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Overview of Distribution System Reliability Optimization Against Lightning

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ABSTRACT

The reliability of the distribution system relies on the occurrence of lightning phenomena, which can significantly affect the distribution of electricity and result in power service disruptions. Therefore, ensuring the reliability of the distribution system is an ongoing challenge that necessitates continuous research for optimal solutions. Researchers have always developed solutions that are always up to date by leveraging advancements in mathematics, engineering technology, and management strategies. This paper presents a comprehensive summary and discussion of various optimization models for enhancing system reliability. It offers an overview of commonly employed mathematical programming techniques and algorithms for Lightning Protection Systems (LPSs), while also highlighting the influence of lightning phenomena on these solutions. The focus of this paper is to present the engineering aspects behind the development of modern LPSs. It encompasses historical reliability data, technical limitations, and economic considerations. By utilizing operations research and optimization theory, researchers have been able to devise more effective approaches for addressing reliability issues, even in highly intricate systems across different domains. Technological advancements have prompted researchers to adopt a new perspective on solving reliability problems, based on practical engineering requirements. In conclusion, the continuous progress in mathematics, engineering technology, and management approaches has enabled researchers to tackle the challenges associated with distribution system reliability. This paper serves as a valuable resource, providing insights into the development of modern LPSs and offering guidance on optimizing system reliability in various practical engineering scenarios.

1. Introduction

The power distribution system can be greatly affected by lightning, which has the potential to cause power outages by directly striking overhead lines or indirectly inducing overvoltage in the wiring when the discharge reaches the ground. As a result, researchers from different nations are consistently working on improving the reliability of distribution systems to minimize power outages

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caused by severe weather conditions [1]. Prior research has shown that lightning presents a significant danger to power systems, leading to frequent interruptions in power supply [2].

Distribution systems have a vital function in delivering electrical power to a large customer base. As a result, customers have higher expectations regarding the reliability and quality of the power in the distribution network. However, overhead distribution feeders have a tendency to experience lightning strikes because of insufficient insulation and protection. Overvoltage results from the electromagnetic impact of lightning in the distribution system, potentially resulting in interruptions or disconnections in the overhead feeders and causing significant financial losses.

Distribution utilities often face a significant challenge due to lightning, which is a frequent cause of disruptions in overhead distribution lines [3]. Lightning strikes can result in overvoltage and further damage to equipment and power service disruptions. Protecting distribution feeders from lightning is crucial as they are susceptible to adverse weather conditions. There are several methods available for safeguarding feeders, but ensuring system reliability is the most crucial aspect.

Reliability engineering is an extensively specialized branch of engineering that employs mathematical principles to methodically examine functional issues in components and systems, aiming to develop dependable designs [4]. By doing this, reliability engineering seeks to ensure that products and services are able to perform the intended functions by design. Advances in technology are fueling increasing engineering system complexity, while consumer demand for improved performance and reliability is also on the rise. This creates a challenge for researchers in system reliability optimization, as new problems keep arising. However, this field is always in need of new insights and investigations, as technology keeps evolving.

Operations research and optimization theory have played a crucial role in formalizing and enhancing the methods for designing reliable systems in diverse technological fields. This has enabled the creation of more dependable systems that can adapt to the ever-changing demands and interests of practical engineering. Consequently, the pursuit of maximum reliability under various technical and economic limitations through the application of formal optimization methods remains an active area of scientific research.

The process of optimization involves defining the decision variables, constraints, and desired performance or objective function(s) of an engineering design problem. The goal is to find the best possible combination of decision variables that will achieve the desired objectives. Every problem has its own specific goals that should be pursued with great determination. In some cases, this can be expressed in mathematical terms, making the problem easier to solve using mathematical programming or effective heuristic algorithms. In the field of mathematical programming, researchers are constantly improving and advancing methods and algorithms that can solve more complex and difficult problems more efficiently.

This paper summarizes and discusses modelling of system transients against lightning, failure rate estimation and different distribution system reliability models. It provides an overview of the different approaches and provides a flow of the evolution of the solutions.

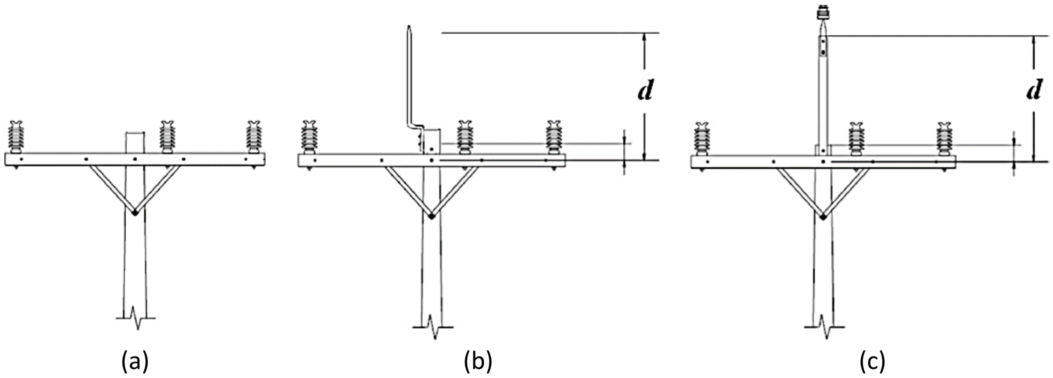
2. System Transients Modelling Against Lightning

Momentary faults that result in the tripping of reclosers cause significant losses in production for industrial customers [5]. Moreover, during stormy conditions, a large number of faults can occur in a short period of time, causing delays in restoring services [6,7]. To evaluate the reliability of the distribution system in relation to lightning, it is essential to define and simulate this phenomenon's impact on the system. The estimation of lightning-induced overvoltage is difficult due to the random nature of the phenomenon and the limited understanding of its main parameters [8]. As a result, multiple studies have developed power system models for analyzing electromagnetic transients [9-12]. Additionally, IEEE and CIGRE working groups have released reports that explain the fundamental characteristics and parameters of lightning phenomena for power system applications [13,14].

The insulation capabilities of the equipment in electric power systems are greatly influenced by the peak value and rise time of the current, resulting in transient overvoltage [3]. When it comes to specifying materials and devices for lightning protection, two crucial parameters are considered: surge current, which is characterized by its peak value and waveform, and the amount of energy transferred to the equipment that is affected by the surge. These parameters play a vital role in determining the effectiveness of the materials and devices in protecting against lightning-related incidents.

In order to assess the critical current of different lightning protection system (LPS) designs in simulated scenarios, ATPDraw and TACS-MODELS software were utilized. The simulated lightning's peak current was incrementally raised until a flashover event took place, determining the critical current (i_0). The lightning resistance level, measured in kA, indicates the highest current magnitude that won't result in an insulation flashover when the lightning strikes the line. By conducting ATP simulations, the amplitude of a flashover current caused by direct lightning was determined.

To assess how the distribution system functions during lightning events, it is crucial to have models for both the lightning source and the system's components. Various research studies have explored power system modelling in transient analyses. These studies have taken into account various types of distribution feeders, including both unshielded and shielded options, as well as different grounding topologies [12,15,16]. The purpose of these investigations is to gain a deeper understanding of the performance of the distribution system in the presence of lightning and to identify any potential vulnerabilities or improvements that can be made. The findings from these studies contribute to enhancing the overall reliability and effectiveness of the distribution system. Figure 1 and Figure 2 depict improvements and proposed combinations of pole structures and grounding system types in previous studies, which were modeled and simulated to determine the lightning current threshold for flashover in a given LPS [17,18].



