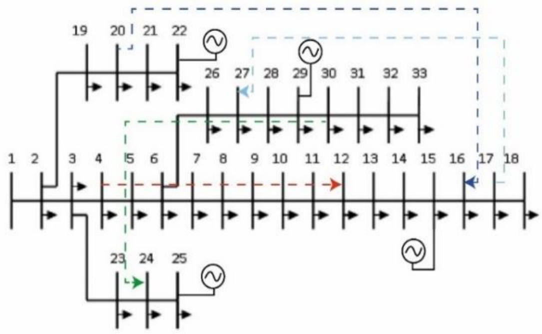

Fig 2. IEEE 33 bus modified system.

A. Study scenarios

two scenarios are used to model the behavior of a category 3 HILP event (hurricanes) with wind speeds of 111/129 mph (178-208 km/h). The Monte Carlo approach is used to randomly replicate both situations, including the event's direction, impacted lines, and affected busses. The image below depicts the two scenarios:

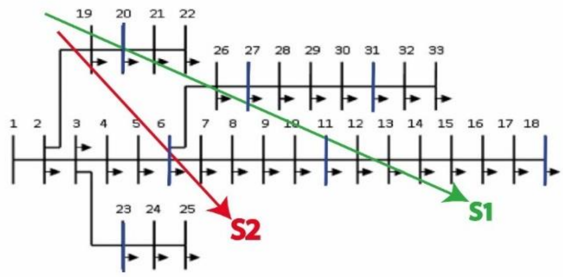

Fig 3. Hurricane scenario trajectory.

The damage caused by simulated hurricanes is presented as follows:

Table 3. Damage caused by simulated hurricanes.

scenarios	Bus number	P_{loss} (MW)	P_{closs} (MW)
Scenario 1	21,26,27,11,12,13	0,4125	0,1155
Scenario 2	19,6,7	0,385	0,066

The resilience rate and the load restoration rate of the IEEE33 bus distribution network after the incident with no enhancement plan is determined as follows with the proposed metric on resilience, R1 and the metric R2:

Table 4. Resilience rate with no enhancement plan.

no enhancement plan	R1	R2 (%)	R_{MGn} (%)
Scenario 1	0.4006	54	47
Scenario 2	0,91	70	63

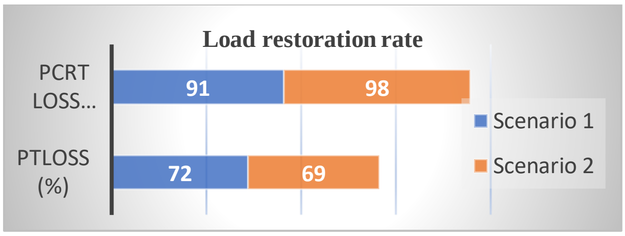

Fig 4. Load restoration rate with no enhancement plan.

B. *Application of the improprement strategy*

As previously mentioned, the study of resilience involves both strategic planning and operational implementation. Based on the method of improving resilience by defensive islanding of the distribution network into multiple microgrids, our approach, which is the second contribution of this paper, is deployed in several successive stages. Following the occurrence of a major incident, daily load monitoring becomes crucial for both regular customers and critical loads, involving power flow execution and monitoring of permissible voltage and current limits. Upon reaching 10% of capacity, the emergency plan activates, transitioning to a multi-microgrid mode by opening islanding breakers. Their optimal placement is determined by a genetic algorithm, ensuring that the formed microgrid loads are equivalent to or lower than the power delivered by the integrated Distributed Generators (DGs) in each microgrid zone, while respecting the permissible limits of each microgrid, verified through power flow (Nweton) and continuous power flow. To restore lost loads, production is increased while maintaining the frequency threshold using Automatic Generation Control (AGC) system functions, alongside the selection of microgrids with surplus production. This surplus is transmitted via switching lines, determined by the PSO (Partical Swarm Optimisation) method, respecting the transmission limits of each line, taking into account the starting point and the destination node. Micrograds are determined by the load repetition rate relative to the DGS generation capacity, where the load center of gravity will be the critical load rate, or the objective is:

$$P_{DG} \geq P_{MGd} \quad (12)$$

The result is displayed in the figure the connection and disconnection points on the IEEE 33 bus network:

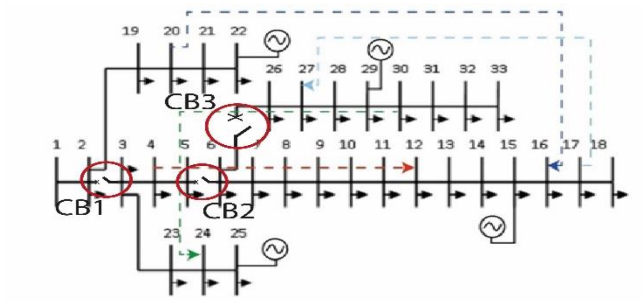

Fig 5. Determined connexion points.

Using the identical defects from scenarios 1 and 2, we compute the resilience rate and the load restoration rate after implementing the enhancement strategy:

Table 5. Resilience rate with enhancement strategy.

with enhancement strategy	R1	R2 (%)	R_{MGn} (%)
Scenario 1	0,89	58	62
Scenario 2	0,9834	77	69

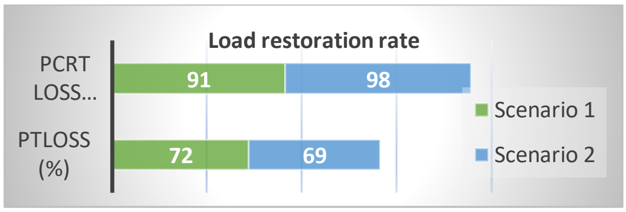

Fig 6. Load restoration rate with enhancement strategy.

Following the improvement, we see an increase in resilience rates and the load restoration rate using three measuring techniques, The chosen improvement approach contributed to the non-propagation of the failure to other regions not affected by the event by switching the microgrids to autonomous operation, avoiding the loss of other loads, as well as recovering lost loads by switching to higher levels of DGS production and transiting through power supplied by other MGs that appear to be in higher production to supply lost loads or compensate for the lack of power supplied by DGs in the affected areas.

VI. Conclusion:

In the subject of electrical systems, resilience is a novel concept. However, there is still no specific and authoritative definition of the concept, nor are there any appropriate techniques of evaluation and modeling. In this piece, we addressed the concept of resilience, measurement approaches, HILP event modeling, and the causes of resilience deterioration. We also spoke about the study approach and several solutions for improving electrical network resilience. First we define resilience in general as well as that of power systems, then we identify the HILP faults that degrade resilience, the methods for measuring and evaluating resilience so that we can choose and select the appropriate improvement method. Resilience enhancement depends on the network or system where it is applied, the fault on which the enhancement technique is chosen, and the trade-offs involved. In terms of future development, combining multiple improvement strategies can increase the system's robustness. By investigating these possibilities, we may get beyond individual components and gain a holistic knowledge of electrical network resiliency. This comprehensive strategy will ultimately result in more resilient, flexible, and sustainable power systems that can survive even the most severe threats.

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