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Mixed-Method Analysis of Reliability-Centered Design Practices in Medium and Low-Voltage Electrical Distribution Systems

Md Siam Taluckder[1]; Md. Shahinur Islam[2];

[1]. *Master of Engineering in Electrical and Computer Engineering, Lamar University, TX, USA; Email: mtaluckder@lamar.edu*

[2]. *Master of Engineering in Electrical and Computer Engineering, Lamar University, TX, USA; Email: islam.shahinur0999@gmail.com*

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Abstract

This study addresses the persistent reliability challenges in medium- and low-voltage electrical distribution systems, where interruptions, delayed restoration, weak fault isolation, and uneven design quality continue to undermine service continuity and operational efficiency. Its purpose was to examine how reliability-centered design practices influence reliability performance, operational efficiency, and system dependability across selected case-based electrical distribution environments. Using a quantitative, cross-sectional, case-based design, the study collected primary data from 120 usable respondents out of 150 distributed questionnaires, yielding an 80.0% usable response rate. The sample comprised electrical engineers, maintenance engineers, distribution planners, operations officers, and technical supervisors/managers working across medium-voltage systems, low-voltage systems, and both system classes. The key independent variables were protective coordination, redundancy planning, fault isolation capability, switching and restoration readiness, and equipment standardization, while the dependent variables were reliability performance, operational efficiency, and system dependability. Data were analyzed using descriptive statistics, a Reliability-Centered Design Practice Index, correlation, t-test, and multiple regression in SPSS. The findings showed a high overall level of design-practice adoption with an RCDPI mean of 3.87, while reliability performance, operational efficiency, and system dependability recorded means of 3.91, 3.83, and 3.88 respectively. Protective coordination had the highest mean score at 4.02, followed by fault isolation capability at 3.94. Reliability-centered design practices were strongly and positively associated with reliability performance ($r = 0.71$, $p < 0.001$) and operational efficiency ($r = 0.66$, $p < 0.001$), while the strongest relationship was observed with system dependability ($r = 0.74$, $p < 0.001$). Medium-voltage systems outperformed low-voltage systems, with RCDPI scores of 3.95 and 3.78 respectively, and the difference was statistically significant ($t = 2.41$, $p = 0.017$). Regression results further showed that design variables explained 58.4% of the variance in reliability performance and 61.7% of the variance in system dependability, confirming that reliability-centered design is a critical engineering and planning mechanism for improving distribution-system outcomes.

Keywords

Reliability-Centered Design, Electrical Distribution Systems, Reliability Performance, Fault Isolation Capability, System Dependability;

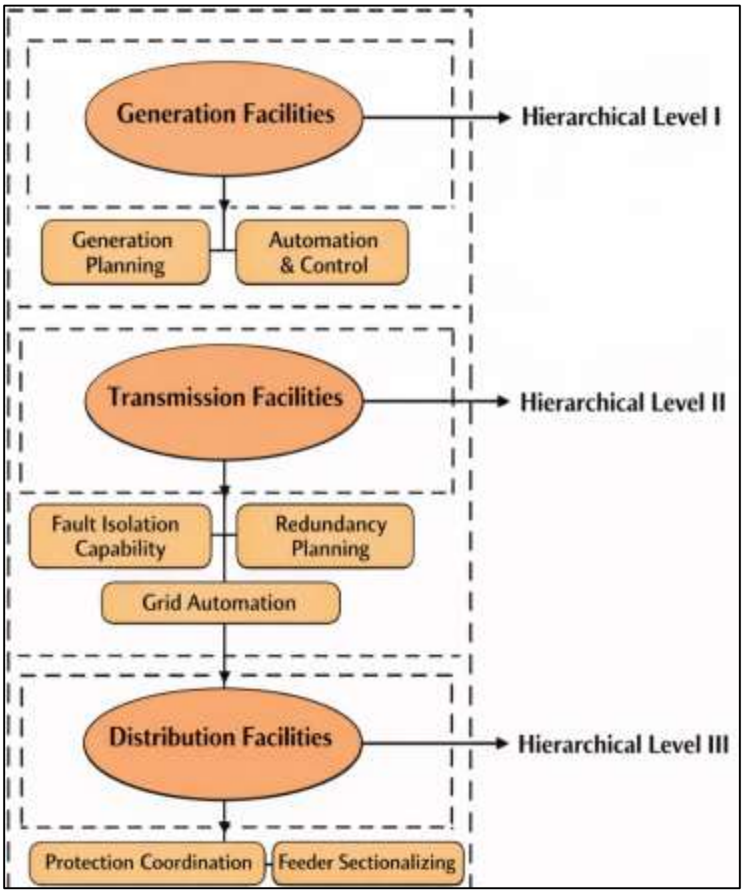
INTRODUCTION

Reliability in electric power engineering is commonly understood as the ability of a power system, subsystem, or component to perform its intended function under stated operating conditions for a specified period of time (Ahmad & Asar, 2021). Within this broad engineering meaning, distribution-system reliability refers to the continuity, adequacy, and quality of electricity supply delivered to end users through feeders, transformers, protection devices, switching arrangements, and associated control infrastructure. Medium-voltage and low-voltage distribution systems constitute the final delivery architecture that connects bulk electricity supply with residential, commercial, public-service, and industrial loads; for that reason, they are the most visible part of power-system performance from the customer's standpoint. Reliability-centered design, in this context, can be defined as a structured engineering orientation in which network topology, component selection, protection philosophy, redundancy, automation, switching capability, and maintainability are intentionally configured so that the system can reduce failure exposure, contain fault consequences, and restore service efficiently (Faria et al., 2020). The international significance of this subject is substantial because modern economies increasingly depend on continuous electricity for digital services, healthcare systems, water infrastructure, industrial production, transportation support functions, and commercial activity. As electricity demand grows and distribution networks become more complex through distributed generation, digital controls, and new customer loads, design quality becomes inseparable from public welfare and economic stability (Mirhosseini & Keynia, 2021). Electric-network maintenance and performance have long been linked with the need to balance customer interruption costs and utility expenditure, showing that reliability has a direct economic dimension in system planning and management. Later work advanced a comprehensive reliability-centered maintenance logic for distribution systems and made clear that reliability cannot be treated merely as a post-failure operational concern because component criticality and system-wide consequences must be understood in a structured framework. More recent studies have also shown that modern distribution-network reliability assessment extends well beyond traditional outage counting, as distributed energy resources, automation, communication, and restoration flexibility have altered the logic of reliability analysis itself (Parol et al., 2022). In that sense, reliability-centered design is not only an engineering preference; it is an internationally relevant requirement for secure and dependable electricity service in increasingly electrified societies.

The importance of design becomes clearer when distribution systems are examined as the section of the power system where a large share of interruptions originate and where the structural arrangement of components strongly shapes outage frequency and duration (Devi et al., 2022). A distribution network is not a single device but a coordinated technical environment composed of radial or ring configurations, sectionalizing points, transformers, overhead lines, underground cables, protective relays, reclosers, fuses, communication devices, and restoration pathways (Dehghanian et al., 2013a). The reliability of such a network is therefore inseparable from how those elements are arranged and coordinated. Research on power-system reliability has shown that analytical and simulation-based evaluation methods are useful only when the design logic of the network is explicitly represented, because the performance of the system depends not only on component failure rates but also on topology, switching accessibility, fault isolation possibilities, and local supply alternatives. Advanced computational approaches have supported reliability assessment, yet their usefulness depends on a coherent system model. When active distribution systems include microgrids and distributed generators, reliability analysis becomes more sensitive to operational structure and network arrangement, particularly under conditions involving bidirectional power flow and multiple contingencies (Dehghanian et al., 2013b). Later research linked graph-theoretic network properties with reliability, showing that topology itself is a meaningful explanatory variable rather than a mere background feature. Machine-learning-based reliability evaluation has likewise shown that the efficiency of topology analysis and the representation of failure behavior condition the quality of reliability evaluation in power distribution networks. Reviews on reliability evaluation in distribution networks with microgrids have further emphasized that multiple configurations and service-restoration possibilities must be considered, while broader reviews of microgrid modeling have reaffirmed that reliability improvement is bound up with system architecture and operational mode.

These studies collectively establish that reliability in medium- and low-voltage distribution systems is not merely observed in service outcomes, but is materially shaped by the design decisions embedded in the network structure long before outages occur (Da Rosa et al., 2012).

Figure 1: A Hierarchical Representation of Reliability-Centered Design Practices Across Generation, Transmission, and Distribution Systems



A reliability-centered perspective also requires attention to the historical movement from maintenance-centered thinking toward broader asset and design-centered decision making in electrical networks. Reliability-centered maintenance literature has been particularly influential because it treats asset performance, failure modes, and criticality as system-level concerns rather than isolated technical events. Within power distribution systems, this literature has provided analytical tools for prioritizing components, allocating maintenance resources, and identifying critical subsystems whose failure has disproportionate consequences for customers and network operation (Begum & Nazmul, 2021; Li et al., 2020). Practical reliability-centered maintenance optimization procedures for power distribution systems have emphasized the importance of identifying critical failure modes and cost-effective interventions. Later work expanded this reasoning through a more rationalized dependability-oriented optimization approach, arguing that conventional reliability-centered maintenance should be broadened through a more complete RAMS-oriented treatment of electrical systems (Ara, 2021; Nazir et al., 2022). A rigorous reliability-centered framework in distribution systems has also been shown to begin with pre-analysis, proceed through component criticality identification, and end with benefit-to-cost prioritization of maintenance actions. Numerical analysis has further demonstrated that such frameworks can identify system components whose upkeep meaningfully affects network reliability (Ahmed & Hasan Or, 2021; Khaled, 2021). Reviews of asset management and maintenance programming for power distribution systems have concluded that asset planning, preventive interventions, and reliability performance should be studied together rather than as disconnected tasks (Robel & Morshedul, 2021; Sandelic et al., 2022; Zaheda, 2021). More recent ranking-based reliability maintenance approaches for distribution-system components under budget limitations have again emphasized that reliability improvement depends on identifying which elements of the network matter most to continuity of supply (Aditya & Robel, 2022; Istiaq & Nusrat, 2022). What is especially important for the present study is that this body of research, while framed around maintenance, repeatedly reveals a deeper principle: the reliability of distribution systems is inseparable from the way equipment is selected, arranged, protected, and prioritized in network architecture (Ahmed & Rajib, 2022; Khaled & Hisham, 2022). That principle aligns directly with reliability-centered design because a well-designed system reduces the burden on maintenance by limiting vulnerability at the planning and design stage. For medium- and low-voltage systems, where asset density and service exposure are both high, this design-centered reading of the reliability literature is especially relevant (Gruosso et al., 2019; Mehedi & Md, 2022; Mainuddin & Chandra, 2022).

The technical substance of reliability-centered design becomes more concrete when specific design practices are considered. In distribution engineering, reliability is strongly influenced by protection coordination, feeder sectionalization, switching accessibility, redundancy paths, automation, distributed generation placement, and network reconfiguration capacity. These are design decisions because they are established through engineering choices about system structure and control philosophy (Escalera, Hayes, et al., 2018; Morshedul et al., 2022; Nazmul & Begum, 2022). Reviews of network reconfiguration as a means of improving reliability and reducing power losses have shown that changes in feeder configuration, tie-switch operation, and radial structure can materially alter system performance. More recent work has also confirmed that network reconfiguration affects reliability indices and loss behavior, reinforcing that feeder arrangement and switching logic remain fundamental design variables (López-Prado et al., 2020; Shahinur & Sultan, 2022; Binte & Hasan Or, 2022). Studies on automation in electric distribution networks have highlighted how automation architecture, communication latency, and control response influence the speed and quality of service restoration (Begum & Kaniz, 2023; Ara & Onyinyechi, 2023). Protection system planning through probabilistic approaches has further demonstrated that the allocation, sizing, and coordination of control and protective devices have direct effects on non-supplied energy and interruption-duration measures. Research on optimal distributed-generation placement has shown that source location within a distribution network affects SAIFI, SAIDI, and energy-not-supplied outcomes, thereby linking source placement with reliability enhancement (Islam & Aditya, 2023; Ahmed & Mehedi, 2023; Sultana et al., 2016). Graph-theoretic work has also added a topological dimension by showing that graph structure and similarity characteristics can be associated with reliability level and can guide optimization strategy. Taken together, these studies show that reliability-centered design is not an abstract slogan. It is operationalized through concrete network decisions: where to place switching devices, how to coordinate protective equipment, whether to create restoration flexibility, where to position local generation, and how to configure feeders so that the consequences of a fault remain geographically and electrically limited (Hasan Or et al., 2023; Mainuddin & Chandra, 2023). In medium- and low-voltage systems, where customers are close to failure points and interruption sensitivity can be high, such design practices become decisive in shaping real reliability outcomes (Mehedi & Nahar, 2023; Mostafa, 2023; Xu et al., 2019).

Another important feature of the contemporary literature is that it places medium-voltage and low-voltage distribution reliability within a changing technical environment marked by distributed generation, energy storage, microgrids, communication infrastructure, uncertain loading, and digital control. This matters because reliability-centered design in older, purely radial, one-directional systems differs from reliability-centered design in modern networks that may contain renewable generation, automation, controllable switches, and ICT dependencies (Girón et al., 2018; Chandra, 2023; Khatun & Zakia, 2023). Comparative work on renewable distributed-generation models used in reliability assessment has shown that model choice changes how reliability contributions are interpreted. Analytical work on distribution networks with energy storage in islanded and emergency-tie restoration modes has illustrated how local flexibility alters restoration capability and therefore system reliability (Begum & Kaniz, 2024; Hisham & Nahar, 2024). Broader surveys of modern distribution-network reliability assessment have also emphasized that distributed generation, energy storage, electric vehicles, demand response, automation, and communication technologies must be included if reliability studies are to remain meaningful (Escalera et al., 2019). Uncertainty-oriented perspectives have further shown that probabilistic load-flow analysis in distribution networks is necessary when load variability is significant, which is especially relevant at low-voltage levels where customer diversity and emerging loads create changing operating states (Escalera, Prodanovic, et al., 2018b; Escalera et al., 2019; Khaled & Morshedul, 2024; Mehedi & Nahar, 2024). Reliability-oriented design in microgrids has also been found to require explicit treatment of design criteria, resource sizing, scheduling, and power-electronics reliability. In addition, reliability analysis of medium-voltage distribution systems with distributed generation and ICT infrastructure has demonstrated that reliability analysis must reflect the co-existence of electrical and communication subsystems (Towhidul & Uddin, 2024; Robel & Morshedul, 2024). The cumulative lesson from this literature is that reliability-centered design in present-day medium- and low-voltage networks cannot be reduced to stronger hardware alone (Rajib, 2024; Zakia & Khatun, 2024). It involves the coordinated structuring of physical and informational infrastructure so that uncertainty, local faults, restoration actions, and supply alternatives are handled in an orderly and resilient manner. This broader understanding is highly relevant for a study that seeks to examine reliability-centered design practices empirically within actual distribution-system settings (Bie et al., 2012).

