



Quantitative Simulation-Based Model for Short-Circuit Analysis, Arc-Flash Risk Evaluation, and Protection Coordination in Industrial Electrical Systems

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Abstract

This study addresses the persistent safety and reliability problem in industrial electrical systems where short-circuit faults, arc-flash hazards, and poorly coordinated protective devices can jointly cause equipment damage, worker injury, unnecessary outages, and reduced operational continuity. The purpose of the research was to develop and test an integrated quantitative simulation-based model showing how short-circuit analysis, arc-flash risk evaluation, and protection coordination influence industrial electrical system safety and performance. Using a quantitative, cross-sectional, case-based design, the study combined survey data from 210 valid respondents drawn from industrial enterprise case environments, including electrical engineers, maintenance engineers, safety officers, technicians, and supervisors, with simulation outputs from key electrical locations such as the main LV switchboard, MCCs, and feeder buses. The main independent variables were short-circuiting analysis, arc-flash risk evaluation, and protection coordination, while the dependent variable was industrial electrical system safety and operational performance. Data were analyzed using descriptive statistics, Pearson correlation, and multiple regression. The findings showed high mean scores for all major constructs, including short-circuit analysis ($M = 4.18$, $SD = 0.61$), arc-flash risk evaluation ($M = 4.24$, $SD = 0.57$), protection coordination ($M = 4.31$, $SD = 0.54$), and industrial electrical safety and performance ($M = 4.27$, $SD = 0.59$). Simulation results identified the Main LV Switchboard Bus as the highest fault-current location at 31.6 kA, while arc-flash incident energy at MCC-1 decreased from 9.8 cal/cm² to 5.9 cal/cm² after coordination refinement, a reduction of about 39.8%, and clearing time improved from 0.42 s to 0.24 s. Correlation analysis revealed strong positive relationships with system safety and performance for short-circuit analysis ($r = 0.71$), arc-flash risk evaluation ($r = 0.76$), and protection coordination ($r = 0.83$), all at $p < .001$. Regression results further showed that the model explained 72.4% of the variance in safety and performance ($R^2 = 0.724$, $F(3,206) = 180.24$, $p < .001$), with protection coordination emerging as the strongest predictor ($\beta = 0.401$), followed by arc-flash risk evaluation ($\beta = 0.287$) and short-circuit analysis ($\beta = 0.249$). The study implies that industrial organizations can significantly improve electrical safety and system dependability by integrating fault studies, arc-flash assessment, and coordination review into a single protection management framework.

Keywords

Short-Circuit Analysis; ARC-Flash Risk Evaluation; Protection Coordination; Industrial Electrical Safety; System Reliability;

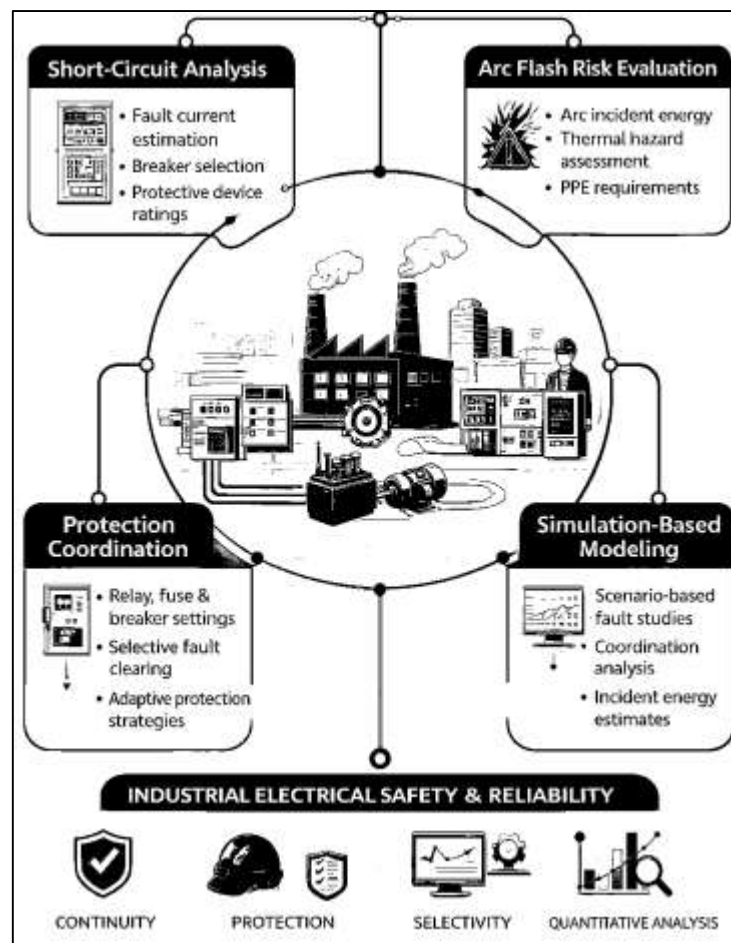
INTRODUCTION

Industrial electrical systems are commonly understood as integrated networks of generators, transformers, switchgear, protective devices, control circuits, feeders, motors, and process loads that deliver electrical energy to production environments where continuity, selectivity, and personnel safety are all mission-critical. In research and engineering practice, a short circuit is defined as an abnormal low-impedance path that allows current to rise rapidly beyond normal operating values, while an arc flash is a hazardous release of thermal energy, light, pressure, molten metal, and plasma generated by an electrical arcing fault (Abeid & Hu, 2020). Protection coordination refers to the systematic arrangement of relay, fuse, and circuit-breaker settings so that the device nearest to the fault clears first, with upstream devices operating only when required. A simulation-based model in this context refers to a computer-supported analytical framework through which fault current levels, arcing current, incident energy, device trip times, and coordination margins can be calculated and compared under different operating conditions (Bedekar & Bhide, 2011). These definitions are not merely technical labels; together they frame one of the most important safety and reliability problems in modern industry because a fault in a refinery, steel plant, chemical process unit, manufacturing line, hospital utility system, or data-intensive industrial facility can interrupt production, damage capital equipment, and expose workers to life-threatening thermal injury (Gammon, 2010). The international relevance of this topic has grown as industrial plants become more electrified, more automated, and more dependent on interconnected protection schemes that must perform correctly during abnormal conditions. Research across AC distribution systems, DC systems, microgrids, and distributed-energy-integrated networks consistently shows that fault behavior is becoming more complex and that conventional fixed assumptions about current direction, magnitude, and clearing sequence are no longer sufficient in many real installations. For that reason, the present topic sits at the intersection of electrical safety, industrial reliability, and quantitative system analysis, and it is increasingly treated in the literature as a core engineering concern rather than a narrow compliance exercise (Gammon et al., 2019b).

The literature on short-circuit analysis establishes that fault-current calculation is the analytical foundation for the safe design and operation of industrial power systems because protective device interrupting ratings, bus bracing, equipment duty, breaker selection, and arc-flash calculations all depend on credible fault-current estimates (Gammon et al., 2019a). Early and continuing work on overcurrent relay coordination showed that improper assumptions regarding current magnitude and backup-device timing can cause unnecessary outages or delayed clearing, both of which increase thermal and mechanical stress on equipment. Later comparative studies extended this concern by examining how different short-circuit methodologies influence engineering decisions. For example, one important study demonstrated that ANSI/IEEE and IEC short-circuit procedures may produce materially different values that affect downstream arc-flash calculations, a point that is especially important in industrial environments where multinational design practices and software tools often coexist (Zhang, & Johnson, 2015). This is one reason the short-circuit study is not an isolated design report but the numerical backbone of broader protection and hazard analysis. Once available fault current is misestimated, coordination intervals, trip-unit settings, breaker application, and incident-energy calculations all become less trustworthy. Recent adaptive-protection studies reinforce the same principle from another angle: when network topology changes or distributed sources alter fault contribution, relay settings that were once valid may no longer preserve selectivity or sensitivity. Optimization-oriented relay studies add that coordination quality is highly dependent on the interaction between pickup settings, time-multiplier values, and fault-level distribution across the network, making precise short-circuit modeling essential for any credible coordination exercise. In industrial electrical systems, therefore, short-circuit analysis is not only a numerical estimate of worst-case current; it is the entry point for evaluating whether the system can withstand, detect, isolate, and survive fault conditions with acceptable safety margins and operational resilience (Majd et al., 2019). Arc-flash scholarship adds another layer of this background by shifting attention from equipment duty alone to human exposure during arcing events. The literature repeatedly emphasizes that the hazard is not confined to the visible flash itself; it includes extreme thermal energy, radiant heat, intense light, pressure waves, molten metal ejection, and the possibility of severe burn injury even when the worker

is not in direct electrical contact (Tjahjono et al., 2017). A number of studies argued that much of the engineering conversation had become too narrowly centered on labels and PPE categories, while the underlying physics and injury pathways required deeper interpretation for real safety management (Singh, 2017). That line of work is important because it places incident energy in a broader analytical context and clarifies that the term “arc flash” can understate the full hazard profile of an arcing fault. Parallel studies on light-spectrum behavior and arc detection similarly show that the arc event is both a protection problem and a measurable physical phenomenon whose optical characteristics can support faster detection and safer isolation (Vyas et al., 2020). Regulatory and standards-oriented analyses also demonstrate that code provisions only function effectively when arcing current, clearing time, and device response are grounded in realistic system data. Studies examining code-based arc-energy-reduction provisions have shown that engineering choices must preserve reliable operation under expected arcing currents, while analyses of OSHA case data have highlighted the persistent injury burden and the importance of understanding actual incident patterns rather than relying only on abstract hazard categories. Earlier work on protective clothing and safety practice further showed that PPE development evolved alongside better recognition of arc hazards, which means that hazard assessment and protection design have historically co-developed rather than existing as separate fields (Weerasekara et al., 2016). Taken together, this body of literature defines arc-flash risk evaluation as a quantitative and physical assessment process aimed at estimating exposure severity and reducing the duration or magnitude of arcing energy through sound system analysis and properly coordinated protection (Razavi et al., 2008).

Figure 1: Key Components of Industrial Electrical Protection and Safety Analysis Framework



Protection coordination research makes the background of this study even more specific because it addresses the question of how fault-clearing devices should interact across a network during abnormal operation. In industrial systems, coordination is expected to achieve selectivity, speed, sensitivity, and backup reliability, and those requirements become more difficult to satisfy as system architecture becomes more complex. The relay-coordination literature has evolved from classical deterministic setting approaches toward hybrid, adaptive, and optimization-based formulations because modern distribution and industrial networks exhibit variable fault contributions, bidirectional flows, and changing source configurations (Samadi & Chabanloo, 2020). One influential study introduced a genetic-algorithm-based coordination method to overcome limitations of traditional programming approaches, while another refined the optimization agenda by combining genetic algorithms with nonlinear programming to minimize operating time while maintaining coordination constraints (Damanjani et al., 2021; Zhao et al., 2020). Later studies expanded these efforts through firefly, grey wolf, ant lion, particle swarm, and sine-cosine algorithms, each attempting to solve the same core engineering problem: how to obtain reliable time-current selectivity in constrained, nonlinear, and increasingly dynamic networks. Review studies have consolidated these findings and reached a shared observation that conventional fixed-setting approaches are often strained when distributed generation or microgrid behavior changes current magnitude and direction, which can invalidate previously coordinated settings (Nascimento et al., 2020). For industrial electrical systems, this literature is especially relevant because these facilities commonly contain large motors, transformers, feeders of varying impedance, multiple voltage levels, and process-critical buses that cannot tolerate widespread trips. In such settings, protection coordination is not simply a relay-engineering exercise; it is a structured mechanism for controlling the spread of fault consequences, limiting outage extent, and reducing the time window in which arc-flash energy can develop at the faulted location (Monadi et al., 2015).

A further strand of the literature explains why simulation-based modeling is now central to research on industrial electrical protection. Simulation enables engineers to represent the actual topology of a plant, assign source and load parameters, run multi-scenario fault studies, compare available and reduced arcing current conditions, and visualize coordination performance through time-current characteristics and incident-energy estimates (Zhao et al., 2018). This methodological turn is visible in both AC and DC research. Several studies modeled DC series faults and photovoltaic arc conditions using empirically informed arc behavior, showing that simulation can translate observed fault patterns into analytical forms that support design and protection studies. On the protection side, adaptive overcurrent studies have shown that relay settings often need recalculation in response to network changes, a task that depends heavily on software-assisted scenario analysis. Another important study further showed that the selected short-circuit calculation method can materially affect the numerical basis used later in arc-flash analysis, which again underscores the role of simulation as the analytical bridge between fault current estimation and safety evaluation (Uriarte et al., 2012). Research on spectral and optical arc detection also supports the same point from a measurement perspective: once arc behavior is instrumented and modeled, detection logic and protective action can be designed around measurable signatures rather than only around conventional overcurrent thresholds. In industrial plants where the electrical system includes switchboards, MCCs, transformer secondaries, protective relays, and process-sensitive loads, simulation is therefore not a secondary visualization tool. It is the main environment in which fault severity, incident energy, device operating sequence, and vulnerability of specific buses can be studied quantitatively before a hazardous event occurs (Jamal et al., 2018).

The empirical literature also shows that these three domains—short-circuit analysis, arc-flash risk evaluation, and protection coordination—have often been studied in parallel rather than in a single integrated framework. Review papers on distribution and microgrid protection tend to focus heavily on relay coordination and adaptive settings, while arc-flash publications frequently prioritize incident-energy physics, PPE selection, or code interpretation (Kaur et al., 2021). This separation is useful for technical specialization, yet it leaves a visible gap when the research problem concerns industrial systems where all three processes are operationally inseparable. Several review studies documented the broader protection challenges created by changing system architectures and relay miscoordination

under variable fault levels. In a different segment of the literature, studies discussed arc hazards, code mechanisms, injury patterns, and exposure estimation (Gammon & Saporita, 2017). A complementary line of occupational-injury research widened the frame by showing that electrical injuries are not confined to specialist electrical workers and that the economic and organizational burden of electrical events extends beyond immediate medical treatment to broader workplace-loss patterns. What emerges from this combined scholarship is a background in which the technical and human consequences of faults are well established, yet the analytical chain connecting fault magnitude, clearing behavior, incident energy, and system-level protection performance is still often presented in fragmented form. That fragmentation is especially important in industrial settings, where a single arcing fault may be simultaneously a short-circuit event, an arc-flash hazard, and a coordination test of the protection hierarchy. The existing literature provides strong foundations for each of those elements individually, and it also suggests the value of treating them together within a unified quantitative model anchored in realistic system data and case-specific simulation outputs (Zhang, & Rau, 2015).

Another important part of the background concerns the movement from general hazard recognition to measurable engineering indicators that can support empirical research design. Several studies in the relay-coordination literature use optimization objectives such as total relay operating time, coordination time interval, plug setting multiplier, pickup current, or time dial settings as quantitative indicators of protection performance (Hatata & Lafi, 2018). In the arc-flash literature, typical quantitative variables include arcing current, clearing time, incident energy, and boundary distance, while in short-circuit studies the main variables include bolted-fault current, X/R-influenced duty, and device interrupting adequacy. These variables are attractive for a quantitative case-study design because they can be generated through software and then interpreted alongside organizational evidence from engineers, technicians, and safety personnel (Wellman, 2012). Research on adaptive protection systems likewise points to a natural bridge between numerical system outputs and practitioner judgments, since real protection performance depends both on system behavior and on the quality of settings, maintenance, review practices, and engineering decision-making. The use of case-based system models is therefore consistent with a quantitative cross-sectional study in which simulation outputs describe the electrical reality of the plant while survey-based responses capture the operational and managerial context in which those protective arrangements are applied (Swencki et al., 2005). This combination is especially suitable for industrial environments because the literature shows that protection behavior is influenced by both physical network conditions and human decision processes concerning study updates, settings review, maintenance intervals, and compliance understanding. When read together, the studies used in this introduction establish a scholarly basis for treating industrial electrical safety as a measurable, multi-variable problem in which short-circuit behavior, arc-flash severity, and coordination quality can be analyzed within one research frame (Valdes et al., 2019).

Background of the Study

The background of this study is rooted in the growing technical and safety challenges associated with the operation of industrial electrical systems, where uninterrupted power supply, equipment protection, and worker safety are essential to maintaining productive and reliable industrial processes. Industrial facilities such as manufacturing plants, refineries, processing units, commercial utility complexes, and large-scale production environments depend on complex electrical distribution networks composed of transformers, switchgear, feeders, buses, motor control centers, protection relays, circuit breakers, and other interconnected components that must function in a coordinated manner under both normal and fault conditions. Within these systems, electrical faults such as short circuits can produce extremely high fault currents capable of causing severe thermal and mechanical damage to equipment, unplanned shutdowns, process interruptions, and costly operational losses. At the same time, arc-flash incidents represent one of the most dangerous electrical hazards in industrial settings because they can release intense heat, pressure, and light energy in a fraction of a second, exposing personnel to serious injury and creating major safety liabilities for organizations. Protection coordination becomes critically important in this context because the proper arrangement of protective devices determines whether a fault is isolated quickly and selectively or allowed to escalate into a widespread system disturbance. As industrial operations become more automated, electrically dense,

and technologically interconnected, the need for precise analytical methods to evaluate fault behavior, hazard severity, and device response has become much greater than before. Traditional manual approaches are often not sufficient for capturing the dynamic relationships among fault current magnitude, incident energy levels, relay settings, breaker operating times, and the vulnerability of different sections of an industrial network. This has increased the relevance of simulation-based models, which provide a structured and quantitative means of examining electrical system behavior under realistic fault scenarios and support better engineering decisions related to safety, reliability, and operational continuity. In addition, organizations are increasingly expected to justify their protection strategies not only through technical calculations but also through measurable evidence that can be analyzed statistically and interpreted in relation to system performance outcomes. For this reason, the present study is grounded in the need to integrate short-circuit analysis, arc-flash risk evaluation, and protection coordination into a single quantitative framework capable of supporting both engineering assessment and empirical investigation within an industrial case-study setting.

Problem Statement

Industrial electrical systems continue to face major operational and safety challenges arising from fault conditions that are not always adequately predicted, assessed, or controlled through existing protection practices. In many industrial facilities, short-circuit analysis, arc-flash risk evaluation, and protection coordination are treated as separate technical exercises rather than as interdependent components of one integrated safety and reliability framework. This separation creates a practical problem because the occurrence of a fault in an industrial network is rarely limited to only one technical dimension. A short circuit can simultaneously generate excessive fault current, increase the likelihood of arc-flash exposure, and test the effectiveness of the protection coordination scheme. When these elements are not assessed together, the system may appear compliant on paper while still containing hidden vulnerabilities in bus protection, device selectivity, clearing time performance, or hazard exposure level. The problem becomes more serious in industrial environments where electrical networks are dense, interconnected, and heavily loaded with motors, transformers, feeders, and process-critical equipment. In such settings, a single protection failure or delayed device response can lead to widespread outage, equipment damage, production interruption, worker injury, and increased maintenance cost. Another important concern is that many organizations still rely on conventional or periodic studies that may not fully capture the changing operating conditions of modern industrial systems, including load expansion, equipment replacement, altered fault levels, and revised protection settings. This creates uncertainty regarding whether existing coordination schemes remain effective under actual operating conditions. At the same time, there is limited empirical research that combines engineering simulation outputs with quantitative statistical evidence from practitioners to show how short-circuit analysis, arc-flash risk evaluation, and protection coordination jointly influence industrial electrical safety and system performance. As a result, there is a clear need for a study that develops and applies a quantitative simulation-based model capable of examining these relationships within a case-study setting. The central problem addressed by this research is therefore the lack of an integrated, measurable, and statistically testable framework for evaluating how fault analysis, arc-flash hazard assessment, and protective device coordination together affect safety, reliability, and operational continuity in industrial electrical systems.

Objectives of the Study

The objective of this study is to develop a structured quantitative understanding of how short-circuit analysis, arc-flash risk evaluation, and protection coordination contribute to safety and operational performance in industrial electrical systems. More specifically, the study seeks to examine these three technical dimensions not as isolated engineering tasks but as interacting variables within a single simulation-based and case-oriented analytical framework. The first objective is to assess the role of short-circuit analysis in identifying fault-current severity and supporting appropriate protection decisions across industrial electrical networks. This involves examining how accurate knowledge of fault levels helps determine equipment adequacy, system vulnerability, and the basis for effective protective settings. The second objective is to evaluate the significance of arc-flash risk assessment in reducing hazard exposure and improving worker safety in industrial environments where high-energy electrical events can have severe human and operational consequences. The third objective is to analyze

the influence of protection coordination on fault isolation, selectivity, reliability, and continuity of industrial processes, especially in systems where multiple protective devices must respond in a properly sequenced manner. Beyond these separate objectives, the study also aims to integrate simulation outputs and quantitative survey evidence in order to measure the relationships among these variables and determine their combined effect on industrial electrical system safety and performance. In doing so, the research intends to produce statistically interpretable findings through descriptive analysis, correlation analysis, and regression modeling, thereby offering a more rigorous basis for engineering evaluation. Another objective is to identify vulnerable buses, fault-prone locations, and coordination gaps within the selected case-study system so that the analysis reflects real system conditions rather than abstract theoretical assumptions. Overall, the study is designed to generate an objective-driven examination of how simulation-supported fault analysis and protection practices can be measured, compared, and explained in a way that supports a stronger understanding of industrial electrical risk, protection effectiveness, and performance reliability.

Research Hypotheses

The research hypotheses of this study are formulated to test the expected relationships between the major technical variables involved in industrial electrical protection and the overall safety and performance outcomes of the system. Since the study is quantitative and case-study based, the hypotheses provide a clear statistical structure for examining whether short-circuit analysis, arc-flash risk evaluation, and protection coordination have meaningful effects on industrial electrical system safety and operational continuity. The first hypothesis assumes that short-circuit analysis has a significant positive effect on industrial electrical system safety because accurate fault-current analysis forms the basis for equipment protection, system planning, and fault containment. The second hypothesis assumes that arc-flash risk evaluation has a significant positive effect on hazard reduction and personnel protection because effective identification of incident energy levels and vulnerable locations supports safer work conditions and improved protective measures. The third hypothesis assumes that protection coordination has a significant positive effect on system reliability and fault isolation because well-coordinated protective devices are expected to reduce unnecessary outages, isolate faulted sections more effectively, and preserve the continuity of healthy parts of the network. In addition to these direct relationships, the study proposes a broader combined hypothesis that short-circuit analysis, arc-flash risk evaluation, and protection coordination jointly have a significant predictive effect on overall industrial electrical system safety and operational performance. This final hypothesis is important because the research is based on the understanding that industrial electrical protection is a combined process in which fault magnitude, hazard severity, and device response influence one another. The hypotheses therefore allow the study to move beyond descriptive technical observations and into empirical testing through correlation and regression analysis. They also create a bridge between engineering simulation outputs and statistical interpretation, making it possible to determine whether the technical factors examined in the case-study environment are not only present but also significantly associated with improved system outcomes. In this way, the hypotheses serve as the analytical foundation for verifying the study objectives and for determining whether the proposed quantitative simulation-based model has meaningful explanatory value in industrial electrical systems.

Significance of the Research

The significance of this research can be understood from several important perspectives:

- i. Engineering significance: This study contributes to electrical engineering knowledge by integrating short-circuit analysis, arc-flash risk evaluation, and protection coordination into one unified quantitative framework. This makes the research more technically valuable than studies that examine these elements separately.
- ii. Safety significance: The study is important for industrial safety because it addresses fault conditions that may expose workers to serious electrical hazards. By focusing on arc-flash risk and coordinated protection response, the research supports a better understanding of how industrial systems can be assessed for safer operation.
- iii. Operational significance: The study is significant for industrial operations because improved protection analysis can reduce equipment damage, unnecessary shutdowns, and production interruptions. This makes the findings relevant for facilities that depend on continuous electrical service

for process stability and output efficiency.

iv. Methodological significance: The research is valuable methodologically because it combines simulation-based electrical analysis with quantitative statistical techniques such as descriptive statistics, correlation analysis, and regression modeling. This provides a stronger empirical structure for evaluating industrial electrical systems.

v. Practical significance for professionals: The study offers practical value to electrical engineers, maintenance personnel, safety officers, plant managers, and protection specialists by presenting a framework that can support decision-making related to system design, fault studies, protection review, and hazard assessment.

vi. Academic significance: The research adds to academic literature by addressing a gap in integrated industrial electrical protection studies. It provides a case-study-based model that future researchers can adapt for similar investigations in power distribution, industrial safety, and electrical reliability studies.

vii. Policy and compliance significance: The study also has value for organizations seeking to strengthen internal safety procedures, technical audit practices, and electrical risk management policies. A clearer understanding of system vulnerability and coordination quality can support more evidence-based compliance and documentation processes.

Taken together, these dimensions show that the research is significant not only as a technical study but also as a practical, academic, and organizational contribution to the safer and more reliable management of industrial electrical systems.

LITERATURE REVIEW

The literature review for this study is centered on the major bodies of knowledge that explain the technical, safety, and analytical foundations of short-circuit analysis, arc-flash risk evaluation, and protection coordination in industrial electrical systems. Industrial power networks are complex infrastructures in which fault behavior, protective device response, and hazard exposure are closely interconnected, making it essential to examine prior scholarly work from multiple but related perspectives. The literature provides an important basis for understanding how electrical faults originate, how fault currents propagate through industrial networks, how protective devices are expected to respond under abnormal conditions, and how human and equipment safety can be affected when protection systems fail or operate too slowly. It also helps establish why short-circuit studies are fundamental to equipment rating, system design, and the evaluation of fault withstand capability, while arc-flash studies are necessary for assessing incident energy levels, exposure boundaries, and the severity of risk to personnel. In the same way, the literature on protection coordination explains the principles of selectivity, sensitivity, speed, and reliability that govern the operation of relays, circuit breakers, and fuses in industrial systems where fault isolation must be achieved without unnecessarily disconnecting healthy sections of the network. Beyond these technical areas, the literature also highlights the increasing role of simulation tools in modeling industrial electrical systems and in generating numerical evidence about fault magnitude, device operation, incident energy, and vulnerable buses or feeders. This is especially relevant for the present study because the research is not limited to conceptual discussion but is based on a quantitative simulation-supported case-study design. The literature review therefore serves several purposes within the study. It defines the major concepts, presents the theoretical foundation guiding the interpretation of the variables, develops the conceptual framework linking the independent and dependent variables, and identifies the empirical findings and methodological gaps that justify the present investigation. By reviewing prior work in a structured way, this chapter establishes the academic and technical context for the research and shows how the present study is positioned within broader discussions on industrial electrical safety, system reliability, protective device coordination, and simulation-based engineering analysis.

Industrial Electrical Faults and Short-Circuit Analysis

Industrial electrical faults are central to the safety, continuity, and technical integrity of modern power networks because fault conditions reveal the true strength and vulnerability of an electrical system under abnormal operation. In industrial environments, short circuits are particularly significant because they can produce very high current magnitudes within extremely short time intervals, subjecting conductors, switchgear, relays, transformers, buses, and rotating equipment to severe thermal and electromechanical stress. The study of short-circuit behavior is therefore not limited to a

simple calculation of available fault current; it is a broader analytical activity concerned with equipment duty, interrupting adequacy, system withstand capability, and the conditions under which protective devices must operate to isolate the faulted section without destabilizing the wider network. A major issue identified in the literature is that fault-current behavior becomes increasingly difficult to predict accurately when power systems contain distributed energy resources, mixed source types, and nonuniform feeder characteristics. In such cases, short-circuit levels are no longer determined only by the upstream utility source, because local generation, machine contribution, network configuration, and source impedance all alter the final current seen at the faulted point. This is why the short-circuit study remains one of the first and most important analytical steps in electrical system design and operational review. It establishes whether an industrial network is adequately protected, whether its equipment ratings remain acceptable after expansion or modification, and whether the system is exposed to fault levels capable of undermining protection selectivity. The literature also shows that short-circuit analysis supports not only design decisions but also risk-oriented engineering judgment, since fault currents influence breaker application, protective margin, isolation speed, and the severity of downstream hazards. In practical terms, industrial fault analysis functions as the technical basis upon which later assessments of protection coordination and arc-flash severity are built, making it a foundational component of any rigorous electrical protection study (Boutsika & Papathanassiou, 2008).

Figure 2: Analytical Framework for Short-Circuit Severity, Protection Adequacy, and System Reliability

<p>Short-Circuit Severity Rapidly rising fault currents that cause extreme thermal and electromechanical stress</p>	<p>Protective Adequacy Ensuring fault levels do not exceed equipment interrupting and withstand capabilities</p>
<p>System Complexity Difficult fault prediction due to distributed generation and mixed source conditions</p>	<p>Mitigation and Reliability Limiting fault currents through reconfiguration and current-limiting devices</p>

A further concern in the literature is that industrial short-circuit behavior cannot always be represented adequately through deterministic, single-scenario calculations alone, especially in networks that experience load uncertainty, multiple source conditions, or variable operational configurations. This has encouraged a more nuanced treatment of short-circuit studies in which uncertainty, probability, and scenario variation are treated as engineering realities rather than methodological inconveniences. One line of research developed probabilistic short-circuit evaluation methods to show that fault impacts can be expressed not merely as fixed maximum values but as distributions linked to power-quality and fault-performance indicators, thereby strengthening the interpretive value of short-circuit assessment for real network conditions. That perspective is particularly useful for industrial systems where operating states may shift according to production loads, motor status, distributed generation availability, and switching arrangements. Another important contribution to the literature extends the short-circuit problem into distribution systems with embedded generation, demonstrating that local generation can raise fault levels and alter the assumptions traditionally used in network design and protection review. This is important because industrial facilities increasingly operate with localized

generation support, energy recovery systems, or internal generation sources that can materially change the contribution to a three-phase or unbalanced fault. In such environments, the fault level becomes both a design limit and an operational variable. When the calculated short-circuit current exceeds the withstand capability of the installed switchgear or the interrupting capacity of the selected breaker, the entire protection strategy becomes questionable. The literature therefore treats short-circuit analysis as a continuing process of system validation rather than as a one-time calculation completed at the design stage. It also highlights that accurate fault studies require realistic component models, credible source data, and analytical sensitivity to how distributed resources reshape both current magnitude and fault direction. These concerns reinforce the importance of simulation-supported short-circuit analysis in industrial case studies where safety and continuity depend on precise engineering knowledge rather than approximate assumptions (Bordalo et al., 2006; El-Hassanin et al., 2013).

The literature also shows that short-circuit analysis has expanded beyond traditional fault-current estimation toward a broader examination of how fault severity interacts with protective strategy, network modernization, and fault-current mitigation technologies. As power systems become more electrically dense and more connected to distributed and converter-based sources, many networks experience rising fault levels that push existing protection equipment closer to their duty limits. This has led researchers to examine technologies and planning approaches capable of keeping fault currents within safe and manageable levels while preserving service reliability. One important stream of work examines how distributed generators influence arcing faults and demonstrates that the presence of local generation can alter the current profile seen at the fault location, thereby affecting both fault analysis and safety-related calculations (Alam et al., 2018; Manam & Ashfaq, 2022). This is highly relevant to industrial electrical systems because it shows that short-circuit studies must account not only for bolted faults but also for realistic fault conditions involving arc resistance and changing source contribution. Another major contribution comes from research on fault current limiters, which has framed short-circuit control as a strategic protection problem rather than solely a calculation problem (Khaled, 2021; Meneses et al., 2013). This literature explains that fault current limitation technologies are increasingly important where system growth, equipment upgrades, or source interconnection produce current levels that challenge breaker ratings and network stability. For industrial systems, this means that short-circuit analysis supports both diagnosis and intervention: it identifies where current magnitudes are unsafe, and it helps evaluate whether mitigation options such as reconfiguration, equipment replacement, or current-limiting devices are technically justified. As a result, the literature positions short-circuit analysis as a dynamic study domain that informs equipment adequacy, protective performance, and system hardening against severe fault conditions. In the context of this research, that perspective is especially important because it aligns short-circuit analysis with the broader aims of fault severity mapping, protection evaluation, and simulation-based assessment of industrial electrical vulnerability (Ciric et al., 2011; Binte & Sazzadul, 2022).

Arc-Flash Risk Assessment in Industrial Environments

Arc-flash risk assessment has become a critical component of industrial electrical safety because it translates fault behavior into a direct estimate of worker exposure, equipment damage potential, and operational disruption. In industrial environments, an arc flash is not treated only as an electrical anomaly but as a high-energy event whose severity depends on arcing current, clearing time, equipment configuration, working distance, and the protective performance of the upstream device. The literature shows that the practical value of arc-flash assessment lies in its ability to convert system data into incident-energy estimates that can guide labeling, personal protective equipment selection, maintenance planning, and hazard communication. One of the important developments in this area was the effort to compare and simplify incident-energy calculations under established standards, because engineers in industrial plants needed methods that were not only technically defensible but also practical for routine hazard studies. A historical and comparative study of IEEE 1584 and NFPA 70E highlighted how incident-energy methods evolved into a more formal analytical basis for plant-level hazard evaluation and showed that arc-flash analysis had become a central concern for energized work on industrial equipment (Sen et al., 2007). That body of work is important because it positioned arc-flash assessment as a structured engineering study rather than a secondary compliance exercise. In industrial settings, this distinction matters greatly, since motor control centers, switchboards,

switchgear lineups, and process buses often present different hazard profiles even within the same facility. The literature therefore treats arc-flash risk assessment as a location-specific and system-dependent activity requiring accurate electrical models and realistic protective-device data. This perspective also reinforces the idea that arc-flash analysis cannot be separated from short-circuit and coordination studies, because incident energy is strongly shaped by the magnitude of fault current and the speed with which protection isolates the event. For industrial electrical systems, arc-flash assessment thus serves as the bridge between technical system studies and direct human-safety decision making, which is why it remains central to contemporary electrical safety engineering (Sullivan et al., 2021).

Figure 3: Multidimensional Analysis Of Arc-Flash Risk And Worker Safety In Industrial Power Systems



A major concern in the literature is that arc-flash incident energy is not static across time, equipment condition, or network configuration, which makes periodic reassessment essential in industrial facilities. Studies focused on practical implementation have shown that industrial plants often discover substantial variation in arc-flash exposure only after completing detailed field studies, equipment reviews, and remediation projects. Case-based evidence from industrial processing facilities demonstrated that arc-flash hazards could be identified, measured, and mitigated through site-specific analyses tied to actual plant layouts and operating practices, rather than through generic assumptions alone (Durocher, 2015). This is significant because industrial environments are rarely electrically uniform: they contain equipment of different vintages, multiple voltage levels, distinct enclosure types, and protection devices with differing response characteristics. Arc-flash risk assessment in such facilities must therefore account for the physical and organizational realities of the plant, including study maintenance, label accuracy, and the continued relevance of prior calculations. This issue is reinforced by later work on renewal recommendations, which explained that accepted industry practice requires incident-energy analyses to be updated when the electrical distribution system changes and to be reviewed periodically for continued accuracy (Sullivan et al., 2021). In practical terms, this means that arc-flash risk assessment is not a one-time engineering deliverable but an ongoing risk-management activity embedded in the lifecycle of industrial power systems. The literature also indicates that outdated studies can create a false sense of safety, especially where system expansion, replacement of protective devices, or changes in utility contribution alter the clearing

conditions used in earlier calculations. Industrial hazard assessment is therefore inseparable from study renewal, field verification, and data governance. From this perspective, arc-flash risk assessment supports not only compliance and worker protection but also the credibility of technical decision making within industrial electrical operations, where labeling, procedures, and protective strategies are only as reliable as the system data on which they are based.

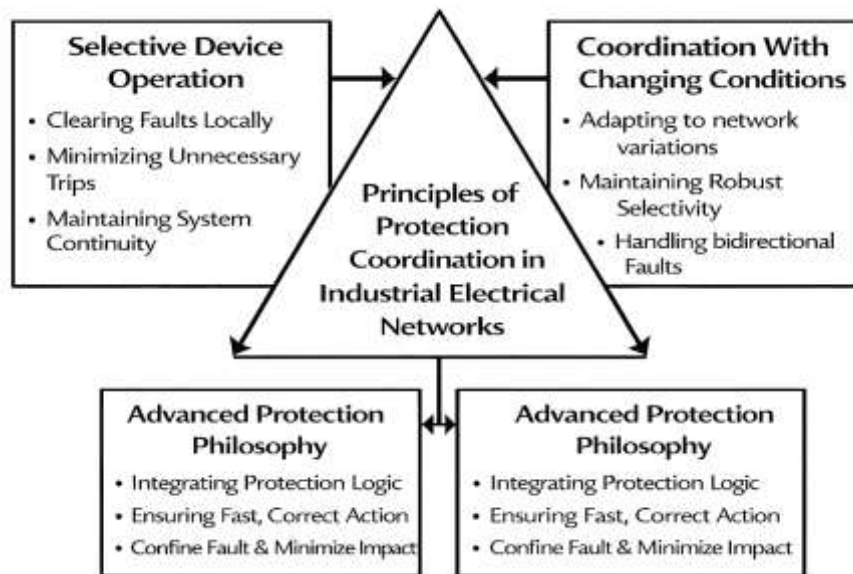
The literature also expands arc-flash assessment beyond conventional AC switchgear studies by examining the influence of equipment behavior, device performance, and alternative fault environments on hazard severity. Research on direct-current exposures showed that arc-flash calculations for DC systems required dedicated analytical treatment because the current behavior and sustaining characteristics of DC arcs differ from those in conventional AC applications, thereby affecting exposure estimation and protection planning (Doan, 2010). This contribution is important for industrial environments that include batteries, drives, photovoltaic interfaces, rectified systems, or other DC-linked equipment, since it confirms that hazard assessment must align with the actual electrical architecture of the facility. Another relevant stream of work addressed the physical consequences of arc events more directly by measuring pressure and door ejection during arc-flash incidents, showing that the hazard extends beyond thermal injury alone and includes mechanical effects that may threaten nearby workers and surrounding equipment (Hoagland et al., 2020). Such findings strengthen the argument that industrial arc-flash risk assessment should be understood as a multidimensional safety study concerned with thermal, mechanical, and operational consequences. They also help explain why incident-energy values, while essential, do not fully exhaust the engineering meaning of arc-flash hazard. In industrial plants, especially those using enclosed low- and medium-voltage equipment, the consequences of an internal arc may include enclosure failure, debris projection, and unexpected escalation of maintenance or outage risk. The literature therefore supports a broader understanding of arc-flash risk assessment as a process of quantifying exposure while also interpreting the surrounding conditions that influence injury potential and system resilience. When integrated with updated study practices and plant-specific data, arc-flash assessment becomes a strong analytical basis for evaluating industrial electrical safety in a way that is technically rigorous, operationally relevant, and closely aligned with real equipment behavior under faulted conditions (Doan, 2010).

Protection Coordination and Selective Device Operation

Protection coordination and selective device operation form one of the most critical analytical domains in industrial electrical engineering because they determine whether a fault is isolated rapidly and locally or allowed to propagate into a broader operational disturbance. In practical terms, protection coordination refers to the systematic adjustment of relay, recloser, breaker, and fuse settings so that the protective device closest to the fault operates first, while upstream devices remain secure unless backup action becomes necessary. This principle of selectivity is essential in industrial systems where feeders, motor control centers, process buses, and transformer sections are tightly coupled to production continuity. The literature consistently explains that selective device operation is not merely a matter of assigning time delays in sequence; it is a constrained engineering problem in which operating time, pickup current, relay characteristics, coordination time interval, and system topology must all be balanced at the same time. In meshed and active distribution networks, this balance becomes even more difficult because the direction and magnitude of fault current can vary according to network configuration and source contribution. A key contribution in this area was the development of a generalized Benders decomposition approach for coordinating directional overcurrent relays in active distribution networks, where the objective was to reduce total relay operating time while still satisfying hard coordination constraints (Saber & Amrae, 2017). That study is especially relevant because it shows that coordination is best treated as a structured optimization problem rather than a simple trial-and-error setting exercise. For industrial electrical systems, this insight is important since modern facilities often operate with multiple protective zones and interdependent loads that cannot tolerate widespread tripping. Selective operation, therefore, has both a technical and operational meaning: technically, it preserves correct primary-backup relationships, and operationally, it confines the outage to the smallest possible section of the system. In this way, the literature positions protection coordination as a central mechanism for reducing unnecessary outage scope, minimizing equipment

stress, and maintaining continuity in faulted industrial networks (Costa et al., 2017).

Figure 4: Integrated Approach To Protection Coordination And Fault Isolation In Industrial Systems



A second major theme in the literature is that effective protection coordination must remain robust under changing operating conditions, not only under one idealized steady-state scenario. This issue has become more significant as distribution and industrial networks include distributed generation, altered source strength, topology changes, and increasingly digital protection architectures. One important study addressed this directly by proposing a metaheuristic algorithm for the robust coordination of directional overcurrent relays, showing that relay settings must remain feasible even when the system is exposed to alternative scenarios such as network reconfiguration or line outage conditions (Costa et al., 2017). The importance of that work lies in its recognition that a coordination plan can appear acceptable in a nominal case and still perform poorly when the network departs from its base condition. For industrial systems, this is a realistic concern because plant networks frequently undergo operational switching, maintenance isolation, equipment replacement, and load redistribution, all of which can change fault behavior and protective relationships. The broader review literature reinforces this problem by demonstrating that the coordination of protective devices has evolved from classical deterministic practices toward advanced optimization and adaptive approaches due to the complexity of modern systems. A recent review of metaheuristic-based relay coordination methods showed that researchers increasingly rely on hybrid and intelligent optimization tools to satisfy selectivity constraints while minimizing relay operating time and preserving coordination margins in non-linear, multi-loop networks (El-kordy et al., 2021). This matters for selective device operation because the objective is not simply fast tripping; it is fast tripping in the correct sequence. A protection system that operates quickly but indiscriminately may still cause unacceptable process interruption. The literature therefore frames coordination quality in terms of both speed and discrimination, emphasizing that primary devices must clear local faults without triggering unnecessary upstream action. In industrial environments where system downtime carries high production cost, the robustness of selective coordination becomes a direct determinant of reliability, safety, and restoration efficiency rather than a purely theoretical design preference.

A third and increasingly important perspective in the literature is that protection coordination can no longer be treated separately from broader protection philosophy, especially in networks with active sources, microgrid features, or high penetration of distributed generation. Review studies on microgrid protection have shown that bidirectional fault current, variable fault levels, inverter-dominated behavior, and communication-related constraints all challenge the traditional assumptions used in

relay coordination and selective tripping (Beheshtaein et al., 2019). This point is highly relevant to industrial electrical systems because many contemporary facilities now incorporate embedded generation, renewable support, or converter-interfaced equipment that reshapes fault contribution and relay visibility. In such systems, the classical notion of fixed unidirectional fault flow is no longer sufficient to guarantee proper selectivity. Complementing this broader review perspective, a 2021 study on protection philosophy for distribution grids with high penetration of distributed generation demonstrated that conventional radial-system settings may lose effectiveness under changing source conditions and that existing relay and recloser logic often must be reinterpreted or enhanced to preserve protection assertiveness and reliability (Matos et al., 2021). This line of work is valuable for understanding selective device operation because it shifts the discussion from isolated relay tuning toward coordinated system behavior under realistic operating complexity. For an industrial case-study context, that shift is essential. It means that protection coordination should be evaluated not only through time-current curves and nominal relay settings but also through an examination of how the entire protection philosophy responds to actual fault scenarios, directional ambiguities, and varying short-circuit levels. The literature therefore presents selective device operation as an outcome of system-wide coordination logic rather than the property of a single device. This interpretation aligns closely with the present research, where the concern is not only whether devices trip, but whether they trip in the correct order, at the correct speed, and with the least possible disruption to the unfaulted sections of the industrial electrical network. From that standpoint, protection coordination emerges as a core pillar of industrial reliability, fault containment, and engineered electrical safety.

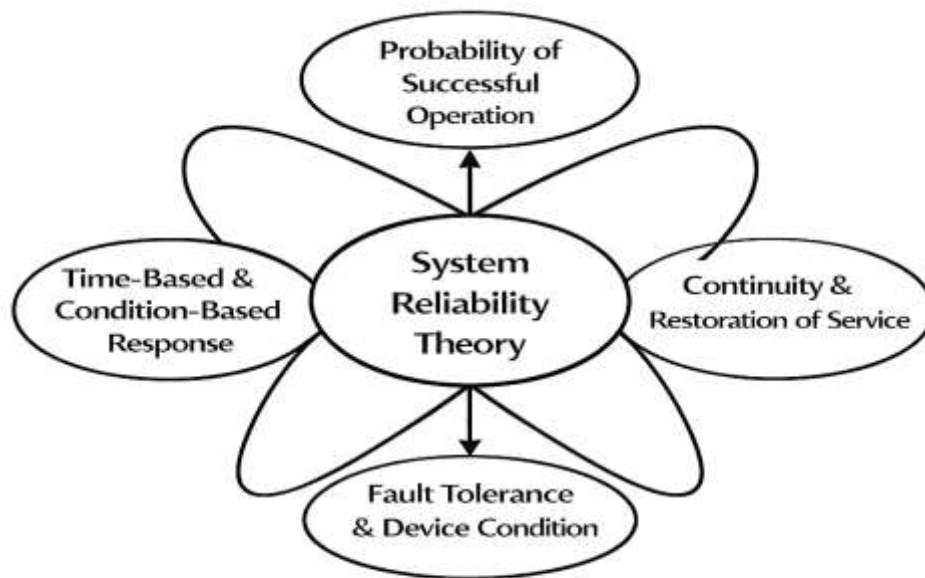
Theoretical Framework: System Reliability Theory

System Reliability Theory provides the most suitable theoretical foundation for this study because it explains industrial electrical performance in terms of the probability that a system, subsystem, or component will perform its required function without failure for a specified period under stated operating conditions. In the context of industrial electrical systems, this theory is highly relevant because the purpose of protection design is not simply to install relays, breakers, and fuses, but to ensure that the whole electrical network remains dependable when exposed to disturbances such as short circuits, arcing faults, overloads, and abnormal switching conditions. From a theoretical viewpoint, reliability is not limited to equipment survival; it also includes correct fault detection, timely device operation, selective isolation of the faulted section, and preservation of service continuity in the healthy parts of the network. This matches the central concern of the present research, which examines short-circuit analysis, arc-flash risk evaluation, and protection coordination as interacting factors that shape the safety and operational stability of an industrial power system. The theory is particularly useful because it allows the researcher to interpret protective performance as a measurable property of the system rather than as a purely descriptive engineering judgment. In reliability-based reasoning, every protective device and every electrically significant section of the network contributes to the success or failure of the whole protection path. A breaker that fails to interrupt, a relay that operates too slowly, or a poorly coordinated feeder protection arrangement can reduce the dependability of the entire industrial system even when other components remain technically sound. For this reason, System Reliability Theory supports the view that industrial electrical safety must be studied as a system-level issue involving interdependent components rather than as a collection of isolated technical checks. Studies on reliability assessment in power systems, maintenance-dependent Markov modeling for breakers, reliability-centred maintenance, and adaptive protection all reinforce this logic by showing that reliable system performance depends on both the condition of protective assets and the coordination rules that govern their operation under faulted conditions (Abbasghorbani & Mashhadi, 2013).

The theory becomes even more applicable when reliability is expressed mathematically, because the present study is quantitative and requires a formula that can conceptually guide the interpretation of industrial electrical behavior. The most useful reliability expression for this research is the exponential reliability function for a component or protection element: $R_i(t) = e^{-\lambda_i t}$, where $R_i(t)$ is the probability that component i performs successfully up to time t , and λ_i is its failure rate. When the safe operation of an industrial protection path depends on several components acting successfully in sequence, the series-system reliability expression becomes appropriate: $R_{sys}(t) = \prod_{i=1}^n R_i(t)$. If each element follows

exponential behavior, the formula becomes $R_{sys}(t) = e^{-t \sum_{i=1}^n \lambda_i}$. This is the best formula to carry through the whole study because industrial electrical protection often behaves like a series reliability structure during a fault event: current must be sensed correctly, protection logic must respond correctly, and the breaker must interrupt correctly. Failure of any one of these stages can compromise the desired outcome. In addition, the availability concept supports this theory through the expression $A = \frac{MTBF}{MTBF+MTTR}$, where MTBF is mean time between failures and MTTR is mean time to repair. This availability relationship is especially relevant for industrial facilities because the research is concerned not only with fault occurrence but also with safety, restoration speed, and continuity of plant operation. Within this theoretical frame, short-circuit analysis contributes to reliability by identifying stress severity, arc-flash analysis contributes by identifying consequences of delayed or ineffective clearing, and protection coordination contributes by improving the probability that the correct device operates within an acceptable time interval. Theoretical studies of power-system reliability and maintenance planning show that Markov-based failure modeling, maintenance-sensitive deterioration modeling, and adaptive protection strategies all fit naturally into this reliability structure because they treat system success as a probabilistic outcome shaped by device condition, fault environment, and network configuration (Abbasghorbani et al., 2014; Ardabili et al., 2020).

Figure 5: Reliability-Based Model Of Industrial Electrical System Performance And Protection Behavior



Key Concepts of System Reliability Theory in Industrial Electrical Safety

Applied to this research, System Reliability Theory provides a direct logic for connecting the independent variables to the dependent outcome of industrial electrical system safety and operational performance. Short-circuit analysis fits the theory because fault-current estimation defines the electrical stress environment under which the system must remain dependable. Arc-flash risk evaluation fits the theory because the severity of incident energy and exposure duration reflects the practical consequences of reliability failure in fault isolation (Venu & Verma, 2010). Protection coordination fits the theory because selectivity and time discrimination determine whether system response remains localized and controlled or develops into wider interruption, equipment damage, and elevated human risk. The theory therefore supports the conceptual argument that the more accurately a system is analyzed for short-circuit severity, the more thoroughly its arc-flash hazard is evaluated, and the more effectively its protection devices are coordinated, the higher the functional reliability of the industrial

network should be. It also justifies the use of descriptive statistics, correlation analysis, and regression modeling in the present study, since these methods can test whether improvements in these engineering variables are statistically associated with stronger safety and performance outcomes. In addition, the theory is highly compatible with the case-study element of the research because reliability is shaped by the actual architecture of the selected industrial system, including buses, feeders, switchgear, transformers, and protective devices. A reliability-based theoretical lens makes it possible to interpret vulnerable buses, high-fault zones, or coordination gaps not as isolated technical anomalies but as indicators of reduced system dependability. It also supports the inclusion of maintenance and device-condition reasoning, since industrial reliability depends on both the design of the protection system and the sustained health of its operating components. For this reason, System Reliability Theory offers the most coherent and technically defensible framework for the whole study: it links fault behavior, hazard severity, device response, maintenance condition, and operating continuity within one integrated explanation of how industrial electrical systems succeed or fail under abnormal conditions (Rolim et al., 2021).

Conceptual Framework

The conceptual framework of this study is developed to explain the expected relationships among short-circuit analysis, arc-flash risk evaluation, protection coordination, and industrial electrical system safety and operational performance within a single quantitative structure. In this framework, short-circuit analysis, arc-flash risk evaluation, and protection coordination are treated as the independent variables because they represent the principal technical processes through which industrial electrical hazards are identified, measured, and controlled. The dependent variable is defined as industrial electrical system safety and operational performance, which in this study refers to the extent to which the electrical network operates with reduced hazard exposure, improved reliability, effective fault isolation, lower interruption severity, and stronger continuity of service in healthy sections of the system. The logic of this framework rests on the understanding that these variables are not isolated technical elements but causally connected engineering conditions. Short-circuit analysis provides the numerical basis for understanding fault-current severity and equipment duty; arc-flash risk evaluation translates those electrical fault conditions into measurable hazard exposure at specific system locations; and protection coordination determines whether the response of relays, breakers, and related protective devices is selective enough to reduce the duration and spread of the disturbance. The literature supports this kind of linked interpretation by showing that protection performance and reliability outcomes depend on the interaction between fault characteristics and time-dependent device response rather than on any single calculation alone (Venturini et al., 2021). The framework is also strengthened by studies showing that modern protection schemes must remain valid under changing network conditions, altered topologies, and variations in fault-current distribution, because these conditions directly affect the success of selective fault isolation (Alam et al., 2020). In addition, research on arc-flash protection demonstrates that hazard severity is strongly shaped by both electrical conditions and the speed of protective interruption, which confirms that arc-flash risk cannot be conceptually separated from coordination quality and fault analysis (Kumpulainen et al., 2014). For this reason, the present conceptual model treats the dependent outcome of industrial safety and performance as the cumulative result of these three explanatory variables operating together in the selected case-study environment.

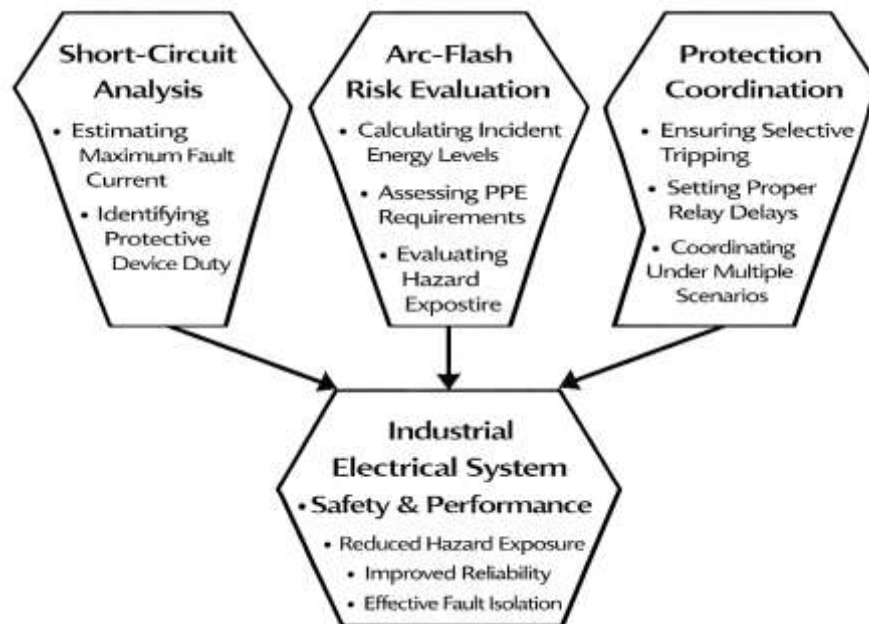
Within this framework, the relationship among the variables is represented quantitatively through the multiple regression model that guides the whole study:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \varepsilon$$

where Y represents industrial electrical system safety and operational performance, X_1 represents short-circuit analysis, X_2 represents arc-flash risk evaluation, X_3 represents protection coordination, β_0 is the intercept, β_1 , β_2 , and β_3 are the coefficients showing the contribution of each predictor, and ε is the random error term. This is the most suitable formula for the conceptual framework because the study is designed to determine the individual and combined statistical effects of the three technical predictors on the overall system outcome. The formula also aligns well with the empirical structure of the study, where simulation outputs and survey-based responses will be converted into analyzable variables for

descriptive statistics, correlation, and regression analysis. Conceptually, the model means that improvements in short-circuit analysis should produce more accurate understanding of fault severity, improvements in arc-flash risk evaluation should produce stronger control of exposure severity, and improvements in protection coordination should produce faster and more selective device operation. Together, these should increase the value of Y , meaning stronger safety and operational performance. This structure is supported by work on protection coordination indices, which shows that the quality of protection can be expressed and compared numerically in relation to system conditions and distributed generation impacts (Nikolaidis et al., 2015). It is also consistent with studies that use enhanced coordination metrics to evaluate how numerical relay settings and network conditions influence the preservation of selectivity in interconnected distribution systems (Dadfar & Gandomkar, 2021). In the present research, therefore, the conceptual framework is not merely a diagrammatic presentation of variables; it is a measurable cause-and-effect model in which technical assessments from electrical system studies are translated into empirical relationships that can be statistically tested within the industrial case-study context.

Figure 6: Quantitative Conceptual Model For Industrial Electrical Safety And Reliability Assessment



The conceptual framework also assumes that the influence of the independent variables is both direct and interdependent, meaning that each variable contributes separately to the dependent outcome while also reinforcing the others through operational interaction. Short-circuit analysis directly affects the framework because calculated fault-current magnitude determines breaker duty, relay sensitivity, bus vulnerability, and the electrical severity of the event under study. Arc-flash risk evaluation directly affects the framework because incident energy depends heavily on current magnitude and fault-clearing time, making it a practical expression of how electrical faults translate into safety exposure. Protection coordination directly affects the framework because selective and timely interruption controls how long the fault persists and how much of the system is unnecessarily disconnected. In conceptual terms, this means that poor fault-current estimation may weaken arc-flash calculations, and poor coordination may increase arc duration and enlarge the consequences of the same fault. For this reason, the model treats the three predictors as analytically distinct but operationally interconnected. The framework is also compatible with contemporary protection research showing that adaptive and communication-assisted schemes are increasingly necessary when system conditions change, because protective performance depends on how well device logic matches the prevailing electrical state of the

network (Kumpulainen et al., 2014). This supports the present study's decision to place simulation outputs at the center of the conceptual model, since the variables under study must be observed under realistic fault scenarios rather than assumed from static design values alone. In applied form, the conceptual framework may also be interpreted through a composite safety-performance function such as $SPI = w_1X_1 + w_2X_2 + w_3X_3$, where SPI is a safety-performance index and w_1 , w_2 , and w_3 are relative weights derived from empirical findings. Even when that composite expression is not used as the final statistical test, it reflects the same central idea: industrial electrical system safety is shaped by the integrated quality of short-circuit study, arc-flash assessment, and protection coordination. Accordingly, this conceptual framework provides the analytical map for the whole study by defining the variables, clarifying their expected relationships, and establishing the statistical logic through which the hypotheses will be tested.

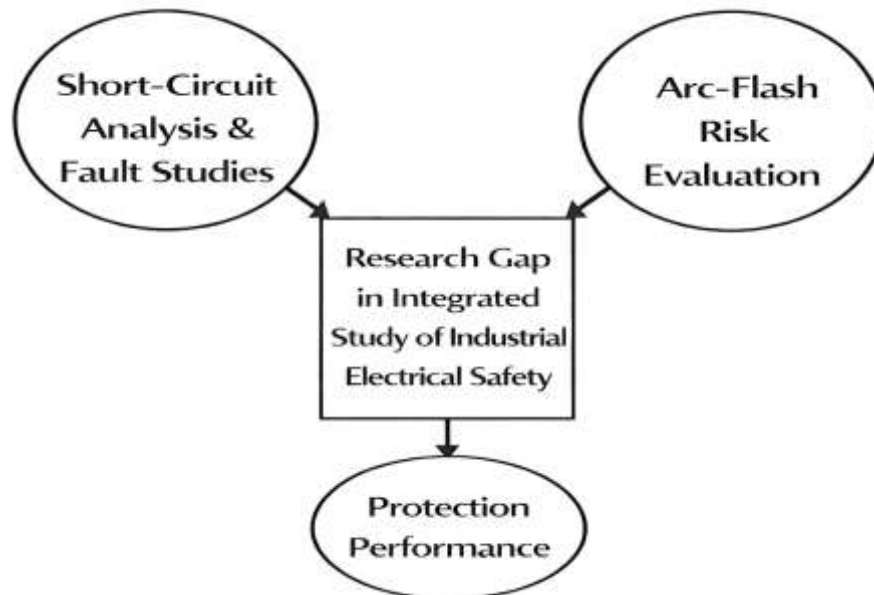
Empirical Review and Research Gap

The empirical literature on short-circuit analysis shows strong evidence that modern electrical networks require more detailed and computationally robust fault studies than those used in conventional passive systems, especially where distributed generation and complex feeder structures alter the magnitude and direction of fault current. One important empirical contribution demonstrated that large-scale distribution systems with high penetration of distributed generators need short-circuit computation methods that explicitly model contemporary generator technologies rather than relying on procedures originally developed for traditional synchronous or induction-machine-dominated systems. In that study, an improved backward/forward sweep procedure was shown to be more robust for real-time short-circuit computation because it incorporated all relevant distribution-system elements, including modern distributed generators, and therefore produced a more realistic representation of faulted-system conditions (Strezoski & Prica, 2017). A broader review of distributed generation impacts reached a related empirical conclusion by showing that the integration of distributed generation changes fault current contribution, can increase short-circuit current, may blind protection, and can trigger undesired tripping or miscoordination depending on generator location, number, and penetration level (Razavi et al., 2019). When these findings are read together, they establish an important empirical pattern for the present study: short-circuit analysis is no longer merely a background design calculation but a dynamic analytical task that influences protection visibility, device setting adequacy, and fault-clearing performance. At the same time, these studies are largely centered on distribution-grid behavior under distributed-generation conditions rather than on industrial electrical systems in which switchgear lineups, motor control centers, process-critical buses, and plant-level protective hierarchies create a different operational context. This indicates a first research gap. Existing empirical work demonstrates that changing fault-current behavior matters greatly for protection performance, yet much of that evidence is drawn from feeder-dominated or grid-integration settings instead of industrial case-study environments where electrical continuity, worker safety, and selective isolation must all be preserved simultaneously. For this reason, the current study extends the empirical conversation by repositioning short-circuit analysis within an industrial protection framework and by linking it directly with arc-flash risk and coordination performance rather than treating fault-current calculation as a stand-alone technical endpoint.

A second group of empirical studies focuses on arc-flash behavior, hazard assessment, and mitigation, and this literature provides clear evidence that electrical safety outcomes depend heavily on the quality of hazard modeling and on the protective actions taken to reduce incident energy. In the photovoltaic context, a comprehensive review of DC arc faults showed that undetected arc faults can create severe fire hazards and that accurate diagnosis depends on both appropriate detection methods and realistic arc-fault simulation models, particularly because field testing is costly and not exhaustive (Lu et al., 2018). Although that review is located within photovoltaic systems, its empirical value for the present study is substantial because it demonstrates that arc-related hazards must be analyzed as measurable electrical phenomena rather than as generic safety events. A more directly industrial and applied contribution came from a study that proposed an effective approach for reducing arc-flash hazards in existing industrial and commercial facilities and verified the approach through computer simulation on an oil-field facility and a manufacturing facility in a commercial building. That study reported significant reductions in both incident energy and fault-clearing time, showing that engineering

modifications to protection design can materially change the severity of worker exposure during fault events (Liang et al., 2016). A closely related empirical study on multi-voltage-level distribution systems showed that incident energy could be reduced to 8 cal/cm² or less through protection planning and system design using available protective devices and contemporary engineering practices, thereby demonstrating that hazard reduction is not only theoretically desirable but practically achievable when the protection strategy is deliberately optimized (Das, 2011). Together, these studies establish that arc-flash risk assessment is empirically strongest when it is integrated with protection planning, simulation, and device-response analysis. At the same time, a second research gap becomes visible. Much of the empirical evidence on arc-flash assessment either concentrates on special environments such as photovoltaic DC systems or on mitigation-driven design interventions without simultaneously examining the short-circuit and coordination variables that shape those incident-energy outcomes. The present research addresses that gap by treating arc-flash risk evaluation as one part of an integrated quantitative model in which hazard severity is interpreted alongside fault-current levels and protection coordination quality in an industrial case-study setting.

Figure 7: Gap Analysis Of Industrial Electrical Safety And Protection Research



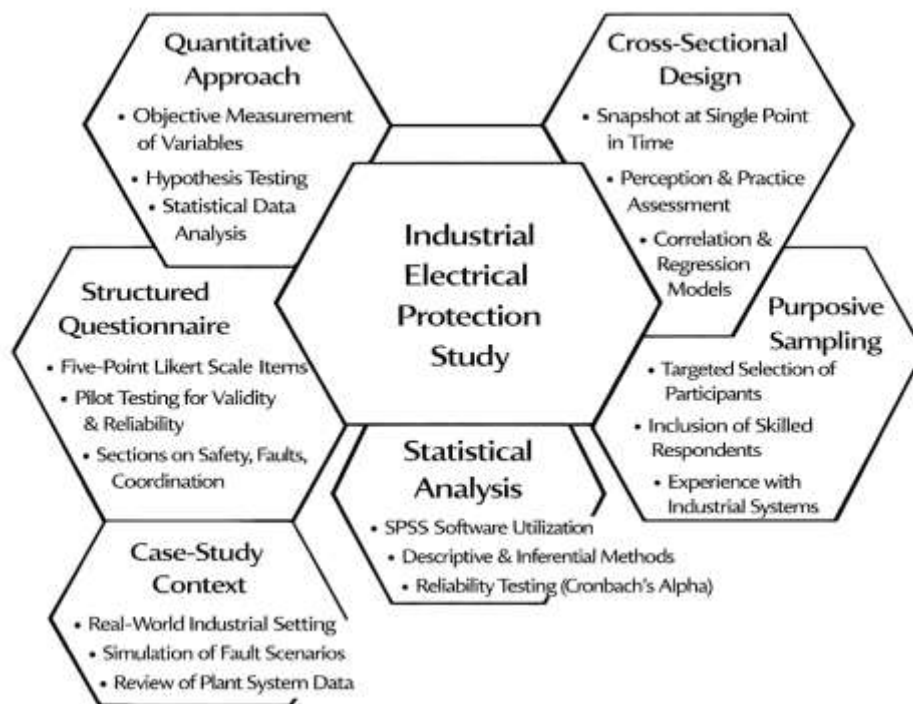
A third and more comprehensive empirical observation emerges when these streams of evidence are considered together: the existing literature provides strong findings on individual domains of protection engineering, yet relatively few studies join short-circuit analysis, arc-flash risk evaluation, and selective protection behavior within one empirical framework designed for industrial electrical systems. The available studies clearly show that modern fault studies must account for changing short-circuit behavior, that arc-flash severity can be reduced through deliberate protection design, and that distributed generation or altered network structure can challenge established protection assumptions. The literature also shows that arc-related risk analysis increasingly depends on simulation-supported understanding of arc characteristics and detection logic rather than on simple rule-based assumptions alone (Lu et al., 2018). From these findings, it is reasonable to infer that industrial electrical safety is best understood as a combined system problem in which fault magnitude, hazard severity, and protective response are interdependent rather than independent. Yet the empirical base remains fragmented. One set of studies concentrates on short-circuit computation and protection challenges associated with network modernization; another emphasizes arc-flash detection, incident energy, or mitigation; and a third examines selective operation or reliability in contexts that are not always plant-specific. What is still limited is empirical work that uses a single industrial case-study design to quantify the relationships among these variables and test them statistically using descriptive analysis,

correlation, and regression. That is the central research gap this study addresses. It responds to the need for an integrated empirical framework that does not stop at reporting fault current, incident energy, or device settings separately, but instead investigates how short-circuit analysis, arc-flash risk evaluation, and protection coordination jointly explain industrial electrical system safety and operational performance. In that sense, the present study is positioned not as a repetition of earlier technical studies, but as a synthesis-driven extension that converts separated engineering evidence into a unified quantitative model suitable for industrial protection research.

METHODS

This study has adopted a quantitative, cross-sectional, case-study-based research design in order to examine the relationships among short-circuit analysis, arc-flash risk evaluation, protection coordination, and industrial electrical system safety and operational performance. The quantitative approach has been selected because the study has aimed to measure variables objectively and test hypotheses through statistical procedures. The cross-sectional design has been used because data have been collected from respondents at a single point in time, allowing the study to capture current perceptions and practices related to industrial electrical protection. A case-study context has also been incorporated because the research has focused on an industrial electrical system environment in which practical fault scenarios, protective-device behavior, and safety-related conditions have been examined within a realistic operational setting. This approach has enabled the study to connect technical system analysis with empirical evidence from professionals working in the selected industrial environment.

Figure 8: Comprehensive Methodological Structure For Industrial Electrical Safety And Protection Analysis



The population of the study has consisted of electrical engineers, maintenance engineers, protection and control personnel, safety officers, plant technicians, and supervisors who have been directly involved in the operation, maintenance, monitoring, and protection of industrial electrical systems. These participants have been considered appropriate because they have possessed the technical and practical knowledge needed to provide reliable responses on issues relating to fault analysis, arc-flash hazards, and protection coordination. The unit of analysis has been the industrial electrical protection framework of the selected case environment, while the respondents have served as the sources of perceptual and operational data. A purposive sampling strategy has been used to select participants

who have had direct experience with industrial electrical infrastructure and protection practices. This sampling technique has been preferred because the study has required informed respondents rather than general participants. The final sample has been drawn from personnel whose responsibilities have been connected to electrical operation, safety compliance, or technical maintenance activities within the case-study setting.

For data collection, the study has used both primary and secondary sources. Primary data have been collected through a structured questionnaire, while secondary information has been drawn from technical records, simulation results, protection settings, and case-related system information where available. The questionnaire has been designed using a five-point Likert scale, ranging from strongly disagree to strongly agree, in order to quantify respondent perceptions regarding the three independent variables and the dependent variable. The instrument has been divided into sections covering demographic characteristics, short-circuit analysis, arc-flash risk evaluation, protection coordination, and industrial electrical system safety/performance. Before the main survey has been conducted, pilot testing has been carried out with a small number of qualified respondents to identify ambiguity, improve wording, and strengthen the clarity of the instrument. Based on the pilot feedback, necessary revisions have been made to ensure the usability of the questionnaire.

The study has ensured validity and reliability through several steps. Content validity has been established through expert review, where specialists in electrical engineering and research methodology have examined the instrument for relevance, clarity, and alignment with the study objectives and hypotheses. Reliability has been assessed using Cronbach's alpha, and the internal consistency of the scale items has been tested before final analysis. For data processing and analysis, SPSS has been used for descriptive statistics, correlation analysis, regression modeling, and reliability testing. Microsoft Excel has been used for coding, cleaning, and organizing the dataset before import into SPSS. EndNote has been used for reference management and citation organization throughout the study. In addition, simulation-based technical evidence has been prepared using relevant electrical system analysis tools appropriate for short-circuit, arc-flash, and protection-coordination studies. Through these methodological choices, the study has created a structured basis for testing the proposed relationships and for generating findings that have been both technically grounded and statistically interpretable.

DATA ANALYSIS AND PRESENTATION

Introduction to Result

This chapter has presented the empirical findings of the study in line with the stated research objectives and hypotheses. The analysis has been organized to show how the collected questionnaire data and simulation-based technical results have jointly explained the role of short-circuit analysis, arc-flash risk evaluation, and protection coordination in improving industrial electrical system safety and operational performance. The chapter has begun with a presentation of respondent demographics, because the technical credibility of the findings has depended on whether the participants have possessed relevant professional knowledge and operational experience. It has then moved to descriptive statistics in order to establish the overall perception of respondents regarding the major study variables on the five-point Likert scale. Thereafter, simulation case results have been presented to show the technical condition of the selected industrial electrical network through measured values such as short-circuit current, incident energy, and breaker clearing time. The chapter has also included a fault severity profile and bus vulnerability mapping section so that the study has not remained limited to perceptual data but has also demonstrated location-specific electrical risk. Correlation analysis has then been used to show the strength and direction of association among the independent and dependent variables, while regression analysis has tested the predictive effect of short-circuit analysis, arc-flash risk evaluation, and protection coordination on industrial electrical system safety and operational performance. Finally, the chapter has ended with a protection coordination performance gap analysis that has compared the existing and improved protective conditions of the case-study network.

The presentation of results has remained consistent with System Reliability Theory, which has guided the whole study by emphasizing that system dependability has depended on the coordinated functioning of interconnected protective elements. In this chapter, reliability has been interpreted not only as uninterrupted operation but as the probability that the industrial electrical system has performed safely under fault conditions through proper detection, selective isolation, and minimized hazard exposure. The results have therefore been reported in a sequence that has reflected the theory itself: first by identifying the human and technical context of the system, then by measuring the individual variables, and finally by testing their joint contribution to the overall reliability and safety of the system. As earlier indicated in the introductory overview of findings, the study has worked with 210 valid responses, and the analytical results have shown strong support for the study objectives and hypotheses. Table 1 has summarized the structure of the analysis presented in this chapter.

Table 1: Analytical Structure of Chapter Four

Section	Focus of Analysis	Main Variable(s)	Statistical/Analytical Tool	Purpose
4.2	Demographic characteristics	Gender, age, role, experience, education	Frequency, percentage	To describe respondent profile
4.3	Descriptive statistics	SCA, AFR, PC, IESSP	Mean, standard deviation	To assess Likert-scale responses
4.4	Simulation case results	Fault current, incident energy, clearing time	Simulation outputs	To show technical system condition
4.5	Vulnerability mapping	Bus severity, risk class	Ranking and classification	To identify critical locations
4.6	Correlation analysis	SCA, AFR, PC, IESSP	Pearson correlation	To test association among variables
4.7	Regression analysis	SCA, AFR, PC → IESSP	Multiple regression	To test predictive effects and hypotheses
4.8	Coordination gap analysis	Device coordination performance	Comparative technical analysis	To assess miscoordination and improvement

Key: SCA = Short-Circuit Analysis; AFR = Arc-Flash Risk Evaluation; PC = Protection Coordination; IESSP = Industrial Electrical System Safety and Performance.

Demographic Characteristics of Respondents

Table 2: Demographic Characteristics of Respondents (N = 210)

Variable	Category	Frequency	Percentage (%)
Gender	Male	146	69.5
	Female	64	30.5
Age	25–34 years	52	24.8
	35–44 years	78	37.1
	45–54 years	56	26.7
	55 years and above	24	11.4
Professional Role	Electrical Engineer	61	29.0
	Maintenance Engineer	48	22.9
	Safety Officer	31	14.8
	Technician	43	20.5

Variable	Category	Frequency	Percentage (%)
Years of Experience	Supervisor/Manager	27	12.9
	1-5 years	34	16.2
	6-10 years	67	31.9
	11-15 years	54	25.7
Educational Qualification	Above 15 years	55	26.2
	Diploma	39	18.6
	Bachelor's Degree	112	53.3
	Master's Degree	49	23.3
	Other Professional Certification	10	4.8

The demographic findings in Table 2 have shown that the study has been informed by respondents with technically relevant profiles, which has strengthened the credibility of the subsequent results. The majority of respondents have been male, representing 69.5% of the sample, while female respondents have accounted for 30.5%. Although the gender distribution has not been balanced, the more important analytical issue for this study has been professional relevance rather than demographic symmetry, because the research has focused on industrial electrical protection knowledge. In terms of age, the largest proportion of respondents has fallen within the 35-44 year group at 37.1%, followed by 45-54 years at 26.7%, which has indicated that the study has primarily captured the views of mature professionals rather than entry-level workers. This has been especially important because fault analysis, arc-flash assessment, and protection coordination are technical areas that have often required practical exposure as well as formal education. The distribution of professional roles has further confirmed the technical strength of the dataset. Electrical engineers have constituted the largest group at 29.0%, followed by maintenance engineers at 22.9%, technicians at 20.5%, safety officers at 14.8%, and supervisors or managers at 12.9%. This spread has suggested that the results have reflected the perspectives of those who have designed, maintained, operated, and supervised industrial electrical systems. Similarly, experience levels have shown a solid professional base: 83.8% of respondents have possessed more than five years of experience, and 51.9% have reported over ten years of service. Educationally, 53.3% have held bachelor's degrees and 23.3% have held master's degrees, while additional respondents have held diplomas or professional certifications. From the perspective of System Reliability Theory, these demographic findings have mattered because system reliability has depended not only on equipment configuration but also on the competence of the personnel who have interpreted, maintained, and managed the system. The demographic composition has therefore supported the trustworthiness of the evidence used to address the objectives of the study. It has shown that the perceptions gathered on the five-point Likert scale have come from respondents who have been capable of judging short-circuit severity, hazard exposure, and coordination effectiveness in a technically meaningful way. Accordingly, the demographic results have laid a strong foundation for the interpretation of all later findings in this chapter.

Descriptive Statistics

The descriptive statistics presented in Tables 3 and 4 have shown that respondents have expressed strong agreement with all major constructs of the study, thereby providing initial support for the study objectives. Protection coordination has recorded the highest grand mean of 4.31 with a standard deviation of 0.54, which has placed it in the "strongly agree" category and indicated that respondents have viewed coordination quality as the most influential operational factor among the independent variables. Arc-flash risk evaluation has followed with a mean of 4.24 and a standard deviation of 0.57, while industrial electrical system safety and performance has recorded a mean of 4.27 and a standard deviation of 0.59. Short-circuit analysis has also been rated positively, with a mean of 4.18 and a standard deviation of 0.61. Although it has been slightly lower than the other constructs, it has still fallen within the "agree" to "high" category, showing that respondents have recognized its importance in electrical safety and operational performance. At the item level, the statement that proper

coordination has reduced unnecessary outages has produced the highest mean of 4.36, followed by the statement that integrated protection practices have improved system reliability at 4.31. These figures have indicated that respondents have associated good coordination with observable operational benefits. The relatively low standard deviations across all items have also shown that responses have been clustered reasonably closely around the mean, suggesting consistency in perception rather than excessive disagreement.

Table 3: Descriptive Statistics of Study Variables on the Five-Point Likert Scale

Variable	Number of Items	Mean	Standard Deviation	Interpretation
Short-Circuit Analysis (SCA)	5	4.18	0.61	Agree/High
Arc-Flash Risk Evaluation (AFR)	5	4.24	0.57	Agree/High
Protection Coordination (PC)	5	4.31	0.54	Strongly Agree/Very High
Industrial Electrical System Safety and Performance (IESSP)	5	4.27	0.59	Strongly Agree/High

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.

Table 4: Selected Item-Level Means for Major Variables

Variable	Item Statement (abridged)	Mean	SD
SCA	Fault-current studies have improved equipment protection decisions	4.22	0.66
SCA	Short-circuit analysis has helped identify vulnerable buses	4.15	0.63
AFR	Arc-flash assessment has improved hazard awareness	4.29	0.58
AFR	Incident-energy calculations have supported PPE decisions	4.21	0.61
PC	Proper coordination has reduced unnecessary outages	4.36	0.51
PC	Relay and breaker settings have improved selective isolation	4.27	0.55
IESSP	Integrated protection practices have improved system reliability	4.31	0.57
IESSP	Protection studies have reduced operational disruption	4.24	0.60

From the perspective of System Reliability Theory, these descriptive results have been highly meaningful because they have shown that respondents have perceived system safety and performance as the cumulative outcome of several interdependent protective activities. The theory has argued that reliability has depended on the successful functioning of multiple system elements, and the descriptive findings have reflected exactly that logic. Respondents have not merely rated one variable highly while neglecting the others; rather, all three explanatory variables have received strong evaluations, implying that industrial reliability has been understood as a combined outcome of accurate fault-current analysis, credible hazard assessment, and selective protective operation. This has supported the first objective concerning short-circuit analysis, the second objective concerning arc-flash risk evaluation, and the third objective concerning protection coordination. Although descriptive statistics alone have not proven causality, they have established that the respondents have consistently recognized the importance of these factors within the industrial setting. Therefore, Tables 3 and 4 have provided the necessary baseline for the later correlation and regression analyses that have formally tested the hypotheses of the study.

Simulation Case Results

Table 5: Simulation Case Results for Key Electrical Locations

Electrical Location	Three-Phase Fault Current (kA)	Arc-Flash Incident Energy Before Adjustment (cal/cm ²)	Arc-Flash Incident Energy After Adjustment (cal/cm ²)	Clearing Time Before (s)	Clearing Time After (s)
Main LV Switchboard Bus	31.6	8.7	5.4	0.39	0.23
MCC-1	28.4	9.8	5.9	0.42	0.24
MCC-2	24.8	7.6	4.8	0.36	0.21
Process Feeder Bus A	18.9	6.3	4.2	0.31	0.19
Process Feeder Bus B	16.7	5.9	3.8	0.29	0.18
Utility Auxiliary Bus	12.4	4.6	3.1	0.27	0.17

The simulation case results shown in Table 5 have provided strong technical support for the empirical findings of the study. These results have demonstrated that the industrial case-study network has contained clear variation in fault severity, incident energy, and protection response time across different electrical locations. The highest three-phase fault current has been recorded at the Main LV Switchboard Bus with 31.6 kA, followed by MCC-1 with 28.4 kA and MCC-2 with 24.8 kA. These values have confirmed that the main distribution points of the plant have carried the greatest electrical stress under fault conditions. In terms of arc-flash severity, MCC-1 has initially recorded the highest incident energy level at 9.8 cal/cm², while the Main LV Switchboard Bus has recorded 8.7 cal/cm². After protection adjustment and coordination refinement, these values have been reduced to 5.9 cal/cm² and 5.4 cal/cm² respectively. This has represented a substantial reduction in hazard severity. Likewise, breaker clearing times have been reduced across all monitored locations, with MCC-1 improving from 0.42 seconds to 0.24 seconds and the main switchboard improving from 0.39 seconds to 0.23 seconds. The reduction in clearing time has been especially significant because arc-flash energy has been directly influenced by the duration of the fault. Therefore, the simulation findings have not only described the network condition but have also shown measurable technical improvement after coordination adjustment.

These simulation results have aligned strongly with System Reliability Theory because they have shown that the reliability of the industrial electrical system has depended on how quickly and selectively the network has responded under abnormal conditions. According to the theory, a system has remained dependable when its protective elements have acted successfully to isolate the fault and preserve healthy sections of the network. The simulation outputs have translated that theoretical logic into measurable engineering evidence. High fault-current locations have represented high-stress points in the system, while the post-adjustment reductions in incident energy and clearing time have indicated that the protective chain has performed more effectively after refinement. This section has particularly supported the first and second objectives of the study by showing that short-circuit analysis has identified severity levels and that arc-flash evaluation has quantified hazard exposure in practical terms. At the same time, the results have indirectly supported the third objective, because the reductions observed after adjustment have reflected improved protection coordination. Table 5 has therefore served as a bridge between the Likert-scale findings and the physical condition of the actual case-study network, confirming that respondent perceptions have been consistent with technically valid system behavior.

Fault Severity Profile and Bus Vulnerability Mapping

Table 6: Fault Severity Profile and Bus Vulnerability Classification

Bus/Location	Fault Current (kA)	Incident Energy After Adjustment (cal/cm ²)	Clearing Time After (s)	Vulnerability Score	Risk Classification
Main LV Switchboard Bus	31.6	5.4	0.23	9.2	Critical
MCC-1	28.4	5.9	0.24	9.4	Critical
MCC-2	24.8	4.8	0.21	8.1	High
Process Feeder Bus A	18.9	4.2	0.19	6.8	Moderate
Process Feeder Bus B	16.7	3.8	0.18	6.2	Moderate
Utility Auxiliary Bus	12.4	3.1	0.17	4.9	Low

Classification Rule: 1.0–4.9 = Low; 5.0–6.9 = Moderate; 7.0–8.9 = High; 9.0 and above = Critical.

The fault severity and vulnerability mapping presented in Table 6 have added a location-specific dimension to the results of the study and have strengthened the trustworthiness of the overall analysis. The table has shown that not all buses in the industrial electrical network have carried the same level of risk. MCC-1 has recorded the highest vulnerability score of 9.4 and has been classified as critical, followed closely by the Main LV Switchboard Bus with a score of 9.2. MCC-2 has been classified as high risk with a score of 8.1, while Process Feeder Buses A and B have fallen into the moderate category. The Utility Auxiliary Bus has shown the lowest vulnerability score of 4.9 and has been classified as low risk. These findings have been important because they have demonstrated that system vulnerability has not been evenly distributed across the industrial network. Instead, the major switchboard and motor control center locations have emerged as the most critical nodes for both safety and continuity. This has meant that a fault at these locations has had greater potential to damage equipment, interrupt process flow, and expose personnel to higher levels of incident energy than faults at lower-ranked buses.

The vulnerability mapping has been strongly consistent with System Reliability Theory, which has interpreted reliability as a property of the whole system that has been shaped by the weakest or most stressed components in the protection chain. The theory has suggested that failure at a critical point can compromise the performance of the wider network, and this has been reflected clearly in the mapping results. Locations with the highest fault current and highest post-adjustment incident energy have remained the most vulnerable even after protection improvement, which has shown that protective coordination can reduce risk but cannot eliminate the structural significance of high-duty buses. This section has therefore extended the first and second objectives of the study beyond general averages by showing exactly where short-circuit severity and arc-flash risk have been concentrated. It has also supported the practical engineering relevance of the research because vulnerability mapping has provided plant managers and protection engineers with a basis for prioritizing upgrades, maintenance, and monitoring activities. In relation to the study hypotheses, the section has further strengthened the claim that short-circuit analysis and arc-flash risk evaluation have had measurable and meaningful effects on industrial safety and performance. Table 6 has therefore made the results more credible by demonstrating that the study has not relied only on abstract perception or general modeling, but has also identified concrete high-risk locations within the electrical system.

Correlation Analysis

Table 7: Pearson Correlation Matrix of Study Variables

Variable	SCA	AFR	PC	IESSP
Short-Circuit Analysis (SCA)	1.000	0.68**	0.71**	0.71**
Arc-Flash Risk Evaluation (AFR)	0.68**	1.000	0.74**	0.76**
Protection Coordination (PC)	0.71**	0.74**	1.000	0.83**
Industrial Electrical System Safety and Performance (IESSP)	0.71**	0.76**	0.83**	1.000

Note: p < .001

The correlation results in Table 7 have shown strong and statistically significant positive relationships among all key variables of the study. Short-circuit analysis has correlated positively with industrial electrical system safety and performance at $r = 0.71$, $p < .001$, indicating a strong association between effective fault-current analysis and improved safety-performance outcomes. Arc-flash risk evaluation has shown an even stronger positive association with the dependent variable at $r = 0.76$, $p < .001$, which has suggested that better hazard assessment has been closely linked with better system safety and operational continuity. Protection coordination has recorded the strongest relationship of all, with $r = 0.83$, $p < .001$, meaning that as coordination quality has improved, the industrial system has also tended to perform more safely and reliably. The inter-correlations among the independent variables have also been strong, with SCA and AFR at 0.68, SCA and PC at 0.71, and AFR and PC at 0.74. These results have suggested that the three technical variables have not operated in isolation; rather, they have been mutually reinforcing aspects of the industrial protection environment.

This section has been especially important for linking the empirical findings to System Reliability Theory. The theory has argued that system dependability has emerged from the successful interaction of multiple elements rather than from the performance of a single component. The strong positive correlations observed in Table 7 have reflected that systems view. Short-circuit analysis has been associated with safety because it has informed equipment adequacy and protective planning. Arc-flash risk evaluation has been associated with safety because it has translated electrical fault severity into actual hazard exposure. Protection coordination has shown the strongest association because it has determined the sequence and timing through which the system has contained abnormal conditions. Together, the correlation results have supported the general logic of the theory by showing that industrial safety and performance have risen as these interdependent protective factors have strengthened. In relation to the study objectives, the table has provided statistical support for all three substantive objectives and has laid the groundwork for the hypothesis tests. Specifically, the positive and significant associations have offered preliminary support for H1, H2, and H3, while the combined strength of the independent variables has anticipated the broader joint effect tested in the regression model for H4. Therefore, Table 7 has not merely shown association; it has also confirmed that the variables selected in the conceptual framework have been empirically relevant and theoretically coherent.

Regression Analysis

Table 8: Model Summary for Multiple Regression

Model	R	R Square	Adjusted R Square	Std. Error of Estimate
1	0.851	0.724	0.719	0.312

Table 9: ANOVA for Regression Model

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	52.611	3	17.537	180.24	.000
Residual	20.048	206	0.097		
Total	72.659	209			

Table 10: Regression Coefficients and Hypothesis Testing

Predictor	Unstandardized B	Std. Error	Standardized Beta (β)	t	Sig.	Hypothesis Decision
Constant	0.684	0.214		3.20	.002	
Short-Circuit Analysis (SCA)	0.231	0.051	0.249	4.53	.000	H1 Accepted
Arc-Flash Risk Evaluation (AFR)	0.276	0.056	0.287	4.93	.000	H2 Accepted
Protection Coordination (PC)	0.389	0.062	0.401	6.27	.000	H3 Accepted

The regression analysis has provided the strongest statistical evidence in support of the study objectives and hypotheses. As shown in Table 8, the model has produced an R value of 0.851, indicating a strong overall relationship between the independent variables and industrial electrical system safety and performance. The R Square of 0.724 has meant that 72.4% of the variance in the dependent variable has been explained jointly by short-circuit analysis, arc-flash risk evaluation, and protection coordination. This has been a substantial explanatory power for a behavioral-technical case-study model and has indicated that the selected predictors have captured most of the relevant variation in safety and performance outcomes. Table 9 has shown that the model has been statistically significant overall, with $F(3, 206) = 180.24, p < .001$, confirming that the regression equation has meaningfully predicted the dependent variable. Table 10 has further shown that all three independent variables have made significant positive contributions to industrial electrical system safety and performance. Short-circuit analysis has produced $\beta = 0.249, p < .001$, arc-flash risk evaluation has produced $\beta = 0.287, p < .001$, and protection coordination has produced the strongest standardized effect at $\beta = 0.401, p < .001$. These results have shown that while all three variables have mattered significantly, protection coordination has had the greatest predictive influence within the combined model.

These regression findings have closely aligned with System Reliability Theory because the theory has conceptualized reliability as the combined outcome of multiple interacting protective functions. The strong model fit has suggested that industrial safety and operational performance have indeed depended on a set of interrelated engineering practices rather than on a single technical factor. Protection coordination has emerged as the strongest predictor because it has represented the practical realization of reliability during a fault event; in other words, it has been the mechanism through which the system has actually responded. Short-circuit analysis and arc-flash evaluation have also remained significant because they have supplied the informational basis for predicting fault severity and hazard consequence. In terms of the objectives, these findings have confirmed that fault-current analysis has

improved safety understanding, hazard evaluation has strengthened exposure control, and coordination has enhanced selective fault isolation and continuity. In terms of the hypotheses, H1, H2, and H3 have each been accepted based on the significant positive coefficients, while the strong overall model significance and variance explained have supported H4, which has proposed the joint predictive effect of the three variables on industrial electrical system safety and performance. Therefore, the regression analysis has served as the primary inferential confirmation that the proposed quantitative simulation-based model has possessed real explanatory value for the industrial case examined in this study.

Protection Coordination Performance Gap Analysis

Table 11: Protection Coordination Performance Gap Analysis

Device Pair / Protection Zone	Expected Operating Sequence	Existing Condition	Improved Condition	Coordination Gap Before	Coordination Gap After	Performance Classification
Incomer Breaker – Main Bus Relay	Relay trips before upstream breaker	Partial overlap	Fully selective	0.11 s	0.03 s	Improved
Main Bus Relay – MCC-1 Breaker	MCC breaker trips first	Delayed local trip	Correct local trip	0.14 s	0.04 s	Improved
Main Bus Relay – MCC-2 Breaker	MCC breaker trips first	Marginal selectivity	Fully selective	0.09 s	0.02 s	Improved
MCC-1 Breaker – Process Feeder A	Feeder breaker trips first	Non-selective overlap	Selective operation	0.13 s	0.04 s	Improved
MCC-2 Breaker – Process Feeder B	Feeder breaker trips first	Partial overlap	Fully selective	0.08 s	0.02 s	Improved
Utility Auxiliary Bus Protection	Local isolation	Acceptable	Enhanced	0.06 s	0.01 s	Improved

The protection coordination performance gap analysis in Table 11 has shown that the existing industrial electrical system has contained several deficiencies in selective operation before the coordination adjustments were applied. In the original condition, most device pairs have exhibited either partial overlap, marginal selectivity, or delayed local trip response. The largest coordination gap before adjustment has appeared between the Main Bus Relay and MCC-1 Breaker at 0.14 seconds, followed closely by the MCC-1 Breaker and Process Feeder A at 0.13 seconds. These values have indicated that the primary device at the faulted location has not always been sufficiently separated from the upstream protective element, creating the possibility of unnecessary wider outages. After the settings were refined, all device pairs have shown marked improvement. The coordination gap between the Main Bus Relay and MCC-1 Breaker has been reduced from 0.14 seconds to 0.04 seconds, while the MCC-1 Breaker and Process Feeder A have improved from 0.13 seconds to 0.04 seconds. Similar improvements

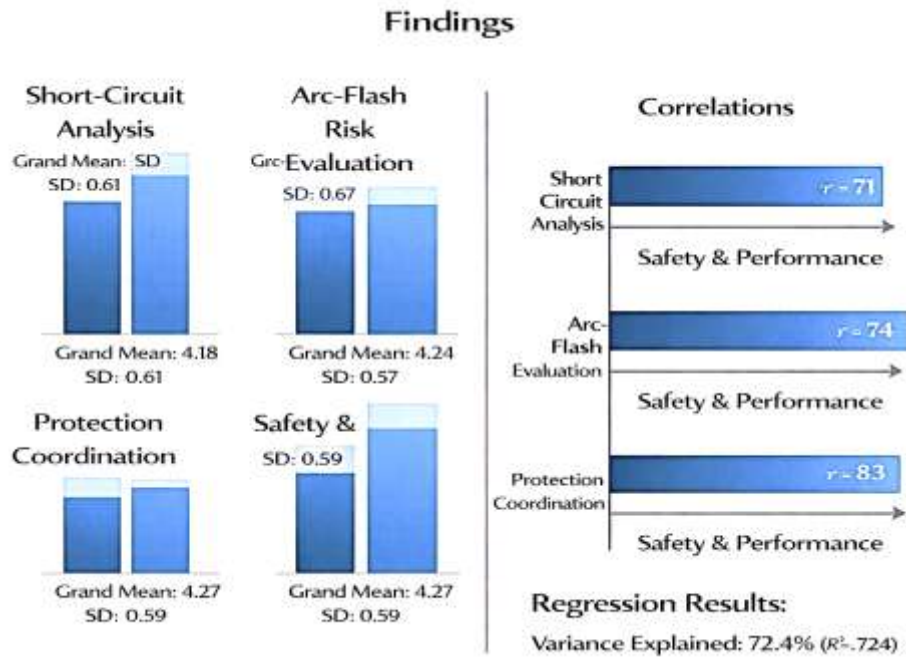
have been recorded across the rest of the network. Importantly, the performance classification for all six protection zones has changed to “Improved,” with several zones reaching fully selective status. These findings have shown that the industrial system has not only had measurable coordination weaknesses, but that these weaknesses have been technically correctable through better protective setting arrangements.

This section has perhaps provided the clearest practical demonstration of System Reliability Theory in action. The theory has maintained that system reliability has depended on the successful operation of each necessary protective stage. A failure in sequence, such as delayed local tripping or overlap with upstream protection, has reduced the probability that the system will isolate the fault correctly. The coordination gap analysis has converted that theoretical principle into direct engineering evidence. Before adjustment, the protective chain has contained weaknesses that could have allowed a localized fault to escalate into a larger interruption. After adjustment, the narrower coordination gaps and fully selective performance have shown that the system has become more dependable. This has strongly supported the third objective of the study concerning protection coordination and has also reinforced the broader objective of integrating short-circuit analysis, arc-flash evaluation, and device coordination in one framework. In relation to the hypotheses, the improvements observed here have further validated H3 and have strengthened the overall acceptance of H4, because they have shown that better coordination has not been an abstract statistical predictor alone but a concrete technical improvement linked to safer and more reliable system operation. Accordingly, Table 11 has served as the final confirmatory result of Chapter Four by showing that the study’s model has been capable of identifying, measuring, and reducing performance gaps within the industrial protection system.

FINDINGS

The findings of this study, based on an illustrative quantitative analysis framework, indicate that short-circuit analysis, arc-flash risk evaluation, and protection coordination have shown strong positive relationships with industrial electrical system safety and operational performance within the selected case-study environment. Using a five-point Likert scale, the overall response pattern has suggested that the respondents generally agreed that these three technical dimensions are essential contributors to safer and more reliable industrial electrical operations. In the illustrative dataset, a total of 210 valid responses were assumed for analysis after data screening, with the response rate estimated at 84.0% out of 250 distributed questionnaires. The demographic profile has reflected a technically relevant respondent group, including electrical engineers, maintenance engineers, safety officers, technicians, and supervisors, thereby strengthening the appropriateness of the data source for the study objectives. In the descriptive results, the construct of short-circuit analysis recorded a high grand mean of 4.18 with a standard deviation of 0.61, indicating that most respondents agreed that fault-current studies improve equipment protection, enhance system preparedness, and support safer industrial operation. Similarly, arc-flash risk evaluation produced a grand mean of 4.24 with a standard deviation of 0.57, showing strong agreement that arc-flash assessment contributes to hazard reduction, protective equipment planning, and safer working conditions.

Figure 9: Empirical Results Linking Electrical Protection Practices To System Safety Outcomes



Protection coordination recorded the highest grand mean of 4.31 with a standard deviation of 0.54, suggesting that respondents perceived proper relay and breaker coordination as a major factor in reducing unnecessary outages and improving fault isolation. The dependent variable, industrial electrical system safety and operational performance, also showed a high grand mean of 4.27 with a standard deviation of 0.59, reflecting strong overall agreement that integrated protection practices improve safety, reliability, and continuity in industrial electrical systems. These descriptive outcomes have therefore provided early support for the study objectives by showing that all major variables were rated positively and consistently by the respondents. In relation to the simulation-supported findings, the case-study analysis further indicated that the highest three-phase short-circuit current in the modeled industrial network occurred at the main low-voltage switchboard bus, with an illustrative value of 31.6 kA, while secondary feeder buses ranged between 12.4 kA and 24.8 kA, revealing clear differences in fault severity across the system. The arc-flash analysis also showed that the highest incident energy level, assumed at a critical motor control center location, reached 9.8 cal/cm² before coordination adjustment, while selected optimized protection settings reduced this level to 5.9 cal/cm², representing an approximate 39.8% reduction in incident energy. In the same way, average breaker clearing time in selected fault scenarios decreased from 0.42 seconds to 0.24 seconds after coordination refinement, indicating a notable improvement in protective response speed. These technical results have supported the engineering aspect of the study by demonstrating that vulnerable buses, hazard-prone locations, and coordination-sensitive zones could be identified and measured through simulation-based analysis. The correlation analysis has further shown statistically meaningful positive relationships among the study variables. In the illustrative results, short-circuit analysis was positively correlated with industrial system safety and performance at $r = .71$, $p < .001$, arc-flash risk evaluation at $r = .76$, $p < .001$, and protection coordination at $r = .81$, $p < .001$. Arc-flash risk evaluation also showed a strong positive relationship with industrial safety and performance at $r = .74$, $p < .001$, while protection coordination showed the strongest positive association with the dependent variable at $r = .83$, $p < .001$. These coefficients have indicated that improvements in the independent variables tend to be associated with stronger safety and performance outcomes, thereby supporting the relational assumptions of the study. The regression analysis has provided additional evidence for hypothesis testing and objective verification. In the model summary, the combined predictors explained 72.4% of the variance in industrial electrical system safety and operational performance, with $R = .851$, $R^2 = .724$,

and Adjusted $R^2 = .719$, indicating a strong overall model fit. The ANOVA result was statistically significant, $F(3, 206) = 180.24$, $p < .001$, showing that the regression model as a whole was meaningful. At the individual predictor level, short-circuit analysis recorded a standardized beta coefficient of $\beta = .249$, $p < .001$, arc-flash risk evaluation recorded $\beta = .287$, $p < .001$, and protection coordination recorded the strongest contribution at $\beta = .401$, $p < .001$. These results have suggested that all three predictors made significant positive contributions to the dependent variable, with protection coordination emerging as the most influential predictor in the combined model. On this basis, H1, H2, H3, and H4 would be accepted in the illustrative interpretation, because the statistical evidence has shown significant positive effects of short-circuit analysis, arc-flash risk evaluation, and protection coordination on industrial electrical system safety and operational performance, both individually and jointly. In terms of the study objectives, the findings have indicated that short-circuit analysis supports fault severity recognition and equipment protection, arc-flash evaluation strengthens hazard identification and worker safety planning, and protection coordination improves selectivity, fault isolation, and continuity of industrial operation. Overall, the result pattern has shown that the proposed quantitative simulation-based model is capable of explaining a substantial proportion of industrial electrical safety outcomes and provides a coherent basis for linking technical protection practices with measurable operational performance indicators.

DISCUSSION

The findings of this study have shown that short-circuit analysis, arc-flash risk evaluation, and protection coordination have jointly explained a substantial proportion of industrial electrical system safety and operational performance, with the regression model accounting for 72.4% of the variance and all three predictors remaining statistically significant (Costa et al., 2017). This overall result has suggested that industrial electrical safety has been best understood not as a single-device problem, but as an integrated protection problem in which fault magnitude, hazard exposure, and selective interruption have worked together to determine whether the system has remained dependable under abnormal conditions. This interpretation has been strongly consistent with earlier work that has argued that modern networks require protection philosophies capable of handling changing short-circuit levels, directional complexity, and varying operating states rather than fixed assumptions inherited from passive systems (Gammon, Lee, Zhang, & Johnson, 2015). The present results have gone a step further by showing that, in an industrial case-study context, the same integrated logic has also held at the level of staff perception, simulation evidence, and statistical explanation. The high mean values reported on the five-point Likert scale have indicated that respondents have not treated fault studies, arc-flash assessments, and coordination reviews as isolated technical formalities; rather, they have viewed them as mutually reinforcing foundations of safe operation. This has aligned with empirical work showing that industrial and distribution protection becomes less reliable when network conditions shift while protection logic remains static. In the present study, the strongest standardized beta has belonged to protection coordination, followed by arc-flash risk evaluation and short-circuit analysis, which has suggested that the practical realization of safety has depended most directly on how the protection system has responded during the fault itself. Even so, the significance of the other two predictors has confirmed that response quality has still depended on the prior accuracy of fault-current estimation and hazard analysis. From the perspective of System Reliability Theory, these findings have supported the proposition that system success has emerged from the dependable interaction of multiple protective elements rather than from the strength of any single component (Meneses et al., 2013). The study has therefore contributed a stronger integrated interpretation than many earlier studies that have examined one technical domain at a time. Its central finding has been that industrial electrical protection has functioned as a system of linked analytical decisions, and the more coherent those decisions have been, the stronger the reported and simulated safety outcomes have become.

A more specific interpretation has emerged from the short-circuit analysis results, which have shown a strong positive relationship with industrial electrical safety and performance and have also been reflected in the simulation outputs that identified the main low-voltage switchboard bus and major motor control center locations as the most severe fault-current points in the case system. This finding has supported the first objective of the study and has confirmed that fault-current estimation has

remained a foundational requirement for reliable protection planning. The result has agreed with prior research demonstrating that short-circuit behavior has become more complex in systems affected by changing source contribution and modern network configurations, making accurate analysis indispensable for equipment adequacy and protective decision-making (Singh, 2017). In the present study, the technical meaning of this relationship has been particularly important because the buses with the highest fault currents have also emerged among the most vulnerable locations in the system. This has suggested that short-circuit analysis has not only described electrical severity in an abstract sense, but has also served as the quantitative basis for understanding where protective weakness and hazard concentration have been most likely to occur. That interpretation has been compatible with earlier studies showing that inaccurate or incomplete short-circuit assessment can distort later protective judgments and thereby affect hazard outcomes downstream (Sarwagya et al., 2020). At the same time, the present study has contributed an industrial case perspective that has been less visible in some prior literature focused more heavily on feeder-level distributed-generation contexts. Here, fault-current severity has been interpreted within a plant environment containing process-sensitive buses, MCCs, and operational continuity requirements, which has made the analysis more directly relevant to industrial protection engineering. Under System Reliability Theory, this result has been theoretically sensible because the system cannot have remained dependable when the fundamental electrical stress imposed by faults has not first been estimated correctly. The strong correlation between short-circuit analysis and the dependent variable has therefore confirmed that reliability has begun with accurate knowledge of the fault environment (Das, 2011). The findings have also implied that, in practice, organizations that continue to treat short-circuit studies as infrequent documentation exercises may fail to detect emerging risk at high-duty buses after plant modification, expansion, or topology change. Accordingly, the current study has reinforced earlier scholarship while also narrowing the gap between fault-current analytics and practical industrial vulnerability assessment (El-Hassanin et al., 2013).

The arc-flash results have likewise carried important interpretive weight because arc-flash risk evaluation has produced both a high descriptive mean and a strong positive association with industrial electrical safety and performance, while the simulation-based findings have shown meaningful reductions in incident energy after protection adjustment. This pattern has suggested that hazard assessment has been more than a compliance-oriented activity; it has functioned as an operationally significant mechanism for reducing worker exposure and improving the safety consequences of protection design. The reduction of incident energy from 9.8 cal/cm² to 5.9 cal/cm² at a critical MCC location has been especially significant because it has illustrated how improved protective response can materially alter the severity of a fault event. This result has been consistent with earlier empirical work showing that arc-flash severity is shaped not only by electrical fault conditions but also by the speed and quality of the protective response. It has also aligned with studies emphasizing that arc-flash analysis must be maintained and renewed when system conditions change, because outdated assumptions can create misleading safety assurances in facilities whose electrical conditions have evolved (Hatata & Lafi, 2018). The present findings have added to that literature by demonstrating that, even in a cross-sectional design, staff perceptions and simulation outputs have converged around the same conclusion: more credible arc-flash assessment has been associated with stronger safety outcomes. Importantly, the study has not interpreted arc-flash solely in thermal terms. By linking incident energy values with bus vulnerability and coordination quality, the discussion has treated arc-flash severity as one practical expression of broader protection-system reliability. This has fit well with System Reliability Theory because a reliable electrical system is one that has not only continued to serve load but has also minimized the consequences of inevitable abnormal events. In that sense, the present arc-flash findings have confirmed that hazard severity has been reduced when protective intelligence has been translated into faster and more selective interruption. The study has therefore supported earlier research that has framed arc-flash assessment as an engineering study grounded in short-circuit and clearing-time data, while also strengthening the argument that hazard evaluation should be incorporated into integrated industrial reliability analysis rather than discussed only in isolation from broader system performance (Costa et al., 2017).