(a) (b) (c)

Fig. 1. Types of pole structures: (a) unshielded, (b) with Franklin captor and (c) with wire guard [17,18]

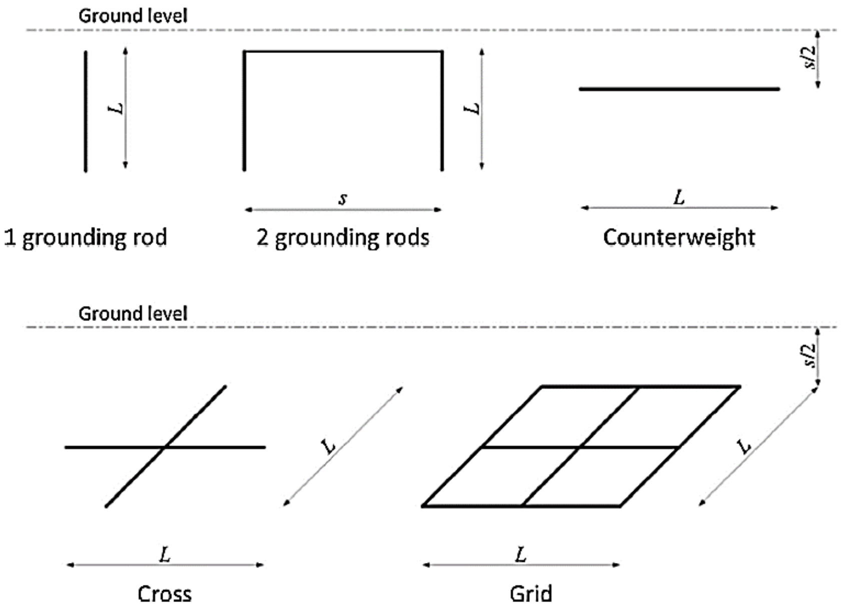


Fig. 2. Grounding topologies [17,18]

Renewable energy is recognized for its ability to assist in reducing greenhouse gas emissions, thereby imposing a restraint on extreme weather and climate consequences. Furthermore, it guarantees heightened reliability, promptness, and economical distribution of energy [19]. In previous research by Grobbelaar and Weber [20] explores the impact of lightning strikes on solar power plants (SPPs) and the subsequent damage to equipment. It highlights the significance of proper lightning protection and earthing to mitigate this damage. Through simulations, the study shows that strategic earthing designs effectively disperse energy, reducing stress on surge protective devices (SPDs). It emphasizes the need for optimized bonding and earthing meshes to safeguard critical equipment, ultimately improving SPP reliability amidst lightning events. The research proposes configurations utilizing above-ground structures as auxiliary earthing systems, providing insights to enhance SPD lifespan and overall system reliability.

In previous study, Zhu *et al.,* [21] investigated lightning-induced surges in wind turbines, analysing surge characteristics and proposing advanced SPD simulations. Lightning strikes affect low-voltage power systems, impacting generators and converters. By using ATP-EMTP simulations, the study identifies the need for SPDs with higher maximum continuous operating voltage (Uc) under repetitive transients and suggests precise surge protection strategies. The findings emphasize the importance of proper SPD selection for wind turbines' safety and equipment protection. It clearly shows the upcoming studies from the researchers focus on improving lightning protection for renewable energy setups. This is essential due to the rising use of renewable energy across industries, commercial, and residential, emphasizing the growing demand for secure integration of these systems into distribution networks.

3. Failure Rate Estimation

To decrease the frequency of lightning strikes and minimize the induced voltages from external sources in overhead distribution feeders, it is suggested by Cabral *et al.,* [17], Bretas *et al.,* [18] and Comassetto *et al.,* [22] to place a shielded guard wire close to the phase conductors. Based on the characteristic parameters of the first return stroke current, it is possible to estimate the failure rate of the feeder caused by direct and indirect lightning strikes. The likelihood of the peak current I0 of the first return stroke surpassing a specific threshold i0 can be expressed using the probability law provided by Paolone *et al.,* [3]:

$$P(I_0 \geq i_0) = \frac{1}{1+\left(\frac{i_0}{31}\right)^{2.6}} \tag{1}$$

where $P(I_0 \geq i_0)$ represents the probability of the first return stroke having a peak current I0 that is greater than or equal to i_0, where i_0 is the prospective peak current of the first return stroke (kA).

The total number of flashovers caused by lightning can be determined by considering the rates of direct and indirect flashovers:

$$N = N_{dir} + N_{ind} \tag{2}$$

where N is the total number of flashover due to lightning (flashes/100 km/yr), N_{dir} is the number of flashover resulting from direct impact (flashes/100 km/yr), and N_{ind} is the number of flashover caused by induced overvoltage (flashes/100 km/yr).

Flashover events do not invariably lead to failures, as failure only happens when a flashover transforms into a stable power frequency arc with a specific probability called the arc over rate [23]. Nonetheless, the optimization methods discussed by Cabral *et al.,* [17] and Bretas *et al.,* [18] disregard the influence of the arc over rate. These methods assume that insulator flashovers will always result in a disruption of the power supply, which contradicts the actual scenario. In reality, failure occurs only when a stable power frequency arc is established following a flashover event. The two references primarily concentrate on analysing and studying lightning rods and lightning wires, overlooking the protection offered by lightning arresters, which exhibit superior lightning protection capabilities. For distribution systems, it is essential to incorporate lightning arrester protection into the LPS model [24].

In previous studies, the authors explore the effectiveness of various protective measures against lightning strikes [25,26]. These measures include the use of lightning wires, lightning rods, and different densities of lightning arresters during installation. To better understand the impact of lightning on the distribution network, the authors create a lightning electromagnetic transient model that simulates the electromagnetic process triggered by lightning. They take into account the arc over rate to calculate the failure rate of distribution lines caused by lightning under different protective measures. The expression below represents the failure rate, denoted as "n", for each specific protective measure:

$$n = N \times \eta \times P(I_0 \geq i_0) \tag{3}$$

where N represents the number of lightning strikes on the 100 km overhead feeder, η is the arc over rate, and $P(I_0 \geq i_0)$ is the probability that the lightning current I_0 exceeds the lightning withstand level i_0 of the overhead feeder.

4. Optimization Models

The design problems related to the reliability of a system can have multiple objectives that are contradictory to each other. However, these objectives are generally aimed at either maximizing or minimizing certain factors. In the case of a distribution system, where reliability is measured based on power interruptions experienced by customers, the objective function is usually focused on minimizing these interruptions. IEEE Std 1366-2012 has identified the reliability indices that are currently useful and may be useful in the future, as well as the factors considered when calculating them [27].

Decision-makers usually give priority to certain goals and choose the most crucial one as the objective function, while placing restrictions on the remaining objectives within acceptable boundaries. When examining or resolving problems related to optimizing reliability, three essential components are required: decision variables, constraints, and one or more objective functions. Decision variables refer to the variables or options that can be adjusted to enhance performance in relation to the objective function(s). For example, decision variables could involve the selection of LPS types with their inherent failure characteristics and reliability, system configuration, and other relevant factors. Constraints are mathematical representations of practical limitations, such as budgetary constraints or acceptable levels of reliability, which limit the selection of decision variables based on their feasibility in meeting the constraints.

The objective function evaluates the system's performance by considering the values assigned to decision variables. It aids in identifying the most suitable combination of variable values for achieving the optimal solution. The objective function commonly aims to maximize system reliability or minimize system cost. There are various types of system reliability optimization problems, each necessitating unique solution approaches due to differences in assumptions and problem structure. Georgilakis *et al.,* [28] provides a comprehensive examination of system reliability optimization.

The LPS allocation problem is the most extensively studied issue regarding reliability optimization. When working with systems that consist of fixed-cost protective devices and structures, the system's design becomes a mathematical problem of combinatorial optimization. Various types of LPSs are typically available, differing in cost, reliability, weight, and other characteristics, in order to meet the required system functions. The practical difficulty lies in selecting the optimal combination of LPS types, which are considered decision variables, that collectively fulfil reliability and weight requirements, among others, while minimizing the cost and/or reliability index as the objective function. Additionally, there is a need to ensure that other system properties satisfy predetermined minimum or maximum values, which serve as constraints.

Reliability indices are used by regulatory authorities and distribution system operators to evaluate the performance and dependability of distribution systems. These indices, such as the System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Momentary Average Interruption Frequency Index (MAIFI), Average System Interruption Frequency Index (ASIFI), and Average System Interruption Duration Index (ASIDI), are commonly employed to measure the reliability of the system, as mentioned in previous research [27].

Researchers have devoted considerable attention to the placement of protective devices such as lightning arrestors, grounding rods, and lightning wires, which comprise the existing LPS. In a study by Zhang *et al.,* [29], a genetic algorithm-based optimization scheme is proposed to determine the optimal installation location for lightning arrestors, considering economic factors. The objective of this optimization approach is to minimize the risk of lightning strikes and enhance the reliability of the power supply. Ekonomou *et al.,* [30] and Comassetto *et al.,* [31] indicated that the optimization of LPS for distribution networks remains an active area of study.

Among the various optimization methods used in power systems, mixed integer linear programming (MILP) stands out for its favourable convergence properties, leading to reduced computation time and improved efficiency. Cabral *et al.,* [17] propose an optimization technique for LPS using MILP and apply the branch-and-bound method to obtain results. Building upon this research, Bretas *et al.,* [18] present a novel approach for optimizing LPS, which incorporates additional constraints to consider multiple distribution reliability indexes. This enhancement allows for a more comprehensive assessment of the LPS, considering the impact of various factors.

A review of existing literature uncovers a lack of mathematical models that take into account how lightning phenomena and the reliability of the distribution system are interconnected. To bridge this gap, Shariatinasab *et al.,* [32] have put forward a model that integrates the design of LPSs with the assessment of system failure risks, using an evolutionary algorithm to discover solutions. Earlier studies by Zhang *et al.,* [25] have also recognized the combinatorial nature of multi-objective problems and suggested an optimized model that considers interdependencies.

Utilities are attempting to enhance the reliability of distribution systems by analysing factors like past reliability data, technical limitations, and economic factors. The optimization of power systems involves finding the most optimal solutions for the system, which can be achieved through various methods like particle swarm optimization, genetic algorithms, ordinal optimization, quasi-Newton optimization, and mixed integer linear programming [17,18,33-37]. Each method has its own characteristics and may require different amounts of time to converge on a solution. Nevertheless, all of these methods are dependable and capable of delivering satisfactory performance for a power system. Recent studies by Ekonomou *et al.,* [30] and Comassetto *et al.,* [31] have shown that enhancing LPSs for distribution networks is difficult yet exploratory work where research project in study by Ekonomou *et al.,* [30] concentrates on enhancing the resistance of high-voltage transmission lines against lightning strikes to reduce failure occurrences, while another project aims to automate the adjustment of protective devices within the distribution system.

A research paper by Ferreira and Bretas [38] introduces a mixed integer non-linear programming (MINLP) model that accurately depicts how the protection system responds to faults and restoration actions in order to allocate and relocate sectionalisers, reclosers, and fuses. The model aims to minimize either the System Average Interruption Duration Index (SAIDI) or the System Average Interruption Frequency Index (SAIFI). Other research papers proposed binary programming (BP) models to tackle the placement of protective devices, taking into account both permanent and temporary faults, with the objective of minimizing the SAIFI [39,40]. Additionally, non-linear binary programming (NLBP) models are presented in papers by da Silva *et al.,* [41] and Zambon *et al.,* [42] to tackle the problem. Table 1 provides a classification of the reviewed models and optimization problems.

Table 1
Reviewed Optimisation Models

Reference	Optimization Method	Types of Devices / LPS	Design Variables	Objective	Objective Function
Popović *et al.,* [43]	Genetic algorithm (GA)	Recloser	Location	Single	Minimization of a composite reliability index
Pregelj *et al.,* [44]	Genetic algorithm (GA)	Recloser	Location	Single	Minimization of a composite reliability index
Wang and Singh [45]	Ant colony system (ACS)	Recloser	Location	Single	Minimization of a composite reliability index

Lei *et al.,* [46]	Mixed integer linear programming (MILP)	Sectionaliser	Number + location	Single	Minimization of SAIDI
Soudi and Tomsovic [39]	Mixed integer linear programming (MILP)	Recloser + fuse	Type + location	Single	Minimization of SAIFI
Zambon *et al.,* [42]	Mixed integer non-linear programming (MINLP)	Recloser + fuse	Type + location	Single	Minimization of SAIFI
da Silva [41]	Genetic algorithm (GA)	Sectionaliser + recloser + fuse	Type + location	Single	Minimization of SAIFI
Ferreira and Bretas [38]	Mixed integer non-linear programming (MINLP)	Sectionaliser + recloser + fuse	Number + type + location	Single	Minimization of SAIDI or SAIFI
Soudi and Tomsovic [40]	Goal programming	Recloser + fuse	Type + location	Multiple	Multi-objective with weights
Izadi [47]	Mixed integer linear programming (MILP)	Sectionaliser	Number + location	Multiple	Multi-objective with weights
Shariatinasab *et al.,* [32]	Mixed integer linear programming (MILP)	Recloser + fuse	Type + location	Multiple	Multi-objective
Mao and Miu [48]	Practical heuristic optimization algorithm	Sectionaliser	Number + location	Multiple	Multi-objective
Zare *et al.,* [49]	Artificial bee colony (ABC)	Sectionaliser	Number + location	Multiple	Multi-objective
Pereira *et al.,* [50]	Genetic algorithm (GA)	Sectionaliser + recloser + fuse	Number + type + location	Multiple	Multi-objective
Cabral *et al.,* [17] and Bretas *et al.,* [18]	Mixed integer linear programming (MILP)	Feeder structure + grounding topologies	Type + location	Multiple	Multi-objective
Zhang *et al.,* [25]	Mixed integer linear programming (MILP)	Lightning rod + Lightning wire + Lightning arresters	Type + location	Single	Minimization of SAIFI

Recent optimization models for lightning protection systems have focused on various aspects, including mathematical expressions, electromagnetic transient models, lightning protection system schemes, metaheuristic algorithms used in optimization, decision variables, objective functions, and constraints. Optimization models often involve mathematical expressions to represent the relationships between different variables and parameters. These expressions can include equations related to lightning current, voltage, grounding resistance, and other electrical properties relevant to lightning protection systems.

Lightning protection systems need to consider the electromagnetic transients generated during lightning strikes. Optimization models incorporate transient models that simulate the behaviour of electrical components and systems under lightning-induced transients. These models capture the complex electromagnetic interactions and provide a basis for optimizing the lightning protection system design.

Optimization models consider different lightning protection system schemes or configurations. These schemes may include the placement and characteristics of lightning rods, grounding systems, surge protection devices, and other components [25,26]. The optimization aims to find the optimal arrangement of these elements to minimize the risk of lightning damage.

Metaheuristic algorithms are widely used in optimization models for lightning protection systems. These algorithms, such as genetic algorithms, branch and bound optimization, simulated annealing, PSOGSA, ant colony optimization and etc, provide efficient and robust techniques to search for the optimal solution within a large solution space [17,18,33,41,43-45,49-51]. The choice of the metaheuristic algorithm depends on the specific optimization problem and the desired performance criteria.

Decision variables in lightning protection system optimization models represent the design parameters or variables that can be adjusted to optimize the system's performance. Examples of decision variables include the placement coordinates of lightning wires, the size and location of grounding systems, the characteristics of surge protection devices, and other design parameters relevant to the system configuration [17,18,25,38].

The objective function quantifies the goal or criterion that the optimization model seeks to optimize. In the context of lightning protection systems, the objective function may involve minimizing the expected damage or downtime due to lightning strikes, maximizing the system's reliability, minimizing the cost of implementation, or a combination of these factors.

Optimization models for lightning protection systems often include constraints that limit the feasible solution space. These constraints may include safety standards, electrical code requirements, budget limitations, geometric constraints, and other technical specifications. The constraints ensure that the optimized solution complies with the necessary regulations and practical considerations.

Recent optimization models for lightning protection systems employ mathematical expressions and electromagnetic transient models to represent the system's behaviour. They explore various lightning protection system schemes using metaheuristic algorithms to optimize decision variables based on an objective function while satisfying relevant constraints. These optimization techniques play a pivotal role across diverse disciplines, refining processes for maximum efficiency. They enable enhanced performance in various domains, not only lightning protection systems, facilitating smarter decisions and improved outcomes through streamlined methodologies and resource utilization. Ng *et al.,* [52], Shah *et al.,* [53], Marghany [54], Radzi and Samsuddin [55], Elsayed [56], and Amran *et al.,* [57] showcase diverse optimization techniques in different fields.

The study by Ng *et al.,* [52] employs Multi-Population Particle Swarm Optimization (MPSO) for feature selection in leukaemia classification. It exhibits MPSO's superiority over conventional PSO in DNA microarray analysis, achieving higher classification accuracy. The diverse exploration of MPSO through multiple swarms improves classification efficiency. Shah *et al.,* [53] have used Taguchi and Grey Relational Analysis (GRA) methods to optimize the CNC turning of S45C carbon steel. The study demonstrates the significant impact of spindle speed in enhancing Material Removal Rate (MRR), surface roughness, and tool wear, showcasing the successful use of Taguchi and GRA methods. Marghany [54] has introduced an Entropy-based Multi-Objective Evolutionary Algorithm (E-MMGA) for oil spill detection using RADARSAT-2 data. E-MMGA accurately delineates oil spills, mitigating the impact of look-alike dark patches, and presenting its potential for practical oil spill detection applications.

Radzi and Samsuddin [55] have focused on Computational-Particle Swarm Optimization (CFD-PSO) to optimize Savonius wind turbine blades. Despite reducing blade mass, challenges persist in meeting minimum power generation requirements, highlighting the potential and challenges of CFD-PSO in turbine design. Elsayed [56] investigates diffuser augmentation in wind turbines using numerical simulations and the Simplex algorithm. The optimized diffuser shape significantly increases entrance velocity, enhancing power output by 2.76 to 5.26 times compared to turbines without a diffuser. Amran *et al.,* [57] has explored the relationship between renewable energy optimization, green innovation, and competitive advantage in green building development. It emphasizes the significance of optimization as a precursor to green innovation, culminating in competitive advantage within the green building sector.

These studies collectively underscore the importance of optimization techniques across various domains, showcasing their effectiveness in enhancing classification accuracy, improving manufacturing processes, mitigating environmental issues, optimizing energy systems, and fostering competitive advantage in green building development. The application of optimization methodologies is crucial in refining processes, improving accuracy, and achieving efficient and sustainable outcomes.

5. Conclusion

This paper examines the evolution of reliability engineering and the grouping of various techniques and solutions into different problems, namely the LPS allocation problem, the reliability allocation problem, and the reliability-LPS allocation problem. This paper focuses on the problems related to distribution systems that exhibit greater complexity and more realistic reliability behaviours. By utilizing data, a deeper understanding of the system's operation is gained and its expected behaviour in various scenarios. This knowledge enables the researchers to develop improved LPS design plans and ensure continuous system enhancement. However, challenges always arise, necessitating the exploration of novel problem-solving approaches.

The study of system reliability is an ever-evolving and vital research area. The combined influence of mathematics, operations research, and optimization theory has propelled the advancement of research ideas and theories. This interdisciplinary collaboration has brought fresh perspectives from the engineering field and led to the development of superior methods and techniques for optimizing reliability. As a result, researchers are consistently devising innovative approaches to tackle previously challenging problems. Simultaneously, engineering and social practitioners constantly seek new advancements to aid them in solving real-world problems.

The dedication lies in pushing the boundaries of operations research and optimization theory, which have empowered the researchers to devise more effective methods for addressing reliability concerns in highly intricate systems across diverse technological domains. As technology continues to advance, these methods are expected to remain aligned with the practical needs of engineering applications.

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