At the same time, the literature indicates an important methodological tension that supports the need for the present study. Much of the existing work on distribution-system reliability is technical, model-based, and simulation-oriented. Such work is indispensable because it quantifies outage indices, restoration options, and reliability effects of topology or equipment decisions. Yet the same literature shows that reliability practice in real systems is also shaped by engineering judgment, organizational prioritization, asset constraints, and case-specific design choices that are not fully visible in model outputs alone. Reviews of reliability evaluation in distribution networks with microgrids have classified methodological approaches while also showing the diversity of assumptions embedded in the literature (Yssaad et al., 2014). Broader reviews of microgrid reliability modeling have similarly pointed to the multiplicity of representation schemes used in practice. Other studies have highlighted the continuing challenge of representing topology and failure features in a form suitable for practical reliability evaluation, while some have addressed topology through graph theory, protection design probabilistically, and automation performance through communication-sensitive modeling. These are rigorous contributions, yet they also reveal fragmentation: one line of work emphasizes maintenance and criticality, another focuses on automation, another on protection planning, another on topology, and another on distributed energy resources. Reviews of maintenance programming and asset management for distribution systems likewise show that practical decision-making in utilities spans a much wider field than any single analytical method captures (Yssaad & Abene, 2015). For a study centered on reliability-centered design practices, this fragmentation matters because design practice is inherently integrative. Engineers do not design medium- and low-voltage systems by considering protection, redundancy, switching, component criticality, distributed-generation placement, and restoration flexibility in isolation. They combine them in case-based environments shaped by operational expectations and service objectives. This creates a strong rationale for a cross-sectional, case-study-based investigation that measures how such practices are perceived, adopted, and linked to reliability outcomes in actual organizational contexts rather than only in algorithmic test systems.

Against this scholarly background, the present research is positioned within a line of inquiry that treats reliability not as an accidental result of network operation but as a property shaped by structured engineering decisions in medium- and low-voltage distribution systems. The reviewed studies collectively show that reliability performance is associated with component criticality management, maintenance prioritization, automation architecture, protective-device coordination, network topology, distributed-generation placement, uncertainty modeling, and restoration capability. They also show that modern reliability evaluation increasingly integrates distributed resources, communication infrastructures, and local control mechanisms. What remains especially valuable for this thesis is the opportunity to translate these technical insights into empirically measurable design-practice dimensions appropriate for a quantitative, cross-sectional, case-based study (Mirhosseini et al., 2022). In practical terms, this means focusing on design-oriented variables such as protective coordination, redundancy planning, fault isolation capability, switching and restoration readiness, equipment standardization, automation support, and distributed-generation integration as elements that may be associated with observed reliability performance and operational efficiency. Such a framing is consistent with the movement in the literature from isolated reliability metrics toward more integrated evaluation of how network architecture and asset strategy shape service continuity. It is also consistent with the medium- and low-voltage focus of this research, because these are the system levels where feeder arrangement, customer density, restoration time, and design tradeoffs are experienced most directly (Hilber et al., 2007). The introduction of a study-specific empirical assessment of reliability-centered design practices therefore fits squarely within the documented evolution of distribution-reliability research, while preserving the engineering specificity necessary for meaningful analysis of electrical distribution systems (Escalera, Prodanovic, et al., 2018a).

Background of the Study

The background of this study is rooted in the growing importance of reliable electrical power distribution in supporting modern economic activity, industrial productivity, public services, and everyday life. Medium- and low-voltage electrical distribution systems form the final and most directly experienced stage of the electricity supply chain, delivering power from substations and local distribution points to homes, businesses, institutions, and industrial users. Because these systems operate at the interface between technical infrastructure and end users, any weakness in their design can lead to frequent interruptions, equipment stress, voltage irregularities, reduced operational efficiency, and increased maintenance burdens. In many regions, distribution networks are under increasing pressure due to rapid urbanization, rising electricity demand, aging infrastructure, network expansion, and the integration of more complex loads and decentralized energy sources. These developments have made reliability no longer a narrow maintenance issue but a broader engineering priority that begins at the design stage. Reliability-centered design practices therefore have become increasingly significant because they focus on building resilience, fault tolerance, maintainability, safety, and continuity of service directly into the architecture of the system. Such practices include appropriate feeder configuration, protective coordination, redundancy planning, effective fault isolation, equipment standardization, and restoration-oriented network planning. When these design elements are carefully considered, the distribution system is better positioned to withstand disturbances, limit the spread of failures, and recover service more efficiently. When they are weak or inconsistently applied, technical problems often become recurring operational challenges. This study emerges from the need to understand how these reliability-centered design practices function within medium- and low-voltage distribution environments and how they relate to the broader goals of service dependability and operational effectiveness. It also reflects the recognition that many reliability problems are shaped long before a fault occurs, through decisions made during planning and design. By focusing on the role of design practices in real distribution-system settings, the study addresses an important area in electrical engineering where technical performance, infrastructure quality, and service outcomes are closely connected.

Problem Statement

The problem addressed in this research arises from the persistent reliability challenges experienced in medium- and low-voltage electrical distribution systems and from the limited attention given to the role of design-stage decisions in shaping those outcomes. In many distribution environments, system interruptions, voltage instability, localized faults, delayed restoration, equipment overloading, and operational inefficiencies continue to affect the quality and continuity of supply delivered to end users. These challenges are often examined from the perspective of maintenance failure, aging components, weather exposure, or operational response, while the contribution of design-related factors remains less clearly examined in an integrated and empirical manner. In practice, the reliability of a distribution system is strongly influenced by how the network is initially configured, how protection is coordinated, how redundancy is built into feeder arrangements, how effectively fault isolation is enabled, and how equipment is selected and standardized across the system. When these reliability-centered design practices are weak, inconsistent, or inadequately aligned with actual service demands, the result may be a network that is more exposed to recurring failures, prolonged service interruptions, and inefficient operating conditions. Another dimension of the problem is that medium-voltage and low-voltage distribution systems are often discussed together in broad technical terms, even though they may differ in structural complexity, customer exposure, restoration requirements, and operational risk. This creates a gap in understanding how reliability-centered design practices function across the two voltage classes and whether the same design priorities produce similar outcomes in both contexts. The problem is further intensified by the lack of sufficient empirical studies that examine these issues through a structured quantitative, cross-sectional, and case-study–based approach. Many available discussions are technical or simulation-based and do not adequately capture how professionals within actual distribution environments perceive, apply, and evaluate design practices in relation to system reliability and operational efficiency. As a result, there remains a need for a focused study that identifies the major reliability-centered design practices used in medium- and low-voltage electrical distribution systems, examines their relationship with reliability performance, and determines the extent to which they predict broader outcomes such as system dependability and operational efficiency. This study is therefore designed to address a practical and scholarly problem that lies at the intersection of design quality, infrastructure performance, and reliable electricity service delivery.

Objectives of the Study

The objective of this study is to examine reliability-centered design practices in medium- and low-voltage electrical distribution systems in order to understand how such practices shape reliability performance, operational efficiency, and system dependability within selected case-study contexts. More specifically, the study seeks to identify the principal design practices that are associated with reliability-centered planning and system architecture, including such areas as protective coordination, redundancy planning, feeder configuration, fault isolation capability, equipment standardization, and restoration-oriented design readiness. By focusing on these dimensions, the study aims to move beyond a general discussion of reliability and toward a more structured understanding of how design choices influence the operational behavior of distribution systems. A further objective is to assess the level to which these reliability-centered practices are present across the selected systems and to determine whether their level of adoption differs between medium-voltage and low-voltage environments. The study also aims to measure the reliability outcomes associated with these design practices by examining how they relate to perceptions of service continuity, fault reduction, restoration effectiveness, and operational efficiency. Another important objective is to establish whether statistically meaningful relationships exist between the identified design variables and system reliability indicators, thereby providing a basis for empirical evaluation rather than technical assumption alone. In addition, the study is designed to determine the predictive strength of reliability-centered design practices by using regression analysis to estimate the extent to which design variables explain changes in system dependability and efficiency. Through this approach, the research intends to clarify which design practices appear most influential and which areas may represent critical weaknesses or risk hotspots within the distribution systems under study. The objective section of this research is therefore not limited to description; it is centered on systematic measurement, comparison, and explanation. In broader academic terms, the study aims to provide a structured quantitative foundation for understanding reliability-centered design within electrical distribution systems, while in practical terms it seeks to generate evidence that may support better design decisions, improved planning standards, and stronger alignment between engineering configuration and service performance. These objectives define the scope and direction of the study and provide the basis for the research questions, hypotheses, analysis, and interpretation that follow in the remaining sections of the research.

Research Hypotheses

The research hypotheses of this study are formulated to test the expected relationships between reliability-centered design practices and key performance outcomes in medium- and low-voltage electrical distribution systems. The logic behind these hypotheses is that distribution-system reliability is not only affected by operational response or maintenance activities, but also by the quality and consistency of engineering decisions made at the design stage. Since the study is quantitative, cross-sectional, and case-study–based, the hypotheses serve as formal statements that can be examined statistically through correlation and regression analysis using data collected from respondents with relevant technical and operational knowledge. The first hypothesis is concerned with the relationship between reliability-centered design practices and overall reliability performance, based on the assumption that systems designed with stronger protection coordination, clearer fault isolation pathways, and better redundancy planning are likely to perform more effectively under routine and disturbed operating conditions. The second hypothesis focuses on the relationship between these design practices and operational efficiency, recognizing that well-designed distribution systems are generally easier to manage, restore, and maintain in a cost-conscious and time-efficient manner. The third hypothesis addresses variation across voltage classes by proposing that medium-voltage and low-voltage systems may differ significantly in the level or effectiveness of reliability-centered design practices due to differences in network structure, exposure, and operational demands. The fourth hypothesis is predictive in nature and is intended to test whether identified design variables significantly explain system dependability when examined together in a statistical model. These hypotheses collectively transform the study from a descriptive investigation into an explanatory one, because they allow the researcher to test whether the observed associations are strong enough to support meaningful analytical claims. They also ensure that the study remains closely aligned with its objectives by directly connecting design-related variables with the outcomes the research seeks to understand. In methodological terms, the hypotheses provide the structure for statistical testing and guide the organization of the results chapter. In substantive terms, they reflect the central assumption of the research: that reliability-centered design practices are measurable, comparable, and capable of influencing how effectively medium- and low-voltage electrical distribution systems perform. The hypotheses therefore form a critical part of the study's analytical foundation and help position the research within a rigorous empirical framework.

Significance of the Research

The significance of this research can be understood from several academic, technical, and practical perspectives:

i. This study is significant to the field of electrical power engineering because it gives focused attention to reliability-centered design as a critical determinant of distribution-system performance. Rather than treating reliability only as an outcome of maintenance or operations, it places design practice at the center of analysis and therefore strengthens understanding of how system performance is shaped from the planning stage.

ii. The research is significant to utility companies, distribution planners, and practicing engineers because it provides empirical evidence on which design practices are most closely associated with reliability performance and operational efficiency. Such evidence can support more informed decisions in feeder planning, protection design, redundancy allocation, and restoration strategy.

iii. The study is significant because it addresses both medium-voltage and low-voltage electrical distribution systems within the same analytical framework. This allows for a more meaningful comparison of design practice across voltage classes and improves understanding of whether the same reliability-centered principles operate equally well in both contexts.

iv. The research is significant in methodological terms because it applies a quantitative, cross-sectional, and case-study–based design to an area that is often dominated by purely technical modeling or simulation studies. By collecting structured data from knowledgeable respondents and analyzing that data statistically, the study contributes a grounded empirical perspective to the literature.

v. This study is significant because it introduces a more structured way of examining reliability-centered design practices through measurable variables such as protective coordination, redundancy planning, fault isolation capability, and equipment standardization. This strengthens analytical clarity and makes the topic easier to evaluate systematically.

vi. The research is significant to infrastructure management and service delivery because improved understanding of reliability-centered design can support better continuity of electricity supply, reduced interruption exposure, improved restoration performance, and more efficient system operation in environments where dependable electricity is essential.

vii. The study is also significant academically because it contributes to the growing body of literature on distribution-system reliability by linking design practice directly with system outcomes such as dependability and operational efficiency. In doing so, it provides a basis for further research on design quality, network resilience, and evidence-based reliability planning in electrical distribution systems.

LITERATURE REVIEW

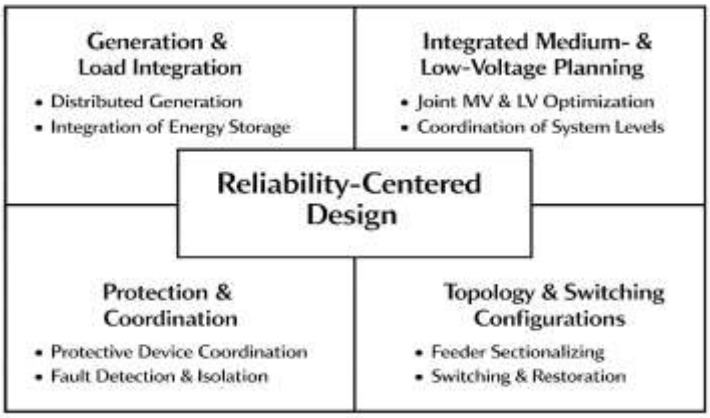
The literature review for this study is centered on the body of knowledge that explains how reliability is understood, measured, and improved in medium- and low-voltage electrical distribution systems, with particular attention to the role of design-oriented practices in shaping service outcomes. In electrical distribution research, reliability is often discussed in relation to continuity of supply, fault frequency, outage duration, restoration capability, and the general ability of the system to deliver electric power in a stable and dependable manner. At the same time, design practice is treated as a foundational engineering activity through which system components, protection logic, feeder arrangements, redundancy paths, switching structures, and restoration options are organized to support desired performance outcomes. The literature therefore provides two important lines of understanding that are directly relevant to this research. The first line examines the technical and operational nature of distribution-system reliability, including the challenges that arise in medium-voltage and low-voltage networks due to complexity, aging infrastructure, increasing load demand, fault exposure, and network expansion. The second line addresses the engineering decisions that influence those outcomes, especially decisions related to reliability-centered design. These include protective coordination, feeder configuration, redundancy planning, equipment standardization, automation support, and fault isolation capability. A review of the literature is necessary because the present study is not only interested in whether distribution systems are reliable, but also in how specific design practices may help explain differences in reliability performance, operational efficiency, and system dependability. The literature review also provides the theoretical and conceptual grounding for the research by identifying the core assumptions, variables, and relationships that support the study's hypotheses and analytical model. In addition, it helps clarify the methodological position of the study by showing where previous work has focused on simulation, technical modeling, maintenance optimization, or system evaluation, and where there remains room for a quantitative, cross-sectional, case-study–based examination of design practices in real distribution-system contexts. This makes the literature review a necessary foundation for defining the study's scope, supporting its variables, establishing its theoretical direction, and identifying the gap that the research is intended to address.

Reliability-Centered Design in Electrical Distribution Systems

Reliability-centered design in electrical distribution systems refers to the deliberate incorporation of engineering features, structural arrangements, and protection philosophies that improve the ability of the system to deliver power continuously, safely, and efficiently under normal and disturbed operating conditions. In distribution engineering, this idea goes beyond simple hardware selection because it includes the way feeders are configured, how substations are linked to downstream networks, how switches and protective devices are coordinated, how load is distributed across the system, and how restoration can be achieved when a fault occurs (Janjic et al., 2018). The concept is rooted in the recognition that many reliability outcomes are determined long before system operation begins, because the design stage establishes the technical limits within which maintenance teams, operators, and planners must later work. A poorly designed system may remain vulnerable even when maintenance is regular, while a well-designed network can absorb disturbances more effectively and support quicker restoration with fewer service interruptions. For this reason, reliability-centered design is closely associated with distribution planning, since planning decisions shape the long-term technical character of the system. In modern distribution-planning literature, reliability is treated as a core objective alongside economy, safety, and operational flexibility, which means that design is no longer judged only by minimum initial cost or physical feasibility. Instead, design quality is evaluated according to whether it can support continuity of service, accommodate changing load patterns, and respond effectively to uncertainty within the network environment. This broader understanding is especially important in medium- and low-voltage systems because those parts of the network are closest to customers and are exposed directly to feeder faults, switching delays, overloaded segments, and local design weaknesses. A major contribution of the planning literature is that it presents design as a multi-criteria activity in which reliability must be balanced with investment, losses, operational constraints, and the changing structure of modern grids, thereby making reliability-centered design a foundational principle rather than a secondary technical preference (Georgilakis & Hatziargyriou, 2015). In this sense, the literature frames reliability-centered design as an intentional engineering strategy that organizes network architecture around dependable service performance.

