RELIABILITY ASSESSMENT OF POWER DISTRIBUTION SYSTEMS TO ADDRESS FREQUENT POWER OUTAGES AND AUTOMATIC LINE SWITCHES USING SCADA SYSTEM

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Abstract— this research presents a comprehensive reliability assessment of power distribution systems, focusing on frequent power outages, the integration of smart distribution technologies, and the role of automatic line switches. The study offers an in-depth review of power system network reliability, evaluates the performance of electric power distribution feeders, and examines specific case studies of 33 kV power distribution systems. By analyzing the reliability of smart distribution systems and the functionality of automatic line switches, this research proposes strategies to enhance the resilience and efficiency of power distribution networks. Advanced reliability metrics and assessment methodologies are utilized to provide robust solutions for mitigating risks and improving overall system performance.

Keywords:
Power Distribution Systems, Reliability Assessment, Smart Distribution Technologies, 33 kV Feeders, Electric Power Reliability, Distribution Feeders

Introduction

Electricity is a crucial driver of any nation's economy, and achieving reliability and quality in power supply is vital for meeting demand and sustaining growth. In the 1980s, the Nigerian Power Sector (NPS) was efficient and reliable, attributed to moderate technological demands, controlled population growth, and a view of electricity as a luxury. However, rapid population growth, technological advances, and a shift to seeing electricity as a necessity have led to the NPS's current challenges with reliability. Insufficient planning and inadequate data have hampered effective management, causing public dissatisfaction and, in some cases, protests and vandalism risks. Reliability analysis is essential in power systems to address outages and disruptions, especially in components like switchgear and control systems. While achieving 100% availability is unrealistic, developed countries often target high reliability rates (about 99.9%), supported by robust infrastructure, sufficient reserve capacity, and efficient maintenance. Nigeria's growing population and technology demands have increased power needs, but the sector often resorts to load shedding, disregarding consumer preferences, which further fuels public discontent. Frequent outages threaten the reliability of power distribution systems, often stemming from equipment issues, environmental factors, or human errors. Tackling these failures requires proactive maintenance, improved infrastructure, and advanced tools like smart meters and automated fault detection. By addressing root causes, systems can enhance reliability and reduce outage frequency and duration. Smart grid technologies provide solutions to many traditional grid issues, using advanced sensors and automated control to improve efficiency, reliability, and resilience. While promising, these technologies bring new complexities and vulnerabilities. Automatic line switches, essential for fault isolation and rapid service restoration, are key in improving grid reliability, yet require careful integration and placement. This review evaluates power distribution systems with a Focus on frequent outages, smart grid technology integration, and automatic line switches, aiming to enhance system reliability and resilience. It addresses strategies to mitigate outages, ensuring a stable and reliable power supply [5], [6].

1.2 Problem Formulation

Frequent outages in power distribution systems challenge grid stability and reliability, disrupting electricity supply and leading to economic Losses and consumer inconvenience. This issue is especially severe in developing countries like Nigeria, due to outdated infrastructure and limited investment. Tackling frequent outages requires upgrading infrastructure, improving maintenance, and utilizing advanced monitoring tools for early issue detection. Smart distribution technologies, such as smart meters and automated control systems, offer solutions to mitigate these outages by providing real-time data for swift anomaly detection and remote grid monitoring. However, implementing these technologies demands substantial investment, regulatory support, and skilled personnel.

Automatic Line Switches (ALS) are vital for enhancing grid reliability by isolating faulty sections and rerouting power. Properly configured ALS can reduce outage duration and impact, though effective deployment requires strategic planning, design, and testing.

Reliability assessments of power distribution systems help identify infrastructure weaknesses and improve resilience. These assessments include analyzing historical outage data and using Reliability-Centered Maintenance (RCM). Collaboration among utilities, regulators, and tech providers is essential for effective reliability improvements.

Research on smart distribution technologies, Automatic Line Switches, and case studies from utilities worldwide shows various strategies for reliability enhancement. For example, smart meters in PG&E's network improved outage response, while ALS deployment at FPL reduced outage duration. Comparisons across regions highlight best practices for specific grid conditions and reliability goals, covering urban, rural, and industrial power systems. These studies underscore the importance of smart technologies and ALS for reducing outages and improving power system resilience[4], [10], [12], [13], [14].

Objectives and Structure of the Review

This review provides a comprehensive analysis of power distribution system reliability, emphasizing traditional challenges and the impacts of digitalization and smart technologies.

Objectives:

- Examine reliability concerns in power distribution systems, including methodologies and indices such as the Markov model.
- Analyze factors influencing outages, evaluate mitigation strategies, and explore smart technology integration.
- Assess Nigeria’s power network reliability and compare it with global benchmarks to identify improvement opportunities.

Structure:

1. **Literature Review**: Examines research on power system reliability, methodologies, and findings.
2. **Frequent Power Outage Failures**: Discusses outage causes, impacts, and mitigation strategies.
3. **Smart Distribution Technologies**: Evaluates their role in improving grid reliability.
4. **Automatic Line Switches**: Analyzes their functionality and optimization in fault management.
5. **Case Studies and Comparative Analysis**: Reviews specific reliability strategies and technologies.
6. **Conclusion and Future Directions**: Summarizes key insights and provides recommendations.

Contextual Insights:

- Nigeria’s growing energy demands and technical challenges have led to reliability issues, frequent outages, and user dissatisfaction. Load shedding is used as a temporary solution, but system flaws result in significant downtime.
- Reliable power distribution is crucial for economic stability, public safety, and quality of life, necessitating advanced solutions to reduce outages and improve performance.

This review aims to highlight critical reliability challenges, assess advanced solutions like smart grids and automatic line switches, and provide actionable strategies to enhance the resilience and reliability of modern power distribution systems.

Literature Review

Power System Network Reliability

Around 80% of power outages stem from distribution system failures, often evaluated through historical data analysis and prediction methods. Utilities prioritize historical analysis over predictive techniques, which highlights the need for reliability studies in distribution network design. Reliability improvements can be achieved by integrating analytical models, such as the Markov model, and reliability indices for failure probability reduction. Nigeria's demand for electricity has increased with population growth, but low reliability results in load shedding as a workaround, causing consumer dissatisfaction. This review assesses Nigeria's power system reliability and compares it to international standards, aiming to enhance its performance pact of Power Distribution Reliability**

Economic Stability: Reliable power is essential for economic growth, reducing costly operational disruptions in industries and critical infrastructures.

A. **Public Safety and Health**: Stable power supports essential services like hospitals and emergency systems, reducing risks associated with outages.
B. **Quality of Life**: power supply improves daily life, preventing discomfort and ensuring safety during extreme conditions.
C. **Integration of Renewable Energy Source**: is crucial to integrate intermittent renewable sources, with advanced technology balancing supply and demand.
D. **Smart Grids and Technology**: with advanced monitoring and automation enhance reliability through faster fault detection and load management.
E. **Environmental Sustainability**: Reliability reduce the need for backup generators, supporting environmental goals by lowering emissions.
F. **Customer Satisfaction**: A dependable power supply customer trust, while frequent outages reduce satisfaction and confidence in utilities.
G. **Regulatory Compