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Ali Reza Kheirkhah

**Optimized Resilience in Power Grid Operations: A
Synergistic Framework for Risk Assessment and Adaptive
Restoration Modeling**

Ilha Solteira - SP
2024

Ali Reza Kheirkhah

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Synergistic Framework for Risk Assessment and Adaptive
Restoration Modeling**

Thesis Presented to the Postgraduate Program in Electrical Engineering Universidade Estadual Paulista - UNESP - Ilha Solteira Campus. In partial fulfillment of the requirements for the degree of Doctor of Philosophy (Ph.D.) in Electrical Engineering

Knowledge Area: Automation

Supervisor:
Prof. Dr. Jônatas Boás Leite

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Ilha Solteira, 05 de março de 2024

DEDICATION

This work is dedicated to all those who pursue knowledge in the face of adversity, embodying the resilience and tenacity necessary for discovery and innovation.

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I extend my deepest gratitude to:

- The Divine, whose boundless love, robust health, unwavering strength, and infinite patience have shepherded me through another milestone in my life's journey;
- To my beloved family, for nurturing my dreams with their boundless encouragement and motivation;
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RESUMO

Esta tese impulsiona o campo da resiliência da rede de distribuição de energia ao introduzir um quadro detalhado que combina de forma sinérgica algoritmos probabilísticos de fluxo de carga com estratégias adaptativas de restauração de carga. Esta abordagem melhora a capacidade da rede de resistir a interrupções. Central para a nossa metodologia é a utilização do Valor em Risco e do Valor em Risco Condicional como métricas quantitativas para uma análise baseada em risco, possibilitando uma avaliação precisa dos impactos contra eventos de alto impacto e baixa probabilidade. Utilizando simulações de Monte Carlo para modelar cenários de vulnerabilidade probabilística, nosso estudo oferece uma ferramenta precisa para operadores de redes de distribuição facilitarem decisões de investimento informadas. Incorporando tecnologias de rede inteligente, o quadro utiliza localização automática de falhas, isolamento, restauração de serviço e gerenciamento do lado da demanda para avaliar dinamicamente as probabilidades de interrupção e calcular precisamente os custos da energia não fornecida. A validade do nosso quadro é demonstrada através da análise empírica em dois estudos de caso do mundo real: O primeiro utiliza um sistema de informação geográfica para visualização de riscos em 4 alimentadores, aprimorando decisões estratégicas de melhoria do sistema. O segundo aplica um algoritmo genético dentro de um sistema de teste de 136 barramentos, destacando os benefícios da reconfiguração da rede para o aprimoramento da resiliência através de vários cenários de seccionamento e alocação de geração distribuída. Esses estudos sublinham a eficácia do nosso método em auxiliar operadores de redes de distribuição na tomada de decisões de investimento para reforçar a resiliência do sistema, impulsionada por estratégias de mitigação de riscos. Este quadro não apenas apoia decisões de investimento informadas, mas também contribui significativamente para o desenvolvimento de uma infraestrutura de energia robusta, capaz de gerenciar e recuperar-se eficientemente de interrupções adversas.

Palavras-chave: restauração adaptativa; métricas de resiliência operacional; interrupção de energia; fluxo de potência probabilístico; gestão de risco.

ABSTRACT

This thesis propels the field of power distribution network resilience forward by introducing a detailed framework that synergistically combines probabilistic load flow algorithms with adaptive load restoration strategies. This approach enhances the network's ability to withstand disruptions. Central to our methodology is the employment of monetary Value-at-Risk (VaR) and monetary Conditional Value-at-Risk (CVaR) as quantitative metrics for a risk-based analysis, enabling a precise assessment of impacts against high-impact, low-probability (HILP) events. By utilizing Monte Carlo simulations to model probabilistic vulnerability scenarios, our study offers a precise tool for distribution network operators to facilitate informed investment decisions. Incorporating smart grid technologies, the framework employs automatic fault location, isolation, service restoration (FLISR), and demand-side management (DSM) to dynamically assess interruption probabilities and accurately compute the costs of energy not supplied. The validity of our framework is demonstrated through empirical analysis on two real-world case studies: The first employs a geographic information system (GIS) for risk visualization across 4 feeders, enhancing strategic system improvement decisions. The second applies a genetic algorithm within a 136-bus test system, showcasing the benefits of network reconfiguration for resilience enhancement through various scenarios of sectionalizing switching and distributed generation allocation. These studies underscore the effectiveness of our method in aiding distribution network operators in investment decision-making to bolster system resilience, driven by risk mitigation strategies. This framework not only supports informed investment decisions but also significantly contributes to the development of a robust power infrastructure, capable of efficiently managing and recovering from adverse disruptions.

Keywords: adaptive restoration; operational resilience metrics; power outage; probabilistic power flow; risk management.

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LIST OF ABBREVIATIONS AND ACRONYMS

AMS	Asset Management System
ANEEL	National Electric Energy Agency (Agência Nacional de Energia Elétrica)
CDF	Cumulative Distribution Function
CVaR	Conditional Value at Risk
DEC	Equivalent Interruption Duration per Consumer Unit
DG	Distributed Generation
DSM	Demand Side Management
DSO	Distribution System Operator
FEC	Equivalent Interruption Frequency per Consumer Unit
FLISR	Fault Location, Isolation, and Service Restoration
GIS	Geographic Information System
HILP	High-Impact, Low-Probability
MCS	Monte Carlo Simulation
OMS	Outage Management System
PDF	Probability Density Function
PPF	Probabilistic Power Flow
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
VaR	Value at Risk

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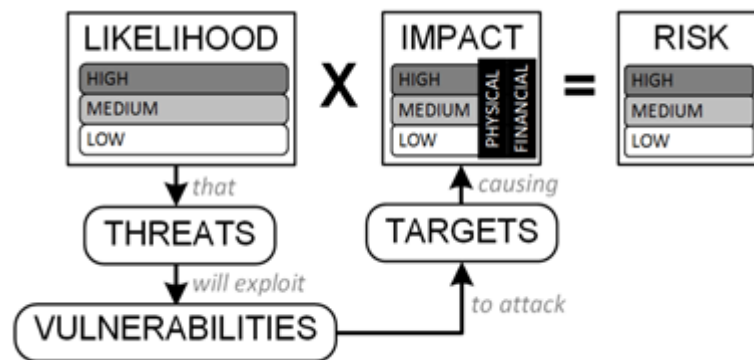
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1 INTRODUCTION

The power system serves as a fundamental pillar of a nation's critical infrastructure, providing the essential backbone for economic progress, societal welfare, and the safeguarding of national interests. Its complex network encompasses various interconnected components, including power generation facilities, transmission lines, distribution grids, and end-user consumption points. Each of these segments plays a vital role in ensuring the reliable and uninterrupted supply of electricity to homes, businesses, and institutions. However, despite its significance, the power system is not immune to threats. It faces a wide range of risks originating from both human activities and natural phenomena. These threats can manifest in diverse forms, ranging from cyberattacks, physical sabotage, and equipment failures to extreme weather events, natural disasters, and climate change impacts. The unpredictability and severity of these hazards pose significant challenges to the resilience and stability of the power infrastructure. Moreover, the complex interplay of factors further complicates the task of safeguarding the power system against potential disruptions. Not all threats are easily identifiable or preventable, and their occurrence can sometimes catch even the most vigilant stakeholders off guard. This inherent uncertainty underscores the importance of adopting proactive measures to fortify the resilience of the power system (Kheirkhah, 2020). In light of these considerations, enhancing the resilience of the power infrastructure becomes a crucial objective within the realm of infrastructure management and support systems. This entails implementing robust strategies aimed at mitigating risks, improving response capabilities, and enhancing overall system reliability. By fortifying its resilience, the power system can better withstand adverse events, minimize disruptions, and expedite recovery efforts in the face of adversity (Wang et al., 2015). When confronted with harsh weather events, essential infrastructure pivotal to national security, public well-being, and economic resilience is exposed to vulnerabilities. Sensitive systems like water supply, electricity grids, healthcare facilities, and emergency services play pivotal roles during such crises. However, the existing reliability standards for power systems often fail to account for the impacts of these unpredictable weather phenomena. Moreover, human-driven threats, such as cyber-attacks, can also inflict significant damage on the power infrastructure, exacerbating the challenges posed by natural disasters (Bajwa et al., 2019). The power system

confronts various threats, encapsulated within the concept of risk, which denotes the interplay between the likelihood of occurrence and the potential severity of its consequences. Fig. 1 illustrates the foundational definition of risk, wherein assessment is based on the correlation between probability and impact. Essentially, risk is evaluated based on the probability that hazards will exploit vulnerabilities, resulting in consequences for a particular target (Ayyub, 2003; Leite et al., 2016). Figure 2 is a Risk Matrix with a High-Impact, Low-Probability (HILP) event high-

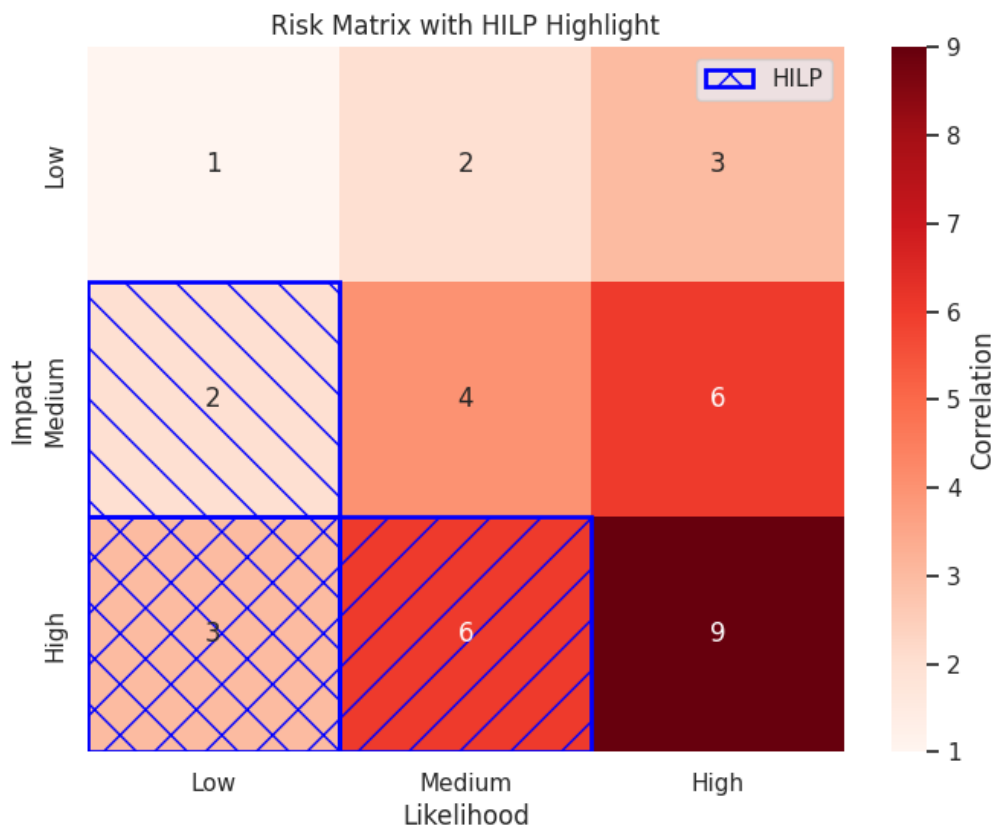
Figure 1 - An assessment structure of risk



Source: Leite et al. (2016)

light. This matrix is a visual tool used in risk management to assess and prioritize risks based on their likelihood of occurrence and the impact they would have if they did occur. The matrix is divided into three main columns representing the likelihood of risk occurrence (Low, Medium, High) and three rows representing the impact of the risk (Low, Medium, High). Each cell in the matrix is numbered from 1 to 9, indicating different risk levels, with 1 being the lowest risk (low likelihood and low impact) and 9 being the highest risk (high likelihood and high impact). The color gradient from light to dark red indicates an increasing level of concern, with darker shades representing higher risk levels. The cells with diagonal stripes are marked to highlight HILP events. These are risks that have a low chance of happening but would have a significant impact if they did. The HILP events are typically the focus of contingency planning because, despite their low probability, their high impact can be severe. An additional crucial consideration revolves around the persistence of risks within the power system, warranting careful examination. While critical risks can swiftly exert substantial impacts on the system, severe events unfolding over an extended duration may initially yield only moderate, short-term effects. However, their cumulative consequences can prove extensive over time. It is essential to recognize and address both immediate and prolonged threats to comprehensively safeguard the stability and resilience of the power infrastructure.

Figure 2 - Conceptual model of risk



1.1 WORK MOTIVATION

The concept of resilience in power systems, as well as its significance within the broader context of critical infrastructures such as telecommunications, natural gas and oil, financial and banking services, water supply systems, government operations, and emergency response, has emerged as a pivotal area of research. These eight essential infrastructures are integral to the functioning of modern societies and economies, and their robustness and ability to withstand and recover from disruptions are of paramount importance. The notion of resilience in power systems was first introduced by (Amin, 2008), marking a shift in focus towards understanding and enhancing the ability of power systems to anticipate, absorb, adapt to, and rapidly recover from potentially disruptive events. This shift reflects a growing recognition of the complex interdependencies between power systems and other critical infrastructures, and the cascading effects that failures can have across sectors. Recent years have seen a surge in scholarly interest in this domain, with researchers exploring various dimensions of power system resilience. This includes the development of methodologies to assess resilience, the design of robust grid

architectures, the integration of renewable energy sources to enhance system flexibility, and the implementation of advanced control strategies to maintain stability during and after disturbances. In light of the increasing frequency and severity of natural disasters, cyber-attacks, and other threats, the resilience of power systems has become a subject of intense study. Ensuring the continuous operation of these systems is not only crucial for economic stability but also for the safety of the population. As such, the ongoing research efforts are critical in paving the way for more resilient power infrastructure capable of withstanding the challenges of the 21st century. The UK Energy Research Center defines power system resilience as follows: resilience is the capacity of an energy system to withstand disturbances and maintain acceptable delivery and service of energy to customers. A resilient energy system can quickly recover from shocks and provide alternative means of energy service in changing external conditions (Chaudry et al., 2011; Preston et al., 2016). Resilience against natural disasters has been raised as one of the most important issues in the distribution network. Resilience can be defined as the system's ability to withstand natural events and return to normal. Natural disasters such as storms, floods, earthquakes, etc, are events that have a low probability of occurrence but have a vast impact on the power system (Wang; Wang; Chen, 2016). Currently, strengthening resilience in the power system is one of the fields studied by researchers.

1.2 JUSTIFICATION

There is an urgent need to maintain resilience in intricate electric power networks given the enormous cost of power system failures brought on by natural catastrophes as well as the effects on public security and safety from the loss of essential infrastructure (Advisers, 2013). Enhancing resilience entails strengthening the ability of these complex grids to withstand and rapidly recover from disruptions. This requires investments in technologies and strategies aimed at preventing failures and containing impacts. Improving situational awareness through sensor networks and analytics facilitates early detection of anomalies. Investing in self-healing technologies enables automatic reconfiguration around failed components. Such solutions can significantly bolster system resilience while providing security and continuity of service that modern society depends on. However, transitioning to more resilient power grids poses numerous technological and regulatory challenges. Solutions must account for the increasing complexity and interconnections of these networks. Upgrading legacy infrastructure requires

balancing cost, feasibility and risk trade-offs. Regulators play a key role in providing effective incentives and appropriate cost-recovery mechanisms. Nevertheless, given the far-reaching ramifications of prolonged grid failures, the need to build resilience is imperative, and strategies must be developed to address this critical issue. Resilience is essential for the aging electricity distribution systems, which are thought to be the cause of 90% of interruptions. The high cost of power system outages due to natural disasters combined with the impacts on personal safety and protection from the loss of essential services urgently calls for improving the resilience of complex electrical power grids (Advisers, 2013). The exigency arises for a paradigm shift necessitating proactive outage management strategies tailored to electrical power distribution systems. This imperative extends beyond the conventional reliability-centric approach, which primarily addresses HILP events. A metric capable of quantifying the potential ramifications of foreseeable HILP occurrences on the network, while also facilitating the assessment and comparison of diverse decision-making alternatives aimed at fortifying the system's operational resilience, becomes imperative. Operational resilience, in the context of electricity distribution systems, denotes the system's aptitude to effectively respond to and recuperate from a HILP event (Panteli; Mancarella, 2015a). Several researchers have proposed different techniques to improve the resilience of distribution networks: microgrids (Liu et al., 2016); reinforcement for robust lines (Wang et al., 2017); distributed generators (DGs) owned by distribution system operators (DSO), especially mobile diesel generators (Arghandeh et al., 2014); and modeling the electrical system as a complex network (Arab et al., 2015; Kheirkhah et al., 2023b). Many optimization-based restoration methods have also been proposed to quantify resiliency based on the amount and duration of restored critical loads (Poudel; Dubey, 2018). Several techniques for quantifying power grid resilience have been developed in relevant research. Because the suggested resilience indicators were primarily non-dimensional numbers, it was hard to place them to real-world implications (Bajpai; Chanda; Srivastava, 2016). Recently, Poudel, Dubey and Bose (2019) have introduced risk-based criteria and a framework for evaluating electricity distribution systems. In Poudel, Dubey and Bose (2019), there is a detailed flexibility quantitative framework that can help to compare the flexibility improvement of the electricity distribution network due to alternative planning measures. It has been proposed a framework for assessing the resilience of electricity distribution systems using risk-based quantitative measures: value at risk (VaR_α); and conditional value at risk ($CVaR_\alpha$). The proposed resilience metrics VaR_α and $CVaR_\alpha$ are motivated by the risk management literature that relates to the quantification of risks