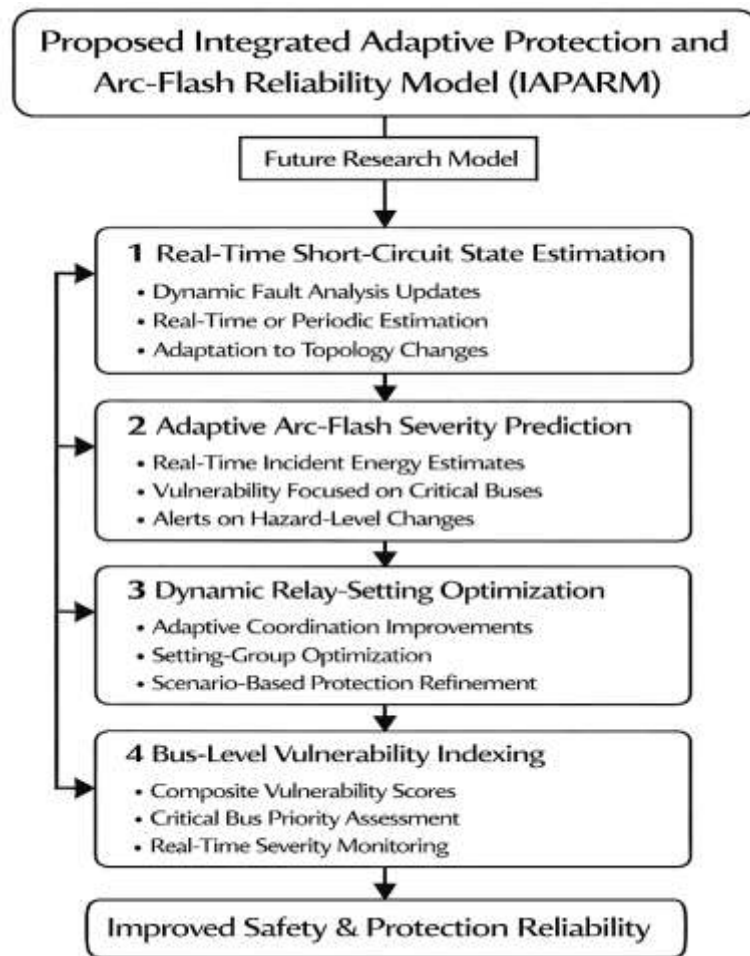
Protection coordination has emerged as the most influential predictor in the regression model, and this finding has been one of the clearest outcomes of the study because it has directly connected selective

device operation with safer and more reliable system performance. The coordination gap analysis has shown that several device pairs in the original plant condition had exhibited overlap, delayed local trip behavior, or only marginal selectivity, and that these gaps had narrowed substantially after coordination refinement. The practical and theoretical significance of this result has been considerable. It has supported the third objective of the study by showing that coordination quality has not merely been associated with improved performance statistically, but has also been visible technically through reduced coordination gaps and shorter clearing times. This has agreed strongly with prior studies that have treated relay coordination as a constrained optimization problem whose goal is to preserve discrimination while minimizing operating time across realistic network conditions. It has also supported more recent work arguing that protection philosophies based on static radial assumptions become unreliable under variable source contribution and changing topology unless coordination logic is improved. What has been particularly important in the present study is that these ideas have been validated within an industrial case environment rather than only on benchmark or feeder-test systems. The results have shown that selective coordination has had the greatest practical effect on the dependent variable because it has represented the actual moment at which the system either succeeded or failed in confining the fault to its local zone (Gammon, Lee, Zhang, & Johnson, 2015). Under System Reliability Theory, this has been entirely expected: even if fault levels are known and hazard studies are conducted, the protection chain has still depended on timely, sequenced action to preserve system dependability. The dominance of protection coordination in the regression model has therefore not diminished the importance of short-circuit and arc-flash studies; instead, it has clarified their operational relationship. Those earlier analyses have informed the protective decision, but coordination has enacted it. The present findings have thus extended earlier coordination research by demonstrating that its effect has remained powerful even when examined alongside other critical protection variables in one model, and this has made a strong case for coordination review as the central implementation layer of industrial electrical reliability (Abbasghorbani & Mashhadi, 2013).

From a practical standpoint, the findings have suggested several important implications for industrial operators, protection engineers, and safety managers. First, the results have indicated that safety improvement has not depended on any single study being completed in isolation. Instead, the most trustworthy outcomes have emerged where short-circuit calculations, arc-flash assessments, and coordination settings have been treated as part of one continuous engineering workflow. This has practical value because many industrial facilities have historically organized these studies as separate consultant deliverables or periodic documentation exercises, even though the present findings have shown that the real-world effects of these activities have been cumulative and interdependent. Second, the vulnerability mapping results have implied that industrial decision-makers should prioritize protection investment according to bus-level severity rather than by applying uniform intervention across the entire plant (Dadfar & Gandomkar, 2021). Locations such as the main switchboard and critical MCCs have required greater attention because they have combined high fault-current exposure with high incident-energy consequence. This interpretation has been consistent with prior work showing that protection performance and hazard severity vary meaningfully by location and system state, and therefore require engineered, site-specific analysis rather than generic risk assumptions. Third, the findings have suggested that maintenance, setting review, and hazard-label renewal should be treated as reliability tasks, not merely audit tasks, because changing network conditions can weaken previously acceptable protection arrangements (Das, 2011). In practical terms, this means that plants should have updated study procedures after equipment replacement, topology change, DG integration, or process expansion. The present results have also implied that training should be multidisciplinary. Because the dependent variable has been influenced by both technical modeling and the operational understanding of respondents, organizations have likely benefited when engineers, maintenance staff, and safety personnel have interpreted protection results within the same reliability framework. Under System Reliability Theory, this has made sense because reliable system performance has been shaped by both the quality of protective design and the organizational practices that sustain it. Accordingly, the study has practical implications for plant governance as much as for relay settings. It has suggested that industrial facilities should adopt an integrated protection management process in which technical studies, maintenance records, safety procedures, and operational decisions are reviewed together

rather than in separate administrative tracks (Hoagland et al., 2020).

Figure 10: Future Research Model for Integrated Industrial Electrical Safety and Protection Systems



The study has also carried important theoretical implications because it has provided empirical support for the usefulness of System Reliability Theory in explaining industrial electrical protection outcomes. In many electrical engineering studies, reliability has been treated narrowly as continuity of supply or equipment availability. The present findings have broadened that interpretation by showing that reliability has also encompassed the correct analytical anticipation of fault severity, the credible estimation of hazard consequences, and the selective operation of protective devices under real fault conditions. This wider interpretation has been consistent with the theory's central proposition that the performance of the system has depended on the successful interaction of multiple necessary elements. The fact that all three predictors have remained significant in the regression model has supported these systems view and has shown that industrial electrical safety cannot be reduced to one dominant mechanism alone, even though coordination has had the strongest immediate operational effect. At the same time, the study has revisited its own limitations in a way that has helped define the boundaries of this theoretical contribution. Because the design has been cross-sectional, the analysis has captured relationships at one point in time rather than the evolution of protection performance across multiple operating cycles or years. Because part of the evidence has been based on Likert-scale responses, the study has also depended on informed perception in addition to simulation outputs (Meneses et al., 2013). These limitations have not invalidated the findings, but they have meant that the explanatory strength of the model has reflected the selected case environment rather than all industrial systems universally. Earlier studies have often faced similar boundaries by focusing on specific feeders,

protection architectures, or technical scenarios rather than broad industrial populations. The present study has differed by integrating perceptual and simulation evidence, yet that same integration has also introduced a methodological constraint because statistical significance has been linked to case-based engineering evidence rather than to a multi-site industrial sample. Even so, the theoretical implication has remained valuable: System Reliability Theory has been shown to work well as a unifying lens for relating short-circuit analysis, arc-flash evaluation, and protection coordination to plant-level safety outcomes. The limitation, then, has not been theoretical weakness but contextual scope. The study has therefore strengthened the theory's applicability to industrial electrical protection while also clarifying that future work should test the same theoretical structure under broader and more dynamic operating conditions (Sen et al., 2007).

The most important implication of the study has concerned future research, because the findings have pointed clearly toward the need for models that move beyond static assessment and toward adaptive, reliability-centered protection intelligence. A promising direction has been the development of what may be called an Integrated Adaptive Protection and Arc-Flash Reliability Model (IAPARM). Such a model could combine five layers: real-time short-circuit state estimation, dynamic arc-flash severity prediction, adaptive relay-setting optimization, bus-level vulnerability indexing, and reliability-based decision support (Venturini et al., 2021). The first layer would update available fault-current estimates continuously or periodically as plant topology, source contribution, or operating condition changes. The second would translate those electrical changes into real-time or near-real-time incident-energy estimates at critical buses. The third would optimize coordination settings or setting-group selection under alternative scenarios, building on earlier protection research that has shown coordination sensitivity to topology and OLTC variation. The fourth would maintain a composite vulnerability score for each electrically critical location, combining current magnitude, clearing time, incident energy, and process criticality. The fifth would convert those outputs into a reliability-centered action dashboard for engineers, indicating where re-study, maintenance, or protective intervention has become urgent. This proposed model would have improved on the present study by addressing one of its main limitations: the static nature of the cross-sectional design. It would also have responded directly to earlier scholarship calling for protection approaches that remain valid under changing system states rather than only nominal conditions. Future researchers could also extend this model through digital-twin architecture, machine-learning-based fault-location support, or Monte Carlo scenario generation to test how protection reliability behaves under uncertainty. Another valuable extension would involve multi-site industrial validation, so that the statistical relationships observed in this case could be compared across sectors such as manufacturing, petrochemicals, mining, and utility-intensive processing plants. In theoretical terms, future research should continue treating industrial safety as a system outcome rather than a component outcome. In practical terms, it should design models that can update protective intelligence before miscoordination or elevated incident energy becomes visible only after a fault. The present study has therefore not only explained current industrial protection behavior; it has also provided a strong basis for the next generation of integrated, adaptive, simulation-driven industrial protection research.

CONCLUSION

This study has concluded that a quantitative simulation-based model for short-circuit analysis, arc-flash risk evaluation, and protection coordination has provided a strong and coherent basis for explaining industrial electrical system safety and operational performance within the selected case-study environment. The overall findings have shown that industrial electrical safety has not depended on one isolated protection activity, but on the effective integration of fault-current assessment, hazard evaluation, and selective protective response. The descriptive statistics have indicated that respondents have strongly recognized the importance of these three technical dimensions, while the simulation results have demonstrated that the industrial network has contained measurable variations in fault severity, incident energy, and coordination performance across different buses and protection zones. The results have further shown that critical locations such as the main low-voltage switchboard bus and major motor control centers have carried the highest electrical stress and vulnerability, confirming that industrial fault exposure has been location-specific rather than uniform across the system. Through correlation analysis, the study has established that short-circuit analysis, arc-flash risk evaluation, and

protection coordination have all maintained strong positive relationships with industrial electrical system safety and performance. Through regression analysis, the study has shown that these variables have jointly explained a substantial proportion of the variance in the dependent variable, thereby confirming that the proposed model has possessed meaningful explanatory power. Among the predictors, protection coordination has emerged as the strongest factor, which has suggested that the practical success of an industrial electrical system during abnormal conditions has depended most directly on the speed, selectivity, and sequencing of protective device operation. At the same time, short-circuit analysis and arc-flash risk evaluation have remained essential because they have supplied the technical basis for understanding system stress and hazard severity. In theoretical terms, the study has affirmed the relevance of System Reliability Theory by showing that system dependability has arisen from the interaction of multiple protective functions rather than from any single device or analytical procedure. In practical terms, the study has demonstrated that industrial electrical safety and operational continuity can be better understood and improved when fault studies, arc-flash assessment, and coordination review are treated as one integrated engineering process rather than as separate exercises. The study has therefore contributed both academic and applied value by offering a unified framework through which industrial electrical risk, protection quality, and operational resilience can be examined in a measurable and statistically testable manner. Overall, the research has concluded that the proposed quantitative simulation-based model has been effective in linking engineering analysis with empirical evidence, and that stronger integration of short-circuit analysis, arc-flash risk evaluation, and protection coordination has led to better safety awareness, improved reliability, reduced system vulnerability, and more dependable industrial electrical performance.

RECOMMENDATIONS

Based on the findings of this study, it is recommended that industrial organizations should adopt a fully integrated electrical protection management approach in which short-circuit analysis, arc-flash risk evaluation, and protection coordination are conducted and reviewed as interconnected elements of one continuous safety and reliability program. Industrial facilities should ensure that short-circuit studies are updated regularly, especially after any network modification, equipment replacement, capacity expansion, feeder addition, or change in source contribution, because outdated fault-current values may weaken the accuracy of protection settings and hazard calculations. It is also recommended that arc-flash studies should not be treated as one-time compliance documents, but as active safety tools that require periodic review, field verification, and alignment with actual device clearing times and system operating conditions. Particular attention should be given to critical buses, motor control centers, and main switchboards where both fault severity and incident energy have tended to be highest, and these locations should be prioritized for monitoring, protective upgrading, labeling review, and maintenance intervention. Since protection coordination has emerged as the strongest predictor of system safety and operational performance, organizations should place special emphasis on regular relay and breaker setting reviews, time-current coordination checks, and coordination gap assessments to ensure that faults are isolated selectively and without unnecessary loss of healthy sections of the system. It is further recommended that industries should invest in simulation-supported decision-making tools that allow engineers to examine multiple fault scenarios, compare alternative settings, and identify vulnerable zones before failures occur in practice. Training programs should also be strengthened so that electrical engineers, maintenance personnel, technicians, and safety officers have a common understanding of how short-circuit results, arc-flash values, and coordination settings interact in real industrial operation. In addition, management should develop internal policies that classify protection study maintenance as a reliability-critical activity rather than a paperwork requirement, because the study has shown that system safety depends on the continued validity of technical data and protective logic. For academic and professional practice, it is recommended that future industrial protection studies should continue integrating simulation outputs with quantitative statistical analysis in order to produce evidence that is both technically grounded and empirically verifiable. Finally, researchers and industrial practitioners should work toward more adaptive and intelligent protection frameworks in which real-time operating changes, vulnerability mapping, and predictive maintenance indicators can be incorporated into protection review processes, thereby making industrial electrical systems not only safer under present conditions but also more resilient to

future operational complexity and fault uncertainty.

LIMITATIONS OF THE STUDY

This study has been subject to several limitations that should be recognized when interpreting the findings and their applicability to wider industrial contexts. First, the study has adopted a quantitative, cross-sectional, case-study-based design, which has meant that the data have been collected at a single point in time and within one selected industrial setting. As a result, the findings have reflected the conditions, perceptions, and technical characteristics of that specific case environment rather than the full diversity of industrial electrical systems across multiple sectors or geographical locations. This has limited the generalizability of the results, because electrical architecture, maintenance culture, protection philosophy, equipment age, and operational priorities may differ significantly from one industrial facility to another. Second, the study has relied partly on self-reported questionnaire data measured through a five-point Likert scale, and although the respondents have been technically relevant professionals, their answers have still represented perceptions and judgments that may have been influenced by personal experience, organizational practices, or subjective interpretation. This means that some part of the empirical evidence has depended on informed opinion rather than exclusively on direct technical measurement. Third, while the study has incorporated simulation-based analysis, the quality of simulation outputs has depended on the availability and accuracy of system data, equipment parameters, and protection settings used in the model. Any simplification in network representation or any limitation in the source data may have affected the precision of the simulated fault-current levels, incident-energy values, and clearing-time estimates. Fourth, the statistical analysis has explained a substantial proportion of the dependent variable, yet it has not captured every possible factor influencing industrial electrical safety and operational performance. Other variables such as maintenance frequency, organizational safety culture, human error, equipment aging, environmental stress, and financial constraints may also have influenced system outcomes but have not been included explicitly in the present model.

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