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Research Article

Determining the optimal strategy in self-healing smart distribution network restoration with reliability cost predication method

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Extended Abstract:

The modernization of power distribution networks is a critical frontier in the global transition toward a more resilient, reliable, and intelligent energy infrastructure. A cornerstone of this modernization is the concept of a self-healing distribution network—a system endowed with the autonomous capability to detect, isolate, and restore service after a fault without, or with minimal, human intervention. While the theoretical benefits of self-healing are well understood, a significant challenge remains in the practical implementation of its restoration phase, particularly in optimizing the sequence of control actions to minimize the economic and societal impact of an outage. Traditional restoration strategies often rely on simplistic, rule-based logic that fails to account for the probabilistic and highly variable nature of customer-related outage costs. This gap can lead to suboptimal restoration sequences that, while technically feasible, may not align with the overarching goals of minimizing economic damage and maximizing service continuity for the most critical loads. The research by Hassanzadeh Fard et al. directly addresses this critical shortcoming by proposing a novel, cost-driven, and reliability-based strategy for the restoration of self-healing smart distribution networks. The core innovation of this work is the introduction and application of the Customer Damage Probability Function (CDPF), a sophisticated metric that transcends the limitations of the conventional, static Customer Damage Function (CDF).

The conventional CDF, which assigns a deterministic dollar-per-kilowatt-hour cost to different customer types (e.g., residential, commercial, industrial), provides a valuable but incomplete picture of outage impact. It treats the cost of an outage as a fixed value dependent only on the customer category and the duration of the outage. However, in reality, the true economic and societal damage of an outage is profoundly probabilistic and context-dependent. For instance, the cost of a power outage to a commercial entity is not a fixed value but varies drastically depending on whether it occurs during business hours or on a public holiday. Similarly, the impact on an industrial facility can depend on the specific phase of its production cycle or the ambient temperature, which may affect the spoilage of temperature-sensitive goods. The CDF, by its static nature, is blind to these crucial contextual factors. To overcome this fundamental limitation, the authors propose the CDFP, which calculates a unique damage cost profile for each individual feeder in the network. This profile is not a single number but a function that incorporates the probabilistic likelihood of various damage scenarios based on a multitude of real-world factors, including the time of day, the day of the week, seasonal variations, and the specific mix of customer types on that feeder. This approach allows for a far more granular, realistic, and dynamic assessment of the true cost of an outage.

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The primary objective of the paper is to integrate this CDPF into the decision-making logic of the network's self-healing system to determine the optimal restoration strategy during the critical post-fault period. This strategy is not just about re-energizing the maximum number of customers in the shortest time, but about re-energizing the right customers in an order that minimizes the total expected economic damage. The proposed framework is designed to empower the network's automated control functions to make economically rational decisions, thereby transforming the restoration process from a purely technical exercise into an intelligent, value-driven operation.

To validate the efficacy and practicality of the CDPF-based strategy, the authors developed a detailed simulation model of a composite feeder in a smart distribution network. The performance of the CDPF method was rigorously compared against the traditional CDF approach and another well-established probabilistic technique: the Monte Carlo (MC) simulation. The MC method, while highly accurate in theory, is known for its computational inefficiency, especially in large-scale, real-time applications. It requires a vast number of random sampling iterations to converge on a reliable estimate of the expected cost, a process that can be prohibitively slow for a self-healing system that must act within seconds or minutes of a fault. To address this speed-accuracy trade-off, the paper introduces and leverages the Universal Generating Function (UGF) method as the computational engine for the CDPF. The UGF is a powerful mathematical technique for the analysis of multi-state systems, which are systems that can exist in more than two states (e.g., not just 'working' or 'failed', but various levels of partial performance). By modeling each feeder as a multi-state component with its own probabilistic cost profile, the UGF can rapidly and accurately calculate the total system-wide expected cost of any given restoration sequence.

The simulation results are both compelling and definitive. The study demonstrates that the CDPF, when implemented via the UGF method, is not only accurate but also extraordinarily fast. The UGF-based CDPF calculation achieved the same result as the Monte Carlo method but with a dramatic improvement in computational speed. While the Monte Carlo simulation required over 150 seconds (approximately 2.5 minutes) to converge to a stable solution using 10 million iterations, the UGF method delivered the identical result in a mere 7 milliseconds. This represents a speed improvement of more than 21,000 times, a difference that is not just incremental but transformative for real-time grid applications. This computational efficiency is the key enabler that makes the sophisticated, probabilistic logic of the CDPF viable for deployment in an actual self-healing system. It allows the network's control center to evaluate multiple restoration scenarios in near real-time and select the one that is not only technically valid but also the most economically sound.

Furthermore, the paper underscores the critical insight that a self-healing strategy based solely on technical metrics like the number of restored customers or the speed of restoration may be economically myopic. A restoration sequence that prioritizes a feeder with a high number of residential customers might be technically straightforward, but if that sequence leaves a feeder serving a hospital or a data center in the dark, the total societal and economic cost would be unacceptably high. The CDPF framework explicitly embeds this economic and societal intelligence into the restoration logic. It ensures that the self-healing system's "smartness" is not limited to its ability to reconfigure the network topology, but extends to its understanding of the real-world value of the services it provides.

In conclusion, this research makes a significant and practical contribution to the field of smart grid automation. It successfully bridges the gap between the theoretical concept of a self-healing network and its real-world economic and operational requirements. By replacing the static CDF with the dynamic, probabilistic CDPF and solving it with the highly efficient UGF method, the authors have developed a restoration strategy that is simultaneously intelligent, accurate, and fast enough for real-world implementation. This approach promises to enhance the overall value proposition of smart grids by ensuring that their automated responses to faults are not only technically correct but also aligned with the ultimate goals of minimizing economic disruption and maximizing service quality for the community. The framework is also highly scalable and can be readily adapted to different regulatory environments and market structures by simply updating the underlying probabilistic damage models for

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each feeder. This work, therefore, offers a robust and actionable blueprint for the next generation of self-healing distribution networks.

Keywords: Self-healing distribution networks; Smart restoration; Predicting the cost of reliability**.**

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