involved with a given financial investment. These metrics assess the impacts of low-probability events that can cause extreme losses for traders (Bardou; Frikha; Pages, 2009). Similar considerations apply when managing the impacts of HILP events, making these metrics suitable for not only quantifying potential impacts but also for bench-marking the potential benefits offered by planning investments. These metrics were also extended to assess the impact of different planning alternatives to resilience enhancement proposals. A well-balanced strategy is required to make the electrical grid more resilient to interruptions. It is not cost-effective to design a distribution network structure that might withstand HILP incidents that occur only seldom. In circumstances like these, it is more acceptable to work on improving the system's capacity to quickly restore from outages. The use of risk assessment is a well-proven strategy for addressing this careful balance. In this procedure, the consequences might range from a health concern to monetary losses, notoriety injury, or profitability decline. The financial effect is most visible in the distribution system and is quantified by estimating the cost of energy not supplied. Typically, cost-benefit assessment involves the evaluation of interruption costs. For instance, in issues of optimal sectionalizing switch placing (Levitin; Mazal-Tov; Elmakis, 1994; Billinton; Jonnavithula, 1996; Celli; Pilo, 1999) and re-allocation (Teng; Lu, 2002), the costs of power losses and capital expenditure in switch equipment configuration are taken into account. These optimization formulas include the blacked-out load, the variety of consumers engaged, and the time-frame of the blackout, which all contribute to the calculation of the interruption cost. Billinton and Wangdee (2005) investigated the total feeder interruption costs as a function of the time of occurrence and the time-frame of the interruption.

1.3 OBJECTIVES

This research project has the following general and specific objectives.

1.3.1 General

This work is intended to minimize the potential risk and maximize the operational resiliency of the electric energy distribution system, taking into account, in an effective way, the economic and social information, of the present and the future. Using predictive models by time series, the determination of the operational conditions for each section of the feeder of the distribution network is related to the risk assessment. Risk mitigation strategies which are self-healing

technologies, thus enable the implementation of various control actions in the automation of the energy distribution system. Operations to increase the reliability and quality of electrical power are supported by the development of these efficient methods that allow system operators to quickly identify the best recovery options.

1.3.2 Specifics

We now outline the major objectives of our research as follows:

- Characterization of resilience in electricity distribution systems;
- Smart grid modeling with probabilistic load flow and unbalanced phases considering distributed renewable generations to determine the state of the grid and calculate the energy not supplied;
- Definition of the most appropriate metrics to quantify and assess the resilience of the distribution system;
- Implementation of a new technique to solve the switching planning problem that allows solving the problem in relatively short computational times and with scalability. This technique may be applicable to electricity distribution companies with an impact on power quality, resilience, and/or reduction in the cost of interruptions in distribution networks;
- Definition of the various terms needed to calculate the resilience metrics of the electricity supply service when subject to interruption;
- Improved system resilience, characterized based on the cost of energy not supplied and system performance assuming probabilistic events;
- Formulation of the switching planning problem through expected and critical operational scenarios;
- Quantitative assessment of VaR_α and $CVaR_\alpha$ risk-based criteria using data from a practical distribution network;
- Use of modern methods of automatic fault location, service isolation and restoration (FLISR), and demand response management (DSM) to reduce risk;

- Effectively increase the operational resilience of the energy distribution system by minimizing potential risk metrics, in particular, VaR_α and $CVaR_\alpha$ values, beyond the specified risk threshold, α .

1.4 CONTRIBUTIONS

We have outlined below the comprehensive framework proposed in our work to enhance distribution network resilience:

- Monetary resilience metrics: definition of risk-based metrics for the total cost of energy not supplied using data from real-world distribution networks. Two risk-based criteria are defined: the monetary value at risk; and the conditional value at risk for an outage exceeding a predefined risk threshold. Thus, resilience is measured as the maximum cost and the expected potential cost;
- Risk mitigation: two smart grid technologies, DSM and FLISR, are employed to assess the proposed metric for the monetary quantification of resilience in distribution networks. Moreover, the advantages of integration are measured using a geographic information system (GIS) visualisation tool;
- Assessment platform: resilience quantification metrics are calculated based on Monte-Carlo simulation (MCS) with probabilistic system vulnerability models for high-impact outage events, as they are non-deterministic.
- In the context of enhancing power grid resilience in an economic network, a probabilistic power flow (PPF) algorithm based on depth-first search (DFS) is applied to analyze and improve the resilience of electric power networks;
- A genetic algorithm is proposed to significantly improve the resilience of the system through network reconfiguration.