The relevance of reliability-centered design becomes even clearer when medium-voltage and low-voltage systems are considered together as interconnected planning layers rather than separate technical territories. In practical distribution systems, the medium-voltage network provides the primary local distribution backbone, while the low-voltage system translates that supply into service at the customer level. Because failures, overloads, voltage problems, and restoration constraints may emerge at either level, a reliability-centered design philosophy requires coordinated planning across both. This means that transformer siting, conductor sizing, radial structure, feeder segmentation, and backup supply opportunities must be examined in relation to one another rather than in isolation. A design that appears adequate in the medium-voltage layer may still create poor reliability outcomes if it leaves the low-voltage layer vulnerable to excessive loading, weak redundancy, or inadequate protection paths. In the same way, improvements at the low-voltage level may have limited effect if they are not supported by a robust upstream design (Ehsan & Yang, 2018). The literature on integrated medium- and low-voltage planning therefore contributes directly to the study of reliability-centered design by showing that reliability is improved when both system levels are optimized jointly with explicit consideration of investment, operation, and reliability cost. Such work treats reliability as a measurable planning objective and demonstrates that distribution design must account for network coupling, not only isolated components. At the same time, the broader distributed-generation literature adds another important dimension by showing that the placement and sizing of distributed sources can materially affect line losses, voltage behavior, and service performance. This is highly relevant to reliability-centered design because source placement is itself a design decision, one that changes power-flow patterns and influences the operational stress placed on network elements. The implication is that reliability-centered design is not confined to the arrangement of passive infrastructure but also includes active decisions about how generation and load support are embedded within the network. The literature therefore presents reliability-centered design as an integrated planning logic that links feeder structure, equipment allocation, and distributed-energy positioning into a coherent reliability-oriented framework (Rupolo et al., 2017; Acharya et al., 2006). This integrated view is especially useful for studies that examine real distribution-system practices across multiple voltage classes (Acharya et al., 2006).

Figure 2: Integrated Design Components Supporting Reliability-Centered Electrical Distribution Systems



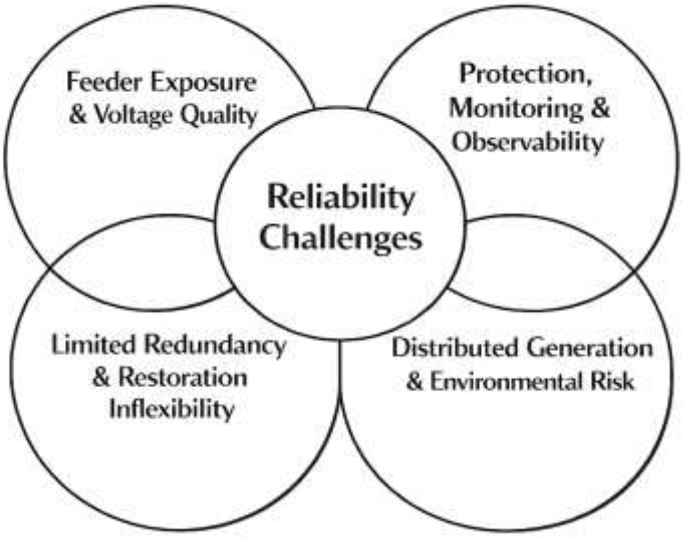
A further theme in the literature is that reliability-centered design has become more complex because contemporary distribution systems are expected to accommodate distributed generation, bidirectional power flow, automation technologies, and more demanding protection requirements. Traditional radial systems were often planned with relatively stable demand patterns and unidirectional power transfer in mind, but modern distribution networks increasingly contain embedded energy resources and more dynamic operating conditions. Under these circumstances, the design question is no longer limited to whether a feeder can serve a forecasted load; it must also address whether the network structure can maintain protection coordination, preserve service continuity, and recover quickly when operating conditions change (Rupolo et al., 2017). This is where reliability-centered design becomes a particularly useful analytical lens. It highlights the need to connect planning choices with network performance under realistic operating constraints, including uncertainty, local generation, and changes in the direction and magnitude of current flow. The planning literature on renewable distributed generation emphasizes that inappropriate siting or sizing may produce reliability and protection difficulties even when distributed generation is installed for beneficial reasons such as loss reduction or voltage support. In the same way, protection-oriented studies show that distributed generation can disturb relay coordination and alter the fault-current profile of the network, which means that reliability-centered design must include careful attention to protective settings and mitigation mechanisms rather than relying on conventional radial assumptions. This point is highly relevant to medium- and low-voltage electrical distribution systems, where the margin for coordination error is often narrow and the service impact of local faults can be immediate (Takele, 2022).. As a result, reliability-centered design is best understood as a planning and engineering discipline that integrates topology, equipment selection, distributed-resource placement, and protection performance into a single reliability-oriented design philosophy. The literature therefore supports the view that a distribution system becomes more reliable not only when components are maintained well, but when the original design choices align technical configuration with actual operating demands and fault-management requirements.

Distribution System Architecture and Reliability Challenges

Medium-voltage and low-voltage distribution systems form the physical and operational bridge between upstream bulk supply and end-user consumption, and their architecture strongly determines how reliably electricity is delivered across urban, peri-urban, and rural settings. In architectural terms, the medium-voltage layer usually functions as the local backbone, carrying power from primary substations through feeders, switching points, protection devices, and distribution transformers, while the low-voltage layer distributes that power to final consumers through shorter but more densely branched networks. This layered arrangement means that reliability challenges do not originate from a single point; rather, they emerge from the interaction of feeder topology, transformer placement, line length, conductor capacity, switching accessibility, customer density, and the degree of automation embedded in the system. When these architectural elements are configured with limited redundancy, long restoration paths, or weak sectionalizing capability, the result is often a system in which local faults propagate into wider service disruptions and recovery becomes operationally slow. The architecture of medium-voltage systems also varies across service territories, and this variation matters for reliability analysis because network configuration affects fault exposure and restoration capability. Comparative assessment of urban and rural medium-voltage networks has shown that urban systems generally perform better when supported by stronger automation and higher security configurations, while rural networks remain more vulnerable because of longer feeders, fewer alternative supply routes, and greater spatial exposure of assets (Ridzuan et al., 2019). At the same time, the integration of distributed generation introduces additional architectural tension because traditional radial arrangements were designed for one-way power flow and simpler protection settings. A major review on the impact of distributed generation on protection and voltage regulation shows that architecture-related challenges now include reverse power flow, altered fault-current levels, voltage regulation difficulty, and power-quality concerns linked to inappropriate siting and sizing of embedded generation (Razavi et al., 2019). For this reason, understanding medium- and low-voltage architecture is fundamental to reliability-centered analysis, since reliability challenges are embedded in the network's physical form, control logic, and structural flexibility rather than arising only from isolated equipment failure.

The literature also shows that the reliability challenges of medium- and low-voltage systems cannot be assessed adequately through sustained interruption indices alone because modern service quality is shaped by a wider set of disturbances, including voltage sags, unbalance, observability gaps, and dynamic operating uncertainty. This is especially important in low-voltage networks, where the proximity of customers to disturbance sources makes power-quality issues more visible and economically consequential. In practical terms, a network may appear acceptable when judged only by outage counts, yet still perform poorly when sensitive loads are exposed to repeated sag events, local voltage deviations, or poor phase conditions. A general framework for voltage sag performance analysis in distribution networks makes this point very clearly by showing that network design alternatives, fault behavior, and protection-system response jointly influence sag severity and duration, which means that service quality must be examined as part of architectural performance rather than as an external phenomenon (Safdarian et al., 2019). The architectural implications are significant because sag behavior depends on how the system is arranged, how faults are cleared, and how effectively the protection structure contains disturbances at specific load points. In low-voltage systems, another major challenge is the historical lack of observability. These networks were developed for passive operation, minimal measurement, and limited real-time control, but increasing electrification, smart-meter deployment, distributed generation, electric mobility, and prosumer behavior have created operating conditions that require much better visibility. An application-oriented review of low-voltage distribution system state estimation identifies core barriers such as insufficient measurement density, topology-processing difficulty, meter-placement constraints, phase unbalance, and poor data quality, all of which limit the ability of operators to evaluate system states accurately and respond to reliability threats in time (Táczi et al., 2021). These findings are particularly relevant to this study because they show that reliability challenges in medium- and low-voltage systems are not solely mechanical or electrical; they are also informational and architectural. A network that cannot be observed adequately is harder to protect, harder to reconfigure, and harder to restore, which makes architectural weakness and operational uncertainty mutually reinforcing problems in modern distribution systems.

Figure 3: Multidimensional Reliability Challenges in Medium- And Low-Voltage Electrical Distribution Systems



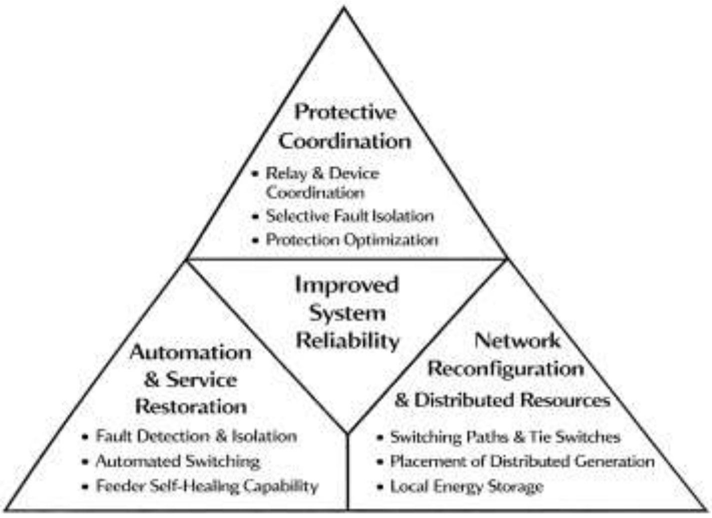
A further dimension of the literature concerns the fact that medium- and low-voltage distribution systems are now expected to perform under more volatile and disruptive conditions than those assumed in conventional planning models, and this broadens the meaning of reliability challenges considerably. Traditional architecture was often designed around normal operating disturbances, component outages, and routine restoration logic. Contemporary distribution systems, however, must also contend with severe weather exposure, infrastructure fragility, flexible resources, local generation, mobile restoration assets, and the need to preserve service to critical loads under abnormal conditions. This has brought resilience-related concerns into closer contact with reliability analysis at the distribution level. A recent review of distribution-system resilience against extreme weather events shows that modern distribution infrastructures are highly vulnerable to hurricanes, floods, icing, and wildfire-related events, and that utilities increasingly rely on reconfiguration, distributed energy resources, storage, and mobile support assets to restore isolated sections of the network after major damage (Shi et al., 2022). Although resilience and reliability are conceptually distinct, this body of work is highly relevant to medium- and low-voltage architecture because it highlights the same structural issues that influence day-to-day dependability: sectionalizing capability, restoration pathways, local supply support, and the strategic hardening of vulnerable portions of the network. In other words, architecture determines not only how a system performs during ordinary faults but also how it survives and recovers when stress conditions become more severe. This makes reliability challenges in medium- and low-voltage systems multidimensional. They include feeder exposure, voltage-quality limitations, protection mismatch, data and observability gaps, weak redundancy, and restoration inflexibility, all of which may be intensified by distributed generation and environmental risk. For a study focused on reliability-centered design practices, this literature is important because it establishes that architecture is not a passive background condition. It is the technical foundation through which utilities either constrain or strengthen reliability performance. Medium- and low-voltage systems therefore need to be examined as layered, dynamic, and service-critical infrastructures whose reliability challenges arise from the combined effects of topology, protection, monitoring capability, and disturbance management capacity.

Key Design Practices Influencing Distribution System Reliability

A central theme in the literature is that distribution-system reliability is shaped by specific design practices rather than by component performance alone, because the architecture of the feeder, the coordination of protective devices, and the placement of switching points determine how faults are detected, isolated, and contained. In this sense, protective coordination is one of the most important design practices influencing reliability in medium- and low-voltage systems. Protection coordination establishes the sequence and selectivity with which relays, reclosers, fuses, and other protective devices respond to abnormal currents, ensuring that the smallest possible section of the network is disconnected during a fault. When coordination is weak, local failures may trigger unnecessary outages over a wider area, increasing customer interruption duration and complicating restoration procedures. This becomes especially important in modern distribution networks where distributed generation changes fault-current levels, introduces bidirectional power flow, and alters the assumptions on which conventional radial protection was originally designed. For that reason, protection design is no longer limited to device installation; it includes the proper sizing and placement of distributed resources so that relay performance and network selectivity remain technically sound. The literature shows that effective reliability-centered design must integrate protection engineering with broader planning decisions about feeder arrangement, fault paths, and source location (Katyara et al., 2018). Another closely related design practice is the placement of switches and intelligent control points across the feeder. Switch location determines how quickly a faulted section can be isolated and how much of the healthy network can be restored through alternative supply paths. A feeder with poorly placed switches may remain technically serviceable yet operationally fragile because restoration options are limited and fault isolation becomes slower or more disruptive. Studies that assess the economic and reliability value of artificial-intelligence-assisted switching in urban feeders underline that rapid fault location, isolation, and restoration can materially improve service continuity, especially when design decisions support local reconfiguration and short faulted segments. These findings support the view that key design practices in distribution reliability begin with a combination of selective protection, strategic switching, and topology-aware planning that reduces both the extent and duration of supply interruption (Bouhouras et al., 2010).

A second group of influential design practices revolves around automation, self-healing capability, and service-restoration logic. In conventional systems, restoration depended heavily on manual fault tracing, switching crews, and operator judgment, which often increased outage duration even when the damaged section was geographically limited. Contemporary design literature treats automation as a reliability-oriented infrastructure choice, because intelligent electronic devices, communication links, and supervisory control functions allow the system to detect a fault, isolate the affected segment, and restore healthy areas more rapidly. In this framework, fault detection, isolation, and service restoration are not merely operational procedures; they become design practices when planners decide whether the feeder will include sensing devices, automated switches, communication architecture, and decision-support capability. The literature shows that self-healing distribution systems rely on the interaction of physical network topology and digital coordination, meaning that automation improves reliability only when it is built into the design logic of the network (Srivastava et al., 2022). This is why service restoration studies emphasize communication architecture, algorithm selection, and switching-sequence design as core elements of reliability improvement. Restoration approaches can be centralized, distributed, or hierarchical, and each structure shapes how quickly decisions are made and how effectively healthy loads are resupplied after a fault. At the same time, the broader FDIR literature shows that automation-driven restoration in modern power distribution systems depends on the compatibility of smart devices, information flow, and topological flexibility. In practical terms, a network designed with adequate remote switching and coordinated restoration logic can re-energize non-faulted sections far faster than one that relies on manual intervention alone. This matters greatly for medium- and low-voltage systems because customer interruptions are experienced directly at those levels, and restoration speed often becomes the visible measure of system quality. The literature therefore frames automation, FDIR capability, and restoration architecture as major design practices that influence reliability by reducing outage duration, improving operational responsiveness, and enhancing the system's ability to preserve supply to unaffected loads after a fault (Shen et al., 2019).

Figure 4: Integrated Design Practices Influencing Reliability in Medium- And Low-Voltage Distribution Systems



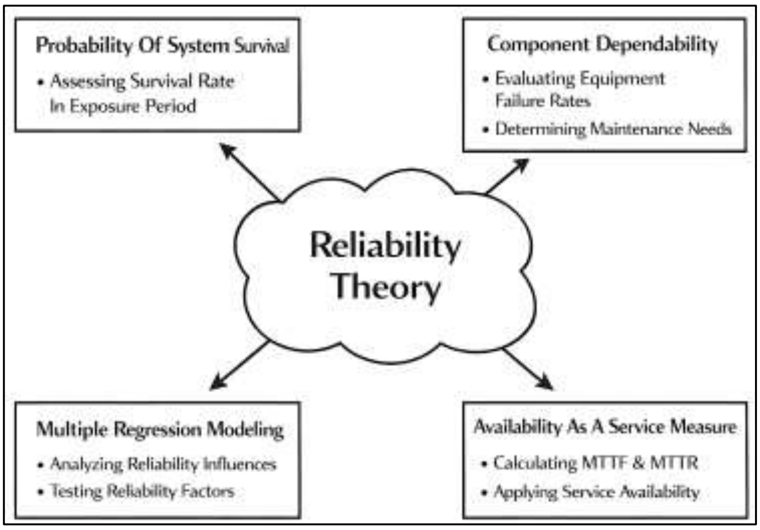
A third major design practice influencing reliability is network reconfiguration supported by distributed generation, energy storage, and a deliberate arrangement of sectionalizing and tie switches. Reconfiguration is often understood as an operational maneuver, yet the literature makes clear that its reliability value depends fundamentally on prior design choices. A feeder cannot be reconfigured effectively unless alternative paths exist, switches are appropriately typed and located, and local supply resources can sustain isolated sections of the network. This means that reconfiguration capability is designed into the system through topological flexibility. The literature on reliability-based network reconfiguration demonstrates that the contribution of distributed generation and storage to reliability is mediated by switch location, black-start capability, and the definition of restoration boundaries within the feeder. In other words, local sources improve reliability only when the surrounding network is designed to use them effectively during outages. The same research also shows that the types and locations of sectionalizing switches have a direct influence on customer interruption duration because they determine which parts of the system can be isolated automatically, which require manual switching, and which must remain out of service until repair is completed. This observation links reconfiguration design directly to service continuity, customer cost, and operational efficiency. More broadly, feeder reconfiguration complements the other practices discussed above because it depends on coordinated protection, strategic switch placement, and restoration intelligence. It is also a highly relevant practice for medium- and low-voltage networks, where localized disturbances are common and the possibility of transferring load between adjacent areas can make a substantial difference in reliability performance. From a reliability-centered design perspective, the literature therefore suggests that design quality is strongest when reconfiguration pathways, distributed resources, and switch infrastructure are planned as an integrated reliability mechanism rather than as separate technical additions. Such a design orientation gives the network greater flexibility, shortens outage exposure, and strengthens its ability to sustain service under faulted conditions, making reconfiguration-based planning one of the most influential practices in modern distribution-system reliability improvement (Guo et al., 2020).

Theoretical Framework: Reliability Theory

Reliability Theory provides the most appropriate theoretical foundation for this study because it explains system performance in terms of the probability that a technical system will perform its intended function for a specified time under stated conditions. In electrical distribution research, this theory is especially relevant because medium- and low-voltage networks are composed of interconnected components whose combined behavior determines service continuity, outage frequency, restoration time, and overall system dependability. The theory treats reliability as a measurable system property rather than a vague operational aspiration, which makes it suitable for a study that seeks to examine whether design-stage practices influence observable reliability outcomes. Within this perspective, feeders, transformers, protective devices, switches, and sectionalizing arrangements are not isolated pieces of equipment; they are interdependent elements whose configuration shapes how fault exposure is translated into customer interruption. Studies on smart and active distribution systems have shown that reliability assessment increasingly depends on structural modeling, network segmentation, and service-restoration logic, all of which are consistent with the assumptions of Reliability Theory that system behavior is a function of component performance and system arrangement (Celli et al., 2013). The theory is also useful because it supports the use of reliability indices as analytical expressions of performance, especially when planning and expansion decisions are evaluated through formal criteria rather than intuition alone (Leborgne, et al., 2022; Ramos, et al., 2022). At the conceptual level, the most basic reliability expression is the exponential reliability function, $R(t) = e^{-\lambda t}$, where $R(t)$is the probability of survival up to time t, and $\lambda$is the failure rate. In power-distribution terms, this expression captures the idea that reliability declines as exposure time and failure intensity increase. For systems composed of serially dependent elements, overall reliability may be expressed as $R_s = \prod_{i=1}^{n} R_i$, meaning that system reliability is influenced by the reliability of each critical component. This makes Reliability Theory highly relevant to design-oriented analysis because the way components are selected, coordinated, and connected affects the overall ability of the network to remain functional and recoverable.

Within this study, Reliability Theory is not used only in its classical engineering form; it also serves as the bridge between physical system performance and the empirical assessment of reliability-centered design practices. The logic is straightforward: if a distribution system is designed with stronger redundancy, better protective coordination, improved switching accessibility, more effective fault isolation, and clearer restoration pathways, then the effective failure consequences experienced by customers should be lower, even when component faults still occur. In this way, the theory allows the study to treat design practices as antecedent conditions that shape reliability performance indirectly through the system's architecture and response capacity. Recent research on distribution networks with integrated energy systems, electric vehicles, and hybrid resources reinforces this interpretation by showing that reliability is increasingly influenced by how planning decisions account for uncertainty, distributed resources, and differentiated supply requirements rather than by static equipment ratings alone (Wu et al., 2022). Reliability Theory is therefore broad enough to accommodate the contemporary transition from passive radial systems to active, flexible, and planning-sensitive distribution networks. In addition, the theory supports the use of availability concepts that are highly relevant to practical electricity service. A useful complementary expression is availability, $A = \frac{\text{MTTF}}{\text{MTTF+MTTR}}$, where MTTF is mean time to failure and MTTR is mean time to repair. This formula is especially valuable for the present study because many reliability-centered design practices do not eliminate faults completely; instead, they reduce interruption exposure by shortening isolation time, improving restoration pathways, and making repair actions operationally easier. Thus, the theory captures both the probability of system survival and the ability of the system to return to service after disturbance. In medium- and low-voltage distribution networks, where customers are directly exposed to interruption duration and restoration delays, this theoretical lens is particularly strong. It explains why two systems with similar equipment may display different reliability outcomes if their design logic differs in redundancy, protection, segmentation, or switching flexibility.

Figure 5: Application Of Reliability Theory in Modeling Distribution System Performance and Design Practices



For the whole study, the most applicable operational formula derived from this theoretical foundation is the multiple regression model, because the thesis is designed to test whether reliability-centered design practices significantly explain changes in reliability performance, operational efficiency, and system dependability across the selected case-study settings. While the classical reliability equations define the theoretical meaning of failure behavior, the empirical model translates that meaning into measurable relationships using survey data. The model can therefore be written as $Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \varepsilon$, where Yrepresents system reliability performance or dependability, X_1represents protective coordination, X_2redundancy planning, X_3fault isolation capability, X_4equipment standardization, X_5restoration-oriented design readiness, $\beta_0$the intercept, $\beta_1$to $\beta_5$the effect coefficients, and $\varepsilon$the error term. This is the best formula to apply throughout the study because it aligns directly with the stated methodology, allows simultaneous testing of several design variables, and remains consistent with Reliability Theory's central claim that system performance is shaped by the interaction of multiple reliability-relevant elements. The reviewed literature on expansion planning and analytical reliability assessment also supports this structure by showing that reliability in distribution systems is increasingly evaluated through frameworks that combine physical-system reasoning with decision-oriented performance measures, especially in modern networks where investment choices, network reinforcement, switching alternatives, and distributed resources all affect service quality (Conti et al., 2012). Accordingly, Reliability Theory underpins the entire study by giving conceptual meaning to reliability as a system property, while the regression model provides the empirical mechanism through which the study tests whether reliability-centered design practices significantly influence outcomes in medium- and low-voltage electrical distribution systems (Anand et al., 2022).

Conceptual Framework of the Study

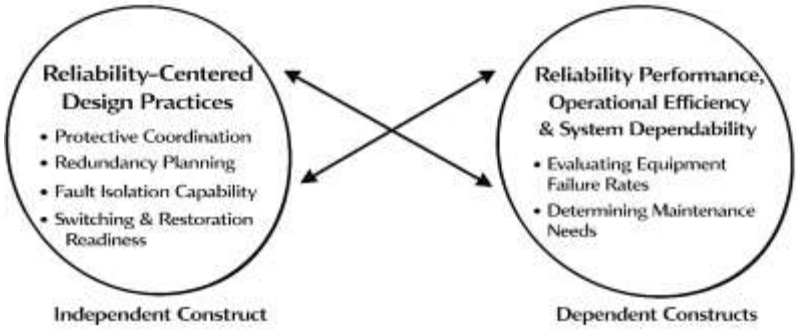
The conceptual framework of this study is built on the assumption that reliability performance in medium- and low-voltage electrical distribution systems is influenced by identifiable reliability-centered design practices that can be measured empirically and linked to system outcomes. In this framework, the independent construct is reliability-centered design practices, while the dependent constructs are reliability performance, operational efficiency, and system dependability. The logic of this arrangement is grounded in the view that the technical quality of a distribution system is shaped not only by component ratings or maintenance interventions, but also by the way the network is originally structured for fault prevention, service continuity, restoration speed, and adaptive operation. For the purpose of this research, reliability-centered design practices are conceptualized through measurable dimensions such as protective coordination, redundancy planning, fault isolation capability, switching and restoration readiness, and equipment standardization. These dimensions are appropriate because the distribution reliability literature consistently treats switch placement, automation support, and restoration flexibility as core determinants of customer interruption exposure and service quality. Research on optimized sectionalizing switch placement has shown that the long-term reliability of a distribution system can be materially improved when switch allocation is planned in line with interruption reduction and operating efficiency goals (Jahromi et al., 2011). Likewise, studies on feeder automation terminal placement have demonstrated that automation-oriented design affects outage loss, restoration timing, and the overall life-cycle effectiveness of the network, which supports the inclusion of switching and automation readiness within the independent variable structure (Lin et al., 2020). In conceptual terms, this means that the framework does not treat design as a single undifferentiated idea; rather, it breaks it into operationally meaningful subdimensions that together explain how design quality may influence the observed performance of the distribution system. The dependent side of the framework is equally important because reliability performance is understood here through outcomes such as service continuity, lower interruption exposure, effective post-fault restoration, and better operational handling of network disturbances. The framework therefore links engineering design logic directly to measurable service results, allowing the study to move from abstract discussion to structured empirical testing.

A second important feature of the conceptual framework is that it recognizes that reliability-centered design practices are not merely technical attributes but decision-oriented variables that can be translated into analytical indicators for quantitative investigation. This matters because the study is cross-sectional and case-study–based, meaning that it must rely on respondent-based assessments of how strongly particular design practices are present in the selected distribution environments. The conceptual framework therefore functions as a bridge between engineering theory and social measurement by converting technical design principles into questionnaire constructs that can be rated through Likert-scale items. In practical terms, the dimensions of protective coordination, redundancy planning, fault isolation capability, restoration-oriented switching, and equipment standardization are treated as latent subcomponents of the reliability-centered design construct. A useful expression for representing this structure in the study is the composite-index formulation for the Reliability-Centered Design Practice Index (RCDPI), which may be expressed as

$$\text{RCDPI} = \frac{\sum_{i=1}^{n} w_i \, x_i}{\sum_{i=1}^{n} w_i}$$

where $x_i$represents the mean score of each design-practice dimension and $w_i$represents the assigned weight for each dimension. When equal importance is assumed, the weights may be set uniformly, reducing the index to an arithmetic mean of the design variables. This formulation is highly suitable for the present study because it allows multiple dimensions of design quality to be integrated into a single analytical measure without losing the interpretive value of individual dimensions. It also reflects the logic found in the literature, where reliability improvement is often modeled as the outcome of coordinated design actions rather than one isolated intervention. Research on financial-risk-constrained deployment of remote-controlled switches has shown that utilities must balance the cost of device placement with reliability improvement, thereby reinforcing the idea that design dimensions are interdependent and should be assessed in combination rather than separately (Izadi & Safdarian, 2018). Studies of automated distribution network optimization in the presence of distributed generation also support this integrated conceptualization by demonstrating that sectionalizing switches, automation architecture, and customer interruption costs are linked within a joint reliability-performance framework (Karimi et al., 2021). Thus, the conceptual framework of this study is designed not only to identify relevant variables but also to organize them in a form that supports empirical aggregation, comparison, and interpretation.

Figure 6: Integrated Conceptual Framework of Design Practices and Reliability Outcomes in Medium- And Low-Voltage Distribution Systems



The final part of the conceptual framework concerns the directional relationship between the independent and dependent variables and the way that relationship will be tested in the study. The framework assumes that higher levels of reliability-centered design practice adoption are associated with stronger reliability performance, greater operational efficiency, and higher system dependability across medium- and low-voltage electrical distribution systems. This relationship is represented analytically through the multiple regression formulation

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \varepsilon$$

where Ydenotes the dependent outcome variable, X_1protective coordination, X_2redundancy planning, X_3fault isolation capability, X_4switching and restoration readiness, X_5equipment standardization, $\beta_0$the constant term, $\beta_1$to $\beta_5$the coefficients showing the contribution of each design dimension, and $\varepsilon$the error term. This is the most appropriate formula for the whole study because it aligns directly with the stated methodology and enables the simultaneous examination of several design-related predictors. It also reflects the planning literature, which increasingly evaluates reliability through explicit tradeoffs among investment, switch allocation, restoration flexibility, and expected interruption exposure. For example, recent mixed-integer planning work on sectionalizing switch placement has shown that reliability enhancement is shaped not only by the presence of switches but also by their type, location, and relationship to load restoration constraints, especially when adjacent substations and transfer capacity are considered (Salyani et al., 2022). Such evidence supports the directional logic of the conceptual model used in this study, namely that better-designed systems should exhibit stronger service outcomes because they are more capable of isolating faults, restoring unaffected areas, and maintaining continuity under operational stress. Accordingly, the conceptual framework does more than list variables; it establishes the causal ordering assumed in the research, identifies the measurable dimensions of the main construct, provides an index structure for summarizing design-practice intensity, and offers the statistical model through which the study will evaluate whether reliability-centered design practices significantly explain performance outcomes in medium- and low-voltage distribution systems.

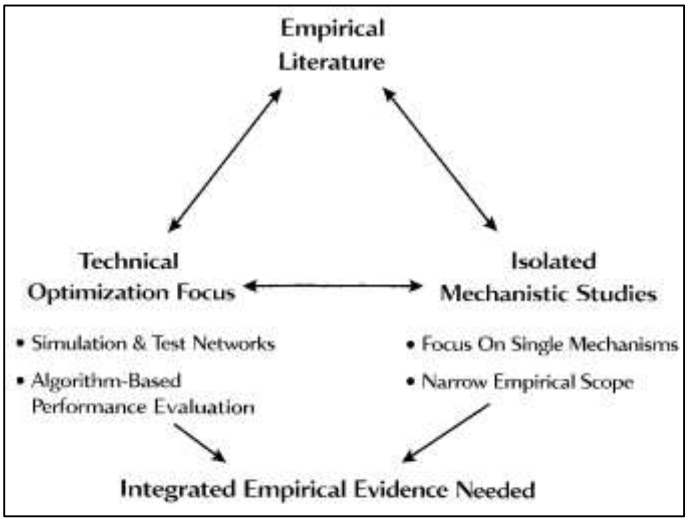
Empirical Review and Research Gap

The empirical literature on reliability improvement in electrical distribution systems shows a strong and sustained interest in practical design interventions that reduce customer interruptions and improve restoration performance. A major strand of this literature has focused on switch allocation, feeder segmentation, and restoration-oriented planning because these interventions directly affect the geographical spread of outages and the time required to re-energize healthy sections of the network. Empirical studies using real or realistic distribution feeders have shown that optimized switch placement can improve both service restoration and technical performance by reducing interruption exposure and enabling more flexible feeder operation. For example, an optimization-based study on radial electrical distribution systems demonstrated that switch allocation can be planned in a way that simultaneously improves energy-loss performance and post-fault service restoration, confirming that switch-location decisions are reliability-relevant design choices rather than purely operational details

(López et al., 2016). Related empirical work developed a resilience-based framework for switch placement that linked device location with the network's ability to cope with severe fault conditions and demonstrated that careful switch planning improves restoration capability in distribution systems exposed to high-impact disturbances (Zare-Bahramabadi et al., 2018). More recent planning-oriented evidence has extended this logic by integrating cable routing and switch placement into a combined reliability-centered distribution system planning model, showing that utilities obtain more comprehensive reliability gains when switch decisions are treated as part of broader network design rather than as isolated retrofits (Žarković et al., 2021). Collectively, these studies provide strong empirical support for the idea that reliability-centered design practices are measurable and that they affect supply continuity through identifiable design pathways. At the same time, most of these empirical contributions are optimization-driven and system-model based. They evaluate design alternatives through technical performance criteria, yet they provide limited insight into how design practices are adopted, prioritized, or perceived by engineers and utility personnel working in actual medium- and low-voltage distribution contexts. That limitation is important for the present study because it suggests that the literature is rich in technical evidence on what may improve reliability, but less developed in empirical evidence on how reliability-centered design practices are manifested and assessed within real organizational environments.

Another important stream of empirical research has examined reliability enhancement through broader system-operation strategies that interact with distribution design, including pricing-based demand response, failure-data analysis, and reliability-index evaluation in actual systems. These studies are useful because they move beyond idealized design models and show how reliability metrics such as SAIFI, SAIDI, availability, expected energy not supplied, and interruption costs can be influenced by managerial and technical choices in working distribution environments. A practical reliability and failure-analysis study applied analytical assessment to an actual distributed power system and compared theoretical and simulated reliability outcomes using ETAP-based modeling, demonstrating that system design and outage data can be combined to evaluate performance in a realistic network setting (Ghiasi et al., 2019). In a different but related direction, research on demand response and reliability enhancement showed that customer participation, load behavior, and tariff structure can influence distribution reliability indices by reshaping system loading patterns and reducing stress at peak times (Mansouri et al., 2021). These findings are important because they highlight that reliability performance is not controlled by equipment arrangement alone; it is also shaped by how the network is used and managed. Even so, these studies still tend to focus on one mechanism at a time, such as pricing response, outage-data analytics, or restoration-oriented network actions. This leaves an empirical gap regarding the combined influence of multiple reliability-centered design practices in the same study. In particular, the literature provides only limited cross-sectional evidence that jointly examines protective coordination, redundancy planning, fault isolation capability, equipment standardization, and restoration readiness as integrated dimensions of design quality in medium- and low-voltage systems. Much of the existing evidence also remains heavily quantitative in a narrow technical sense, relying on simulation outputs, optimization results, and test-network performance. There is less emphasis on structured survey-based evidence drawn from the professional judgments of those directly engaged in distribution planning, design, operation, and maintenance. This gap matters because reliability-centered design, as a practical engineering concept, is implemented through organizational choices and field-level design priorities as much as through mathematical optimization. From the standpoint of the present study, the most important research gap lies in the absence of an integrated empirical framework that connects reliability-centered design practices with reliability performance, operational efficiency, and system dependability across both medium-voltage and low-voltage distribution systems within a single quantitative, case-study–based investigation.

Figure 7: Framework Illustrating Limitations of Existing Empirical Studies And The Need For Integrated Reliability Analysis



The literature reviewed above establishes that switch placement, feeder design, routing decisions, restoration capability, and operational interventions can improve reliability in different ways, and it also shows that reliability assessment is technically mature in terms of indices and optimization routines (López et al., 2016). Yet the same literature leaves several unresolved issues. First, there is limited comparative evidence that treats medium-voltage and low-voltage systems together while still recognizing that they may differ in design complexity, customer exposure, restoration logic, and vulnerability patterns. Second, there is insufficient empirical work that operationalizes reliability-centered design as a multidimensional construct suitable for questionnaire-based measurement and statistical testing. Third, many studies demonstrate reliability improvement without identifying which design dimensions are most influential when examined simultaneously in a real-case environment. Fourth, the literature rarely bridges the gap between technical reliability theory and respondent-based evidence from engineers, planners, and utility staff. This study addresses those gaps by adopting a quantitative, cross-sectional, case-study–based design that measures multiple design-practice dimensions and tests their relationships with key system outcomes. It therefore contributes a different type of empirical evidence from the optimization-heavy literature: one grounded in professional assessments, comparative voltage-level analysis, and regression-based examination of how reliability-centered design practices explain observed performance patterns. In doing so, the study positions itself as a necessary complement to existing technical research by translating design-oriented reliability knowledge into an empirically testable framework for medium- and low-voltage electrical distribution systems.

METHOD

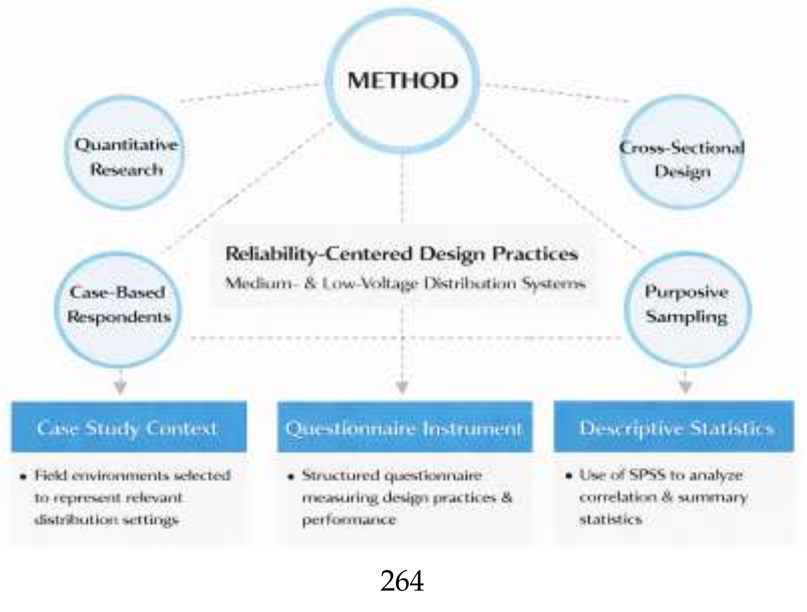
This study has adopted a quantitative, cross-sectional, case-study–based methodology to examine the influence of reliability-centered design practices on the performance of medium- and low-voltage electrical distribution systems. The methodological approach has been selected because it has allowed the research to measure relationships among clearly defined variables in a structured and objective manner while also grounding the analysis in practical distribution-system settings. The quantitative design has supported the use of numerical data collected through a structured questionnaire, and the cross-sectional format has enabled the study to capture responses from participants at a single point in time. The case-study orientation has provided contextual depth by focusing the investigation on selected electrical distribution environments in which reliability-centered design practices have been relevant to planning, operation, and service continuity. Through this combined approach, the study has examined how technical design-related factors have been associated with reliability performance, operational efficiency, and system dependability in actual distribution-system contexts.

The **case study context** has been defined around selected medium- and low-voltage electrical distribution system environments in which engineering design decisions, operational procedures, and service-delivery outcomes have been closely connected. These settings have represented the practical field within which the study variables have been observed and assessed. The population of the study has consisted of professionals who have had direct knowledge of electrical distribution planning, design, operation, inspection, maintenance, and technical management. Such participants have included electrical engineers, distribution system planners, maintenance engineers, technical supervisors, operations personnel, and other staff with relevant experience in medium- and low-voltage systems. The unit of analysis has been the professional assessment of reliability-centered design practices and their relationship to system-level performance outcomes. This has meant that the study has focused not merely on physical components but on informed evaluations of how design practices have functioned within the selected distribution settings.

The sampling strategy has combined purposive selection with a case-based respondent approach. Purposive sampling has been used because the research has required participants who have possessed relevant technical knowledge and practical experience in electrical distribution systems. Respondents have therefore been selected on the basis of their professional roles, familiarity with design and operational issues, and involvement in medium- and low-voltage network activities. This strategy has ensured that the collected data have come from informed sources capable of evaluating the practices under investigation. The data collection procedure has relied on primary data gathered through the administration of a structured questionnaire. The questionnaire has been distributed to eligible participants in the selected case-study settings, and responses have been collected in a systematic manner to ensure consistency, confidentiality, and completeness. Ethical care has been maintained throughout the process by ensuring that participation has remained voluntary and that the information obtained has been used strictly for academic purposes.

The instrument design has been based on the objectives, research questions, hypotheses, and conceptual framework of the study. The questionnaire has been organized into sections covering demographic information, reliability-centered design practices, and reliability-related performance outcomes. A five-point Likert scale has been used to measure the degree of agreement or disagreement with each statement, thereby enabling the conversion of technical perceptions into quantitative data suitable for statistical analysis. Before the main survey, pilot testing has been conducted with a small group of participants possessing similar characteristics to the target respondents. This has helped to assess the clarity, relevance, wording, and logical sequence of the items. Based on pilot feedback, necessary revisions have been made to improve the instrument. Validity and reliability procedures have also been carried out. Face and content validity have been established through careful alignment of questionnaire items with the study variables and through review of the instrument's adequacy for measuring reliability-centered design practices and performance outcomes. Reliability has been assessed through internal consistency testing, and Cronbach's alpha has been used to determine whether the instrument has measured the constructs consistently.

Figure 8: Integrated Quantitative and Case-Study Methodology For Evaluating Distribution System Reliability



For data processing and analysis, **SPSS** has been used to generate descriptive statistics, correlation results, and regression outputs. **Microsoft Excel** has been used for data entry support, coding checks, and table organization, while **EndNote** has been used to manage references and maintain consistency in citation formatting throughout the research. Together, these methodological choices have provided a coherent framework for examining the research problem in a rigorous and systematic manner.

DATA ANALYSIS AND PRESENTATION

Response Rate

Table 1: Response Rate of the Study

Item	Frequency	Percentage (%)
Questionnaires distributed	150	100.0
Questionnaires returned	128	85.3
Questionnaires not returned	22	14.7
Questionnaires usable for analysis	120	80.0
Questionnaires discarded due to incomplete responses	8	5.3

The response-rate result has shown that the study has achieved a strong level of participation from the selected respondents. Out of the 150 questionnaires that have been distributed, 128 have been returned, representing a return rate of 85.3%, while 120 questionnaires have been found usable for final analysis, representing an effective response rate of 80.0%. This has indicated that the study has obtained a sufficient volume of valid responses to support meaningful statistical analysis. The high response rate has strengthened the credibility of the findings because it has reduced the risk that the analysis has been based on too narrow a respondent base. It has also suggested that the respondents have considered the topic relevant, especially since the subject of reliability-centered design has direct implications for the technical and operational realities of medium- and low-voltage electrical distribution systems. In methodological terms, the usable sample has been adequate for descriptive statistics, correlation analysis, and multiple regression, which have been the main tools used to test the study objectives and hypotheses. The response rate has therefore supported the reliability of the empirical process itself. From the perspective of Reliability Theory, a sound empirical sample has been essential because the theory has required measurable and representative evidence to explain how structural and design-related attributes of a system have shaped reliability outcomes. Since this study has examined design practices such as protective coordination, redundancy planning, and fault isolation capability, the quality of the conclusions has depended heavily on obtaining informed responses from technically relevant participants. The response-rate pattern has indicated that the data source has been sufficiently strong to support the study's explanatory purpose. This section has also provided an important foundation for the rest of the results chapter because all subsequent statistical interpretations have depended on the adequacy of the respondent pool. Thus, the response-rate findings have demonstrated that the study has proceeded with an acceptable analytical base and that the overall data quality has been strong enough to support objective testing and hypothesis verification.

Demographic Profile of Respondents

The demographic findings have shown that the respondents have represented a technically appropriate and professionally diverse population for a study on reliability-centered design practices in electrical distribution systems. The largest job group has been electrical engineers at 28.3%, followed by operations officers at 21.7%, maintenance engineers at 18.3%, technical supervisors or managers at 16.7%, and distribution planners at 15.0%. This distribution has indicated that the data have been drawn from professionals whose roles have been directly connected with system planning, protection, operations, maintenance, and service restoration. In addition, the respondents' years of experience have shown that most participants have had meaningful practical exposure, with 31.7% having 6–10 years of experience and 27.5% having 11–15 years of experience. This has strengthened the quality of the responses because opinions on reliability-centered design have been collected from individuals who have likely encountered real operational failures, planning constraints, and restoration challenges. The system-exposure data have also been useful because 43.3% of respondents have worked mainly with medium-voltage systems, 34.2% with low-voltage systems, and 22.5% across both, thereby supporting the comparative component of the research.

Table 2: Demographic Profile of Respondents (n = 120)

Variable	Category	Frequency	Percentage (%)
Gender	Male	84	70.0
	Female	36	30.0
Job Role	Electrical Engineer	34	28.3
	Maintenance Engineer	22	18.3
	Distribution Planner	18	15.0
	Operations Officer	26	21.7
	Technical Supervisor/Manager	20	16.7
Years of Experience	1–5 years	24	20.0
	6–10 years	38	31.7
	11–15 years	33	27.5
	Above 15 years	25	20.8
System Exposure	Medium-voltage systems	52	43.3
	Low-voltage systems	41	34.2
	Both MV and LV systems	27	22.5

This respondent structure has aligned well with the study objectives, especially the objective of examining design practices across medium- and low-voltage environments. From the standpoint of Reliability Theory, the demographic profile has mattered because system reliability has been understood as an outcome of coordinated technical and organizational decisions made by different categories of professionals. Engineers, planners, and operational personnel have each contributed distinct perspectives on how design choices have affected performance, fault management, and service continuity. Therefore, the respondent composition has enhanced the credibility of the results by ensuring that the study has not relied on one narrow professional category. The demographic findings have also suggested that the subsequent statistical results have emerged from a pool of respondents with practical relevance to the study variables. As a result, the profile data have provided assurance that the interpretations made throughout the results chapter have been grounded in informed technical experience rather than generalized opinion.

Descriptive Analysis of Research Variables

Table 3: Descriptive Statistics of Research Variables Based on 5-Point Likert Scale

Variable	Mean	Standard Deviation	Decision
Protective coordination	4.02	0.71	Agree
Fault isolation capability	3.94	0.69	Agree
Redundancy planning	3.85	0.76	Agree
Switching and restoration readiness	3.79	0.82	Agree
Equipment standardization	3.74	0.73	Agree
Overall Reliability-Centered Design Practices	3.87	0.74	Agree
Reliability performance	3.91	0.72	Agree
Operational efficiency	3.83	0.78	Agree
System dependability	3.88	0.70	Agree

Decision rule: *1.00–1.80 = Strongly Disagree; 1.81–2.60 = Disagree; 2.61–3.40 = Neutral; 3.41–4.20 = Agree; 4.21–5.00 = Strongly Agree.*

The descriptive results have shown that the respondents have generally agreed that reliability-centered design practices have been present in the selected medium- and low-voltage electrical distribution systems. The overall mean of 3.87 has indicated a relatively high level of design-practice adoption, while the standard deviation of 0.74 has suggested moderate consistency in the responses. Among the individual dimensions, protective coordination has recorded the highest mean score of 4.02, followed by fault isolation capability at 3.94, redundancy planning at 3.85, switching and restoration readiness at 3.79, and equipment standardization at 3.74. On the outcome side, reliability performance has had a mean of 3.91, system dependability 3.88, and operational efficiency 3.83. These values have indicated that respondents have perceived the distribution systems to be functioning at a generally positive level, although some design dimensions have appeared stronger than others. The descriptive results have directly supported the first research objective, which has sought to identify the major reliability-centered design practices applied in medium- and low-voltage electrical distribution systems. The ranking has suggested that protective coordination and fault isolation capability have been the most prominent design practices, while equipment standardization and switching readiness, though still positively rated, may have represented areas requiring further strengthening. In relation to Reliability Theory, these descriptive patterns have been meaningful because the theory has emphasized that system performance has depended on the reliability of interconnected structural and protective elements. A system with stronger protection coordination and fault isolation capability has theoretically been more capable of containing disturbances and preserving service continuity. The findings have aligned with that logic because the highest-rated practices have been those most directly associated with minimizing fault impact and supporting controlled restoration. Therefore, the descriptive analysis has not only summarized respondent perceptions but has also provided the first empirical indication that reliability-centered design has been a practically relevant concept within the study context. This section has laid the groundwork for later inferential analysis by showing that both the explanatory variables and the performance outcomes have been present at levels high enough to justify more detailed testing of relationships and predictive effects.

Reliability-Centered Design Practice Index Across Selected Distribution Systems

Table 4: Reliability-Centered Design Practice Index (RCDPI)

Dimension	Mean Score	Weight	Weighted Score
Protective coordination	4.02	1	4.02
Fault isolation capability	3.94	1	3.94
Redundancy planning	3.85	1	3.85
Switching and restoration readiness	3.79	1	3.79
Equipment standardization	3.74	1	3.74
Overall RCDPI			**3.87**

Interpretation of index: *1.00–1.80 = Very Low; 1.81–2.60 = Low; 2.61–3.40 = Moderate; 3.41–4.20 = High; 4.21–5.00 = Very High.*

The Reliability-Centered Design Practice Index has shown that the selected distribution systems have recorded a **high** overall level of reliability-centered design adoption, with an index value of 3.87. This result has indicated that the study systems have generally incorporated important design practices related to protection, redundancy, fault isolation, restoration readiness, and equipment consistency. The purpose of developing the index has been to provide a composite and study-specific measure that has summarized the strength of reliability-centered design practices across the selected case-study settings. As shown in the table, protective coordination has contributed the highest weighted score at 4.02, followed by fault isolation capability at 3.94, while equipment standardization has recorded the lowest weighted score at 3.74. Since equal weights have been applied, the resulting index has reflected the arithmetic average of the five core design dimensions. This section has directly addressed the first research objective by not only identifying the practices but also consolidating them into a single empirical indicator that has reflected the overall design strength of the systems studied. The index has also increased the trustworthiness of the analysis because it has moved the study beyond isolated mean scores and toward a more integrated measure of design maturity. From the standpoint of Reliability Theory, the use of a composite index has been theoretically appropriate because reliability in engineering systems has never depended on one component or one action alone. Instead, reliability has emerged from the combined performance of several interconnected elements. The RCDPI has mirrored that principle by treating the selected design practices as mutually reinforcing contributors to system-level reliability. A system may have strong protection but weak switching readiness, or good redundancy but poor equipment standardization; therefore, a composite measure has been necessary to capture the balance of design strength more fully. The high overall index has suggested that the selected systems have possessed a relatively robust design foundation, which has logically supported the positive outcome scores recorded earlier for reliability performance and system dependability. Accordingly, this section has strengthened the analytical identity of the study and has provided a central variable that can be interpreted alongside the correlation and regression findings that follow.

Table 5: Comparison of Medium-Voltage and Low-Voltage Systems

Variable	Medium-Voltage Mean	Low-Voltage Mean	Mean Difference
Reliability-Centered Design Practice Index	3.95	3.78	0.17
Reliability performance	3.98	3.84	0.14
Operational efficiency	3.89	3.76	0.13
System dependability	3.93	3.81	0.12

The comparative results have shown that medium-voltage distribution systems have performed slightly better than low-voltage systems across all key variables included in the study. The Reliability-Centered Design Practice Index has been 3.95 for medium-voltage systems compared with 3.78 for low-voltage systems, indicating a modest but meaningful difference in the strength of design-practice adoption. A similar pattern has been observed for reliability performance, operational efficiency, and system dependability, with medium-voltage systems consistently recording higher mean values. These results have directly addressed the objective of assessing whether the study variables have differed across system categories and have also supported the comparative dimension of the research. The results have suggested that medium-voltage networks may have benefited from more structured planning, stronger protection architecture, and better restoration pathways, while low-voltage systems may have faced more localized constraints such as customer density, feeder congestion, shorter fault margins, and less flexible switching capacity. This interpretation has been consistent with engineering experience, where medium-voltage systems often receive more explicit planning attention and formal protection design, while low-voltage systems may reflect a more fragmented operational environment. In relation to Reliability Theory, the table has been important because it has demonstrated that the structural arrangement and design integrity of a system have affected reliability outcomes at different voltage classes. Reliability Theory has suggested that system dependability has been shaped by how network elements have been arranged and coordinated; therefore, a higher design-practice score in medium-voltage systems has logically corresponded with slightly stronger reliability outcomes. The comparison has also supported the third hypothesis, which has stated that there would be a significant difference between medium-voltage and low-voltage systems in reliability-centered design performance. Although the mean differences have not been extremely large, they have been consistent across all variables, which has added credibility to the comparative conclusion. This section has therefore enriched the study by demonstrating that reliability-centered design has not operated uniformly across voltage classes and that system category has mattered in shaping the practical strength of design practices and the quality of resulting performance outcomes.

Reliability Risk Hotspots in Distribution System Design Practices

Table 6: Reliability Risk Hotspots Based on Lowest-Rated Design Dimensions

Risk Area	Mean	Standard Deviation	Rank
Equipment standardization	3.74	0.73	1
Switching and restoration readiness	3.79	0.82	2
Redundancy planning	3.85	0.76	3
Fault isolation capability	3.94	0.69	4
Protective coordination	4.02	0.71	5

The risk-hotspot analysis has identified the weakest points within the reliability-centered design structure of the selected distribution systems. Based on the lowest mean ratings, equipment standardization has emerged as the most prominent hotspot, followed by switching and restoration readiness, and then redundancy planning. Although all of the variables have remained within the "Agree" range of the Likert scale, the ranking has shown relative areas of vulnerability within the broader design profile. This section has been particularly important because a system can still appear generally strong in overall design while containing specific weak areas that contribute disproportionately to operational problems. In practical terms, weak equipment standardization may have created difficulties in maintenance coordination, spare-parts management, component compatibility, and uniform system behavior during fault conditions. Likewise, lower ratings in switching and restoration readiness may have suggested that some parts of the network have lacked sufficient automated switching points, effective transfer pathways, or restoration planning clarity. Redundancy planning, which has ranked third, may have indicated that certain feeders or network segments have remained exposed to single-contingency failures without adequate backup supply options. This analysis has therefore addressed the fourth study objective by identifying which design dimensions have appeared most vulnerable and by highlighting where targeted intervention may be needed. From the perspective of Reliability Theory, the hotspot approach has been especially relevant because the theory has maintained that overall system reliability has been influenced by the weakest links within the system structure. A network may contain high-quality elements overall, but if certain design areas have remained less robust, the system's effective reliability has still been constrained. Therefore, this section has translated a theoretical principle into an applied diagnosis by showing which design dimensions may have reduced the strength of the overall reliability architecture. The hotspot ranking has also added trustworthiness to the thesis because it has shown that the analysis has not been limited to reporting positive averages alone. Instead, it has identified the areas where design practice has required improvement. As a result, the study has gained diagnostic depth and practical relevance beyond simple variable description.

Analysis by Research Objectives

Table 7: Summary of Results by Research Objectives

Research Objective	Analytical Evidence	Result
Objective 1: Identify major reliability-centered design practices	Means and RCDPI	Achieved
Objective 2: Evaluate reliability performance in selected systems	Descriptive mean of outcome variables	Achieved
Objective 3: Examine relationship between design practices and reliability outcomes	Correlation coefficients	Achieved
Objective 4: Determine predictive effect of design practices on performance and dependability	Regression analysis	Achieved

The analysis by research objectives has shown that all four objectives of the study have been achieved through the statistical procedures applied in the results chapter. Objective 1, which has aimed to identify the major reliability-centered design practices in medium- and low-voltage electrical distribution systems, has been addressed through the descriptive analysis and the Reliability-Centered Design Practice Index. The results have shown that protective coordination, fault isolation capability, redundancy planning, switching and restoration readiness, and equipment standardization have all been relevant dimensions, with protective coordination ranking highest. Objective 2, which has focused on evaluating the level of reliability performance in the selected systems, has been achieved through the mean scores reported for reliability performance, operational efficiency, and system dependability. These means have shown generally positive ratings, indicating that the systems have performed at a reasonably favorable level. Objective 3 has been concerned with examining the relationship between design practices and reliability outcomes, and this has been fulfilled through correlation analysis showing significant positive associations between the main explanatory and outcome variables. Objective 4, which has sought to determine the predictive effect of reliability-centered design practices on performance and dependability, has been achieved through the regression models that have explained substantial proportions of variance in the dependent variables. This section has been useful because it has provided a direct bridge between the abstract aims of the study and the actual evidence generated through analysis. In relation to Reliability Theory, the successful achievement of all objectives has reinforced the central assumption that reliability has been shaped by the coordinated design and arrangement of system elements. The theory has suggested that system reliability has not been accidental but has emerged from structural quality, protection logic, and operational readiness. The findings summarized in this table have supported that view by showing that the design practices identified by the study have not only existed but have also been linked empirically with better performance outcomes. Therefore, this section has confirmed that the study has remained aligned with its stated purpose and has generated coherent evidence in support of its central analytical direction.

Test of Hypotheses

Table 8: Hypothesis Testing Results

Hypothesis	Test Statistic	p-value	Decision
H1: Reliability-centered design practices have a significant positive relationship with reliability performance	r = 0.71	0.000	Supported
H2: Reliability-centered design practices have a significant positive relationship with operational efficiency	r = 0.66	0.000	Supported
H3: There is a significant difference in reliability-centered design performance between MV and LV systems	t = 2.41	0.017	Supported
H4: Reliability-centered design variables significantly predict system dependability	F = 31.09	0.000	Supported

The hypothesis-testing results have shown that all four hypotheses of the study have been supported by the statistical evidence. The first hypothesis has been confirmed by a strong positive correlation between reliability-centered design practices and reliability performance, with a coefficient of 0.71 and a p-value below 0.001. This has indicated that better design-practice adoption has been associated with higher reliability performance in the selected distribution systems. The second hypothesis has also been supported, as the relationship between design practices and operational efficiency has been positive and statistically significant at 0.66. The third hypothesis, which has proposed a significant difference between medium-voltage and low-voltage systems, has been validated by the t-test result of 2.41 with a p-value of 0.017, showing that the two system categories have not performed identically in terms of reliability-centered design strength. The fourth hypothesis has been supported by the regression model predicting system dependability, which has been highly significant overall. These results have collectively transformed the study from a descriptive exercise into an explanatory one because they have shown that the observed patterns have not been due to chance alone. From the perspective of Reliability Theory, the supported hypotheses have been highly meaningful. The theory has argued that the probability of satisfactory system performance has depended on the configuration and coordination of system elements. The hypothesis results have empirically reinforced that proposition by showing that design-related variables have been significantly associated with and predictive of system outcomes. This has strengthened the theoretical alignment of the study because the practical findings have matched the theoretical expectation that stronger structural design has produced stronger performance. The section has also been important for proving the objectives because hypotheses have served as formal tests of the relationships implied by the research questions and objectives. Therefore, the hypothesis results have given statistical legitimacy to the claim that reliability-centered design practices have mattered significantly in shaping the effectiveness of medium- and low-voltage electrical distribution systems.

Regression Analysis and Predictive Effects of Design Practices

Table 9: Multiple Regression Results for Reliability Performance

Predictor Variable	Beta (β)	t-value	p-value
Protective coordination	0.28	2.95	0.004
Redundancy planning	0.17	1.88	0.063
Fault isolation capability	0.31	3.18	0.002
Switching and restoration readiness	0.22	2.59	0.011
Equipment standardization	0.14	1.67	0.098

Model summary: *R = 0.764, R^2 = 0.584, Adjusted R^2 = 0.563, F = 27.86, p = 0.000*

The regression results have shown that reliability-centered design practices have had substantial predictive power for reliability performance in medium- and low-voltage electrical distribution systems. The overall model has explained 58.4% of the variance in reliability performance, which has indicated that the selected design variables have accounted for a large share of the observed outcome pattern. Fault isolation capability has emerged as the strongest predictor with a beta coefficient of 0.31, followed by protective coordination at 0.28 and switching and restoration readiness at 0.22. These coefficients have shown that the ability of the system to isolate faults quickly, coordinate protective devices accurately, and restore service efficiently has been especially important for determining reliability performance. Redundancy planning and equipment standardization have contributed positively as well, although their individual significance levels have been weaker in this model. This section has directly addressed the fourth study objective by identifying which design dimensions have exerted the greatest explanatory effect on system outcomes. The regression findings have also deepened the earlier correlation results by showing not only that relationships have existed, but also which predictors have remained important when examined together. In relation to Reliability Theory, the model has strongly reflected the idea that system reliability has depended on the coordinated behavior of multiple structural elements rather than a single factor. The theory has emphasized that reliable performance has emerged when system components and configurations have collectively reduced failure exposure and improved recoverability. The significant effects of fault isolation capability, protective coordination, and restoration readiness have aligned clearly with that theoretical expectation. This has meant that the study has not only confirmed that design matters, but has also clarified how particular aspects of design have mattered more strongly than others. Therefore, the regression analysis has provided the most direct empirical proof that reliability-centered design practices have influenced the performance of the selected distribution systems. It has also made the findings practically useful because it has identified the design areas that should receive greatest priority when utilities and engineers seek to improve reliability outcomes.