5 CONCLUSIONS AND FUTURE WORK

In conclusion, this work presented a comprehensive proof-of-concept study aimed at enhancing the resilience of distribution energy networks through the application of advanced risk assessment and mitigation strategies. The utilization of monetary metrics, specifically VaR_α and $CVaR_\alpha$, for evaluating the cost of energy not supplied proves to be effective in quantifying operational resilience. Through simulations on a realistic 136-bus test system and a real-world distribution network, the proposed metric demonstrates its capability to compare various grid resilience strategies. Also using simulations under a test system with four real-world feeders and a GIS tool, the method proved to be effective. The integration of load balancing, dynamic load redeployment, and self-healing mechanisms, particularly through the application of FLISR, showcases tangible improvements in risk severity assessment and the overall operational resilience of the power distribution network. Risk mitigation strategies, such as FLISR and DSM, play a pivotal role in minimizing outage duration and their associated impacts, providing decision-makers with valuable insights into cost-effective approaches. The framework also uses heat histogram visualizations to demonstrate the effectiveness of these techniques in reducing the duration and impact of outages and assesses their cost-effectiveness to aid decision-makers. The proposed method could be expanded to develop regulatory policies and incentive-penalty systems to achieve resilience goals. This study expands the scope by proposing the application of evolutionary algorithms, including techniques for probabilistic power flow calculations and feeder section identification. The incorporation of stochastic methods, such as Monte Carlo simulations, further enhances the accuracy of risk assessment and the cost of energy not supplied estimation. In parallel, this study delved deeper into complementary methods, such as techniques for load transfer between neighboring feeders, island operation of DGs, and the determination of the maximum penetration capacity of DG. These methods are critical components for effective grid resilience, enabling system operators to quickly identify optimal restoration options. The investigation into these techniques aims to enhance the operational efficiency of the power distribution network and further contribute to the overall resilience of the system. Furthermore, the proposed model's real-world application and evaluation on a distribution

network underscore its practical utility in comparing grid resilience strategies. The potential for developing regulatory policies and incentive-penalty systems based on the resilience metric opens avenues for achieving optimal levels of system resilience in the electricity distribution network. In essence, this work contributes to the field by providing a framework for quantifying and improving the resilience of distribution energy networks. The combination of advanced risk assessment, mitigation strategies, and the proposed resilience metric offers a holistic approach toward achieving a more resilient and reliable power distribution infrastructure. In the pursuit of advancing the presented research, several promising avenues for future work have been identified, each aimed at further enriching the exploration of power distribution network resilience. These planned future endeavors focus on the application of additional optimization algorithms, the refinement of resilience measures, and the development of complementary methodologies. First and foremost, the inclusion of alternative optimization algorithms, such as NSGA-II, stands as a key area for exploration. The intention is to broaden the coverage of the proposed criteria and systematically assess the efficacy of these algorithms in optimizing the mathematical models introduced in this study. Furthermore, the integration of the Gurobi® solver into the optimization process will serve as a benchmark, ensuring a comprehensive comparison and evaluation of algorithmic performance. In future work, the inclusion of alternative optimization algorithms, such as deep reinforcement learning for load restoration, stands as a key area for exploration. In addition to algorithmic enhancements, future work will involve the development of an expansive multi-objective optimization mathematical model. This advanced model will not only encompass the proposed criteria but also incorporate considerations for load modeling, equipment cost, and quality indicators. The overarching goal is to minimize challenges associated with resilience measures and project management risk mitigation. This comprehensive optimization framework aims to provide a holistic approach to decision-making within the realm of power distribution network resilience. Future work will involve the development of an expansive multi-objective optimization mathematical model. This advanced model will not only encompass value-based criteria but also incorporate considerations for time-based quality indicators. In summary, the envisioned future work seeks to elevate the research by incorporating diverse optimization algorithms, expanding mathematical models to accommodate multiple objectives, and exploring complementary methodologies for bolstering grid resilience. These efforts are poised to not only contribute to the academic understanding of power distribution network resilience but also furnish practical insights and solutions for system operators

and decision-makers in the field. As these avenues are pursued, the research is expected to evolve, offering a nuanced and comprehensive perspective on the dynamic landscape of power distribution network resilience.

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