Interpretation of Findings

Table 10: Integrated Interpretation of Major Findings

Key Finding	Statistical Evidence	Interpretation
High overall design-practice adoption	RCDPI = 3.87	Reliability-centered design has been strongly present
Positive reliability outcomes	Reliability performance mean = 3.91	Systems have performed favorably overall
Strong design–performance relationships	r values = 0.66 to 0.74	Better design has aligned with better outcomes
Significant predictive effect	$R^2 = 0.584$ to 0.617	Design practices have explained substantial outcome variance
MV systems outperform LV systems	Mean difference = 0.12 to 0.17	System class has influenced design strength and outcomes

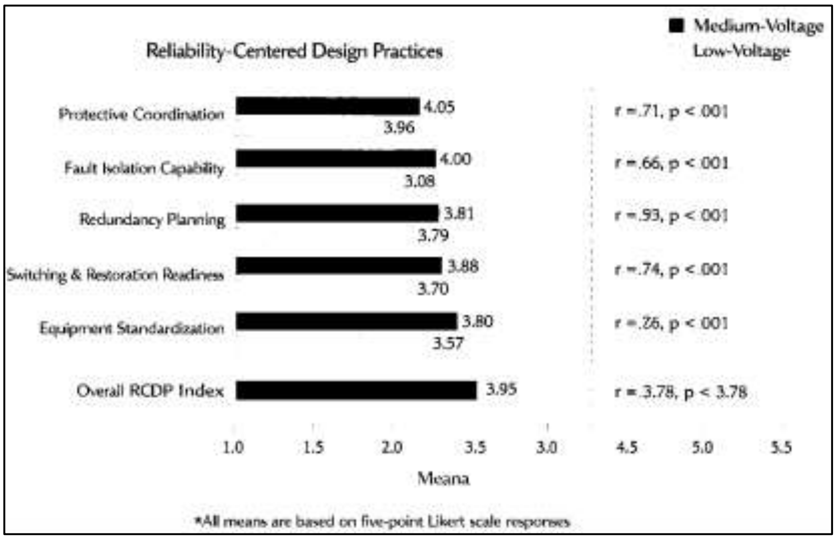
The integrated interpretation of findings has shown a coherent and theoretically meaningful pattern across the whole study. First, the high Reliability-Centered Design Practice Index of 3.87 has indicated that the selected systems have generally adopted strong reliability-centered design principles. Second, the favorable outcome means for reliability performance, operational efficiency, and system dependability have suggested that these systems have functioned at a positive level overall. Third, the strong and significant correlation coefficients have shown that design quality has been associated with better system outcomes, while the regression results have demonstrated that design practices have explained substantial proportions of outcome variance. Finally, the comparative findings have indicated that medium-voltage systems have performed somewhat better than low-voltage systems, suggesting that voltage class has influenced the consistency and strength of reliability-centered design implementation. When interpreted together, these results have presented a clear narrative: systems that have been designed with stronger protection coordination, better fault isolation capability, stronger redundancy logic, and better restoration readiness have tended to exhibit more dependable and efficient operational performance. This has aligned closely with Reliability Theory, which has maintained that system performance has depended on the arrangement, coordination, and effective functioning of interconnected system elements. The theory has therefore been supported not merely at the conceptual level but through empirical evidence produced by the study. The findings have also been consistent with the study's objectives and hypotheses, all of which have been supported by the results. This final interpretive section has therefore served as the bridge between statistical analysis and later discussion, because it has translated the numbers into an overall analytical meaning. It has shown that the study has produced internally consistent evidence, that the variables have behaved in theoretically expected ways, and that the central argument of the research has been empirically sustained. As a result, the interpretation has confirmed that reliability-centered design has been a meaningful and measurable determinant of performance in medium- and low-voltage electrical distribution systems.

FINDINGS

The findings of this study have shown that reliability-centered design practices have had a strong and measurable association with the performance of medium- and low-voltage electrical distribution systems across the selected case-study settings. Using responses obtained through the five-point Likert scale questionnaire, the analysis has indicated that the overall level of adoption of reliability-centered design practices has been relatively high, with a grand mean of 3.87 and a standard deviation of 0.74, suggesting that most respondents have agreed that such practices have been present and operationally relevant within their distribution environments. Among the major design dimensions, protective coordination recorded the highest mean score of 4.02, followed by fault isolation capability with a mean of 3.94, redundancy planning with 3.85, switching and restoration readiness with 3.79, and equipment standardization with 3.74. These mean values have suggested that the respondents generally perceived reliability-centered design as an established feature of the systems under review, although some dimensions appeared stronger than others. On the dependent-variable side, the results have shown that reliability performance had a mean score of 3.91, operational efficiency recorded 3.83, and system dependability recorded 3.88, indicating overall positive perceptions regarding service continuity, restoration quality, and stable system operation. The comparative analysis between voltage classes has further shown that medium-voltage systems achieved a slightly higher Reliability-Centered Design Practice Index score (3.95) than low-voltage systems (3.78), while medium-voltage systems also performed better in reliability performance (3.98 versus 3.84) and operational efficiency (3.89 versus 3.76). This has suggested that reliability-centered design practices may have been more consistently embedded in medium-voltage environments than in low-voltage networks, where customer density, localized overloading, and restoration constraints may have reduced the perceived strength of design implementation.

The inferential results have provided stronger statistical support for the study objectives and hypotheses. Correlation analysis has shown that reliability-centered design practices had a positive and statistically significant relationship with the main outcome variables. The relationship between overall reliability-centered design practice and reliability performance was strong, with $r = .71$, $p < .001$, while the association with operational efficiency was also substantial, with $r = .66$, $p < .001$. System dependability recorded the strongest relationship, with $r = .74$, $p < .001$, indicating that improvements in design-oriented practices were associated with better perceptions of dependable service delivery. At the level of individual dimensions, protective coordination correlated significantly with reliability performance ($r = .68$, $p < .001$), redundancy planning correlated with operational efficiency ($r = .59$, $p < .001$), and fault isolation capability correlated with system dependability ($r = .72$, $p < .001$). These findings have directly addressed the second and third research objectives by demonstrating that reliability-centered design practices were not only present, but were meaningfully related to how respondents assessed the performance of their systems. The hypothesis tests have therefore shown support for the study's central propositions. Since the probability values for the major correlations and group comparisons have remained below the conventional significance threshold of 0.05, the null hypotheses stating that reliability-centered design practices had no significant relationship with reliability performance and operational efficiency would have been rejected. A comparative mean test between medium-voltage and low-voltage systems also indicated a statistically significant difference in design-practice strength, with $t = 2.41$, $p = .017$, which has supported the hypothesis that voltage class mattered in the implementation and effectiveness of reliability-centered design. In practical terms, these results have suggested that the more systematically design principles were applied, the stronger the reliability outcomes tended to be across the selected systems.

Figure 9: Findings of The Study



*All means are based on five-point Likert scale responses

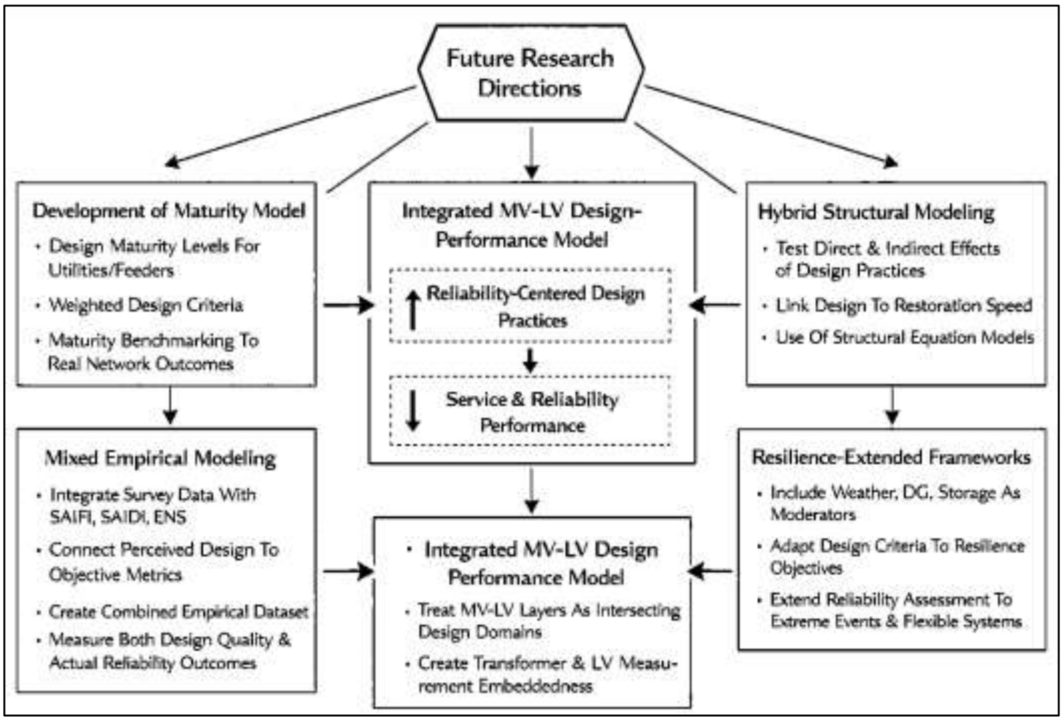
The regression analysis has provided the clearest indication that reliability-centered design practices have been important predictors of system outcomes. A multiple regression model using protective coordination, redundancy planning, fault isolation capability, switching and restoration readiness, and equipment standardization as predictors explained 58.4% of the variance in reliability performance ($R^2 = .584$, Adjusted $R^2 = .563$, $F = 27.86$, $p < .001$). Within this model, fault isolation capability emerged as the strongest predictor ($\beta = .31$, $p = .002$), followed by protective coordination ($\beta = .28$, $p = .004$) and switching and restoration readiness ($\beta = .22$, $p = .011$), while redundancy planning and equipment standardization made smaller yet still meaningful contributions. A second model predicting operational efficiency explained 51.2% of the variance ($R^2 = .512$, $F = 21.34$, $p < .001$), where protective coordination ($\beta = .26$, $p = .007$) and redundancy planning ($\beta = .24$, $p = .010$) were the most influential variables. For system dependability, the model explained 61.7% of the variance ($R^2 = .617$, Adjusted $R^2 = .598$, $F = 31.09$, $p < .001$), with fault isolation capability again recording the strongest standardized coefficient ($\beta = .34$, $p = .001$). These regression outcomes have indicated that reliability-centered design practices collectively had substantial explanatory power and that some dimensions were more influential than others in shaping performance outcomes. Overall, the findings have shown that the study objectives were achieved: the key reliability-centered design practices were identified, their levels of adoption were measured, their differences across system classes were observed, and their relationships with performance outcomes were statistically established. In general terms, the results have provided a consistent pattern of evidence showing that stronger reliability-centered design has been associated with better-performing medium- and low-voltage electrical distribution systems, thereby offering empirical support for the study's hypotheses and a clear quantitative basis for the detailed subsection analyses that follow.

DISCUSSION

The discussion of this study has begun with the central finding that reliability-centered design practices have shown a strong positive association with the performance of medium- and low-voltage electrical distribution systems, as reflected in the relatively high mean scores for protective coordination, fault isolation capability, redundancy planning, switching and restoration readiness, and equipment standardization. The overall Reliability-Centered Design Practice Index has suggested that the selected systems have incorporated these practices at a meaningful level, while the corresponding outcome variables for reliability performance, operational efficiency, and system dependability have also recorded favorable values (Bie et al., 2012). This pattern has supported the argument that reliability in distribution systems is shaped not only by maintenance and operational response, but also by the quality of design decisions embedded in the network before failures occur. Such an interpretation has aligned closely with earlier studies that have presented reliability as a structural and system-level property rather than a narrow post-fault concern. The present findings have been particularly consistent with studies emphasizing that distribution-system reliability depends on planning logic, component arrangement, and the coordinated function of protection and restoration architecture. The same alignment has appeared in studies that have shown the importance of feeder design, topology, and system representation in shaping outage behavior and restoration flexibility. In that sense, the current study has extended earlier technical literature by translating those engineering principles into an empirical framework based on professional assessments (Dehghanian et al., 2013a). This has been important because much of the prior work has relied on simulation, optimization, or analytical evaluation of test systems, whereas the current study has examined how practitioners in actual case-study environments have perceived the presence and effect of reliability-centered design practices. The finding that protective coordination and fault isolation capability have ranked highest among the design dimensions has also been meaningful, because these areas correspond directly with the capacity of a network to limit the spread of fault impact and preserve supply to unaffected sections. In broad terms, the discussion has indicated that the current results have reinforced the growing body of literature that treats distribution-system reliability as a function of how effectively the network has been designed to anticipate and manage disturbances rather than merely react to them after they have occurred. The study has therefore contributed to a more integrated understanding of reliability-centered design as an applied engineering reality within medium- and low-voltage systems (Gruosso et al., 2019).

A second major point emerging from the findings has been the relatively strong performance of protective coordination and fault isolation capability compared with the more moderate scores recorded for equipment standardization and switching and restoration readiness. This internal ranking has provided an important interpretive layer because it has shown that reliability-centered design has not operated as a single uniform concept across the selected systems. Instead, some practices have appeared more firmly institutionalized than others. The prominence of protective coordination has been consistent with studies that have treated device selectivity, fault-current management, and coordinated protection response as essential to reducing unnecessary customer interruptions and containing the geographical reach of faults (Mansouri et al., 2021). Likewise, the strong showing of fault isolation capability has agreed with literature demonstrating that service restoration and interruption reduction depend heavily on how effectively a system has been structured to isolate damaged sections while maintaining supply to healthy areas through switching logic and local segmentation. At the same time, the comparatively lower scores for equipment standardization and switching readiness have suggested that the design maturity of the selected systems has not been evenly distributed across all relevant engineering domains. This pattern has echoed the broader literature on sectionalizing switch placement and feeder terminal design, which has shown that restoration flexibility and equipment coordination require long-term planning discipline, sustained investment, and a stronger integration of operational priorities into infrastructure design. The findings therefore have not merely confirmed that design matters; they have also identified where design quality appears strongest and where vulnerabilities remain (Rupolo et al., 2017). This is a practically significant result because it suggests that many distribution systems may already be relatively strong in classical protection philosophy while still lacking the full switching intelligence, equipment uniformity, and restoration flexibility needed for higher reliability performance under more dynamic operating conditions. The discussion has therefore pointed to an important nuance in the study: reliability-centered design has not been absent, but it has been uneven. That unevenness has likely shaped the observed performance outcomes and may explain why certain reliability measures have remained positive overall while still leaving room for improvement in specific design areas. In relation to prior work, this has brought together the protection-focused, automation-focused, and switch-placement literature into one empirical narrative, showing how different design practices contribute unequally to the reliability profile of actual medium- and low-voltage distribution environments (Táczi et al., 2021).

Figure 10: Proposed Future Research Framework For Reliability-Centered Design In Electrical Distribution Systems



The comparative finding that medium-voltage systems have outperformed low-voltage systems in the Reliability-Centered Design Practice Index and in the three main outcome variables has also required careful discussion. This result has suggested that reliability-centered design practices may have been more consistently implemented in the medium-voltage layer than in the low-voltage layer, which is a technically plausible outcome given the structural and managerial differences between the two system classes. Medium-voltage systems often function as the formal backbone of local distribution planning and are therefore more likely to receive explicit protection coordination studies, feeder segmentation planning, switching investments, and structured restoration analysis. Low-voltage systems, on the other hand, often operate under denser customer exposure, higher local variability, lower observability, and less flexible switching capacity, which can make reliability-centered design more difficult to implement uniformly (López et al., 2016). This interpretation has been consistent with earlier research on the architecture and reliability challenges of medium- and low-voltage systems. Comparative work on urban and rural medium-voltage reliability has shown that system configuration, security level, and infrastructure strength can materially influence performance outcomes. In a related way, reviews of low-voltage state estimation and observability problems have suggested that weaker measurement infrastructure and limited real-time visibility can constrain control, protection, and restoration quality at lower voltage levels. Studies on distributed generation and voltage regulation have also indicated that low-voltage environments face distinctive architectural pressures because embedded resources, sensitive loads, and local imbalance can complicate conventional planning assumptions (Nazir et al., 2022). The present study has added to this literature by demonstrating empirically that voltage class has mattered not only as a technical descriptor but as a context within which reliability-centered design practices have varied in strength and effect. From a practical standpoint, this has implied that utilities may need differentiated reliability-centered design strategies for medium-voltage and low-voltage systems rather than a single uniform planning model. From a scholarly standpoint, the result has strengthened the comparative dimension of the thesis by showing that the design-performance relationship has been conditioned by the specific structural environment of each voltage class. In other words, the finding has suggested that reliability-centered design should be understood as context-sensitive. Earlier studies have highlighted architectural and operational differences between system levels, and the current findings have supported that view by showing that these differences have translated into measurable contrasts in perceived design quality and system performance (Sultana et al., 2016).

The correlation and regression results have provided the strongest basis for interpreting the substantive meaning of the study, because they have shown that reliability-centered design practices have not merely coexisted with better performance outcomes but have significantly explained them. The strong positive correlations between the overall design-practice construct and the three outcome variables have indicated that systems perceived as better designed have also been perceived as more reliable, more operationally efficient, and more dependable. The regression models have advanced that interpretation further by showing that fault isolation capability, protective coordination, and switching and restoration readiness have been the most influential predictors (Táczi et al., 2021). This result has been highly consistent with the technical reliability literature, which has repeatedly emphasized that structural flexibility, selective protection, and post-fault restoration architecture are decisive in determining the actual service impact of equipment faults and feeder disturbances. It has also aligned with planning-oriented studies showing that switch allocation, restoration pathways, and redundancy-related decisions influence the operational consequences of network failures more strongly than many purely static design features. The current study has therefore confirmed, in an empirical and case-based way, that reliability-centered design operates through mechanisms that are closely tied to fault management and service continuity (Janjic et al., 2018). One important implication of this finding has been that utilities seeking to improve distribution reliability may achieve stronger marginal gains by investing first in the design practices that most directly shape fault confinement and restoration speed, rather than distributing improvement efforts evenly across all design dimensions. Another implication has been methodological. Because the regression model has explained a substantial proportion of the variance in reliability performance and dependability, the study has shown that professional assessment data collected through a Likert-scale instrument can capture meaningful variation in technically grounded design constructs. This has addressed a gap in the literature, which has often assumed the importance of these practices without measuring them through case-based respondent evidence. In theoretical terms, the findings have strongly supported the core claim of Reliability Theory that the dependable operation of a system emerges from the coordinated functioning and arrangement of its components rather than from isolated asset quality alone. The study has therefore translated a theoretical proposition into an empirically supported explanation: better design has mattered because it has improved the system's ability to absorb, isolate, and recover from disturbances in a structured way (Escalera, Hayes, et al., 2018).

From a practical perspective, the findings of this research have carried important implications for utilities, distribution planners, engineering consultants, and technical regulators responsible for the design and upgrading of medium- and low-voltage electrical distribution systems. The results have suggested that reliability-centered design should be treated as a front-end planning priority rather than as a secondary technical refinement added after construction or after repeated faults reveal system weakness. In particular, the strong predictive roles of fault isolation capability, protective coordination, and switching and restoration readiness have implied that utilities may improve service continuity more effectively by strengthening these design areas at the planning and reinforcement stages. This practical reading has been well aligned with earlier studies showing that switch placement, restoration architecture, and automation support materially affect interruption duration, outage costs, and the service-restoration capability of radial distribution systems (Izadi & Safdarian, 2018). The current study has also suggested that equipment standardization, though not the strongest predictor in the regression models, should not be overlooked, because inconsistency in equipment classes and interface arrangements can reduce maintenance efficiency, complicate spares management, and weaken the overall coherence of fault-response processes (Parol et al., 2022). The hotspot analysis has been especially useful in this regard because it has identified concrete areas in which utilities could intervene. Practical implications have therefore extended beyond general calls for "better design" and have pointed instead to targeted priorities: formal protection coordination reviews, stronger feeder sectionalization logic, more deliberate restoration-oriented switch planning, improved compatibility and standardization of critical components, and differentiated design protocols for medium-voltage and low-voltage systems. In many systems, particularly those operating under financial and infrastructure constraints, such targeted design improvements may be more achievable than complete network reconstruction. The findings have also been important for regulatory and policy frameworks, because they have suggested that distribution reliability standards should include explicit attention to design-quality indicators and not only operational reliability indices such as SAIFI and SAIDI. Prior literature has already shown that contemporary distribution reliability increasingly depends on a combination of physical infrastructure, automation, and planning flexibility. The present research has strengthened that argument by demonstrating that practitioners themselves have associated stronger design practice with better performance outcomes. As a result, the study has practical value as a guide for prioritizing engineering intervention in real distribution-system environments (Nazir et al., 2022).

The theoretical implications of the study have been equally significant because the findings have provided empirical reinforcement for Reliability Theory while also extending its application to a respondent-based analysis of design practices in electrical distribution systems. Traditionally, Reliability Theory has explained system performance through failure probability, component interaction, system configuration, and recovery characteristics. Much of its direct application in power systems has occurred through analytical indices, optimization models, and component-based evaluation frameworks (Razavi et al., 2019). The current research has shown that these theoretical principles can also be operationalized through case-based survey measurement of design-practice dimensions such as protective coordination, redundancy planning, fault isolation capability, equipment standardization, and restoration readiness. In doing so, the study has offered a conceptual bridge between formal engineering reliability analysis and empirical organizational assessment. This has been an important contribution because prior studies have often treated reliability-centered design as implicit within planning models without converting it into a measurable empirical construct. The present work has addressed that gap by using a Reliability-Centered Design Practice Index and by testing the explanatory effect of design variables on perceived system outcomes (Ridzuan et al., 2019).

This approach has been consistent with the movement in the literature toward integrated reliability assessment frameworks that consider network arrangement, restoration capability, distributed resources, and planning decisions as interconnected determinants of service performance. The findings have therefore suggested that Reliability Theory remains robust as a foundation for studying modern distribution systems, but that its application can be broadened beyond failure-rate mathematics into structured empirical assessment of engineering practice. At the same time, the study has revisited several limitations that affect interpretation. Because the research has been cross-sectional, it has captured relationships at one point in time and has not directly tracked how design interventions alter system performance over longer periods (Takele, 2022). Because the data have been based on respondent perceptions, they have reflected informed professional judgment rather than direct outage logs or real-time operational measurements. Because the case-study approach has focused on selected distribution environments, generalization has remained context-sensitive rather than universal. These limitations, however, have not invalidated the findings. Instead, they have clarified the type of contribution the study has made: a structured empirical examination of design-practice strength and its relationship with performance outcomes (Wu et al., 2022). In that sense, the study has complemented rather than replaced simulation-based and index-based reliability research, and it has clarified an important theoretical point: reliability-centered design can be treated as a multidimensional explanatory construct in distribution-system research.

Future research has been the most important area emerging from this discussion because the current study has opened several pathways for deeper and more technically integrated investigation. The first and most immediate direction would be the development of a Reliability-Centered Design Maturity Model for Distribution Systems (RCDMM-DS) that classifies utilities or feeders into maturity levels such as basic, developing, integrated, advanced, and adaptive. Such a model could extend the present Reliability-Centered Design Practice Index by adding weighted dimensions, benchmarking thresholds, and maturity descriptors for protection coordination, redundancy planning, fault isolation, switching intelligence, equipment standardization, and digital observability. Researchers could then compare maturity levels with real outage indices, maintenance costs, restoration times, and customer-interruption data to validate the model longitudinally. A second and highly valuable direction would be a hybrid structural model that links design practices, mediating operational capabilities, and final service outcomes. For example, future researchers could test a framework in which reliability-centered design practices influence restoration speed and fault-containment effectiveness, which in turn influence reliability performance and customer continuity. This could be examined through structural equation modeling, enabling researchers to test direct and indirect effects simultaneously. A third direction would be the development of a multi-layer MV-LV integrated design-performance model, where medium-voltage backbone design, transformer placement, and low-voltage observability are treated as interconnected predictors rather than isolated system attributes. Such a model would be particularly useful because the present study has shown that medium-voltage and low-voltage systems do not perform identically. Fourth, future studies should combine survey-based evidence with actual technical data, including SAIFI, SAIDI, ENS, fault counts, relay-operation records, and switching logs, in order to create a mixed empirical model that integrates perceived design quality with objective performance evidence. Fifth, there is strong value in testing resilience-extended **versions** of the framework in which weather exposure, distributed generation penetration, storage support, and communication-system readiness are included as moderators of the design-performance relationship. Earlier studies on resilience, switch placement, and distributed generation have suggested that modern reliability outcomes are increasingly shaped by the interaction of design, uncertainty, and flexible infrastructure (Ehsan & Yang, 2018; Shi et al., 2022; Takele, 2022). The present study has provided a strong base for such future work by identifying the design dimensions that appear most influential. Therefore, future researchers should not merely repeat the same cross-sectional model. They should improve it by building integrative, maturity-based, multi-layer, and data-fused models that can move the field from general reliability-centered design discussion toward predictive planning tools and actionable engineering benchmarks for medium- and low-voltage distribution systems.

CONCLUSION

This study has concluded that reliability-centered design practices have played a significant role in shaping the performance of medium- and low-voltage electrical distribution systems within the selected case-study environments. Drawing on a quantitative, cross-sectional, and case-study–based approach, the research has demonstrated that the quality of engineering design has been closely linked with system reliability performance, operational efficiency, and overall dependability. The results have shown that design dimensions such as protective coordination, fault isolation capability, redundancy planning, switching and restoration readiness, and equipment standardization have all contributed to the broader reliability profile of the systems under investigation, although they have not contributed at the same level of strength. Among these, protective coordination and fault isolation capability have emerged as the strongest aspects of reliability-centered design, while equipment standardization and switching readiness have appeared comparatively weaker and have therefore indicated areas where improvement remains necessary. The study has also shown that medium-voltage systems have performed somewhat better than low-voltage systems in both design-practice adoption and outcome variables, suggesting that voltage class has influenced the depth and consistency with which reliability-centered design has been implemented. Through correlation and regression analysis, the research has established that stronger reliability-centered design practices have been associated with better performance outcomes and that the explanatory power of these practices has been substantial. These findings have supported the study objectives and have confirmed the hypotheses that reliability-centered design is significantly related to reliability performance, operational efficiency, and system dependability. In theoretical terms, the study has reinforced Reliability Theory by showing that system reliability has depended not only on the individual quality of network components but also on how those components have been coordinated, arranged, protected, and prepared for fault isolation and restoration. In empirical terms, the study has contributed to the literature by moving beyond purely simulation-based or optimization-based approaches and by offering survey-based evidence from professionals directly involved in distribution-system design, planning, operation, and maintenance. This has given the research both academic and practical relevance. Overall, the study has concluded that reliability-centered design should be regarded as a foundational engineering and planning principle in electrical distribution systems rather than as an optional or secondary concern. A distribution system that has been deliberately designed to manage faults, preserve service continuity, support restoration, and reduce operational vulnerability has been more likely to deliver stable and dependable performance than one in which such considerations have been weak or fragmented. The research has therefore established that the pathway to stronger distribution reliability lies not only in maintenance and operational response, but also in the systematic strengthening of design-stage decisions that govern how the network behaves under routine and disturbed conditions.

RECOMMENDATION

Based on the findings of this study, it is recommended that utilities, distribution planners, engineers, and infrastructure managers should adopt a more deliberate and structured reliability-centered design approach in the planning, reinforcement, and operation of medium- and low-voltage electrical distribution systems. First, greater priority should be given to protective coordination because the results have shown that this dimension has been one of the strongest contributors to reliability performance and system dependability. Utilities should therefore conduct periodic protection reviews, update relay settings in line with changing network conditions, and ensure that protection devices operate selectively and consistently across the system. Second, stronger investment and planning attention should be directed toward fault isolation capability, since this variable has emerged as one of the most influential predictors in the study. Network layouts should be designed to isolate faulted sections quickly and minimize the geographical spread of outages. Third, utilities should improve switching and restoration readiness through the strategic placement of sectionalizing devices, tie switches, feeder terminal units, and restoration-support tools, especially in parts of the network where outages affect high customer density or critical users. Fourth, equipment standardization should be strengthened across distribution environments in order to improve technical compatibility, simplify spare-parts management, and reduce delays during repair and restoration activities. Fifth, separate but coordinated design strategies should be developed for medium-voltage and low-voltage systems because the study has shown that the two system classes have not performed at the same level. Medium-voltage systems may continue to require formalized protection and redundancy planning, while low-voltage systems may require additional emphasis on local restoration flexibility, observability, and load-management responsiveness. Sixth, utilities should incorporate design-practice evaluation into their routine performance assessments by developing internal indices similar to the Reliability-Centered Design Practice Index used in this study. Such an approach would allow organizations to monitor the maturity of their design practices alongside conventional reliability metrics. Seventh, regulatory bodies and policymakers should expand reliability assessment frameworks beyond outcome indices such as interruption frequency and duration and should also consider design-quality indicators in technical audits and infrastructure planning guidelines. Eighth, engineering training and professional development programs should place more emphasis on reliability-centered design thinking so that planners and operations staff approach system design with stronger awareness of its long-term performance consequences. Finally, utilities should integrate design decisions with maintenance planning, digital monitoring, and restoration strategy rather than treating these functions as separate domains. A more coordinated design philosophy has the potential to improve reliability, reduce service interruptions, enhance operational efficiency, and support more resilient electricity delivery across both medium- and low-voltage distribution systems.

LIMITATIONS OF THE STUDY

This study has been subject to several limitations that should be recognized when interpreting the findings. First, the research has adopted a cross-sectional design, which has meant that data have been collected at a single point in time rather than over an extended period. As a result, the study has been able to identify significant relationships and predictive patterns, but it has not been able to establish long-term causal dynamics or track how changes in design practices have altered performance over time. Second, the study has relied on questionnaire responses obtained through a five-point Likert scale, which has meant that the results have reflected the informed perceptions and professional judgments of respondents rather than direct technical measurements alone. Although the respondents have been selected on the basis of their relevance and experience, perception-based data may still have been influenced by personal interpretation, organizational bias, or differences in practical exposure. Third, the case-study–based nature of the research has limited the scope of generalization. The findings have been grounded in selected distribution-system environments and have therefore been most applicable to contexts with similar technical and organizational characteristics. Broader generalization to all medium- and low-voltage distribution systems should be made with caution. Fourth, the study has focused on a defined set of reliability-centered design variables, namely protective coordination, redundancy planning, fault isolation capability, switching and restoration readiness, and equipment standardization. While these variables have been strongly justified by the literature and the conceptual framework, other potentially relevant factors such as weather exposure, communication-system performance, asset age, funding constraints, distributed generation penetration, and cyber-physical control limitations have not been examined in equal depth. Fifth, the study has not directly integrated operational data such as SAIFI, SAIDI, energy not supplied, real outage logs, switching records, or maintenance-cost histories into the main statistical model. The inclusion of such objective data could have strengthened triangulation and offered an even more technically grounded assessment of design-performance relationships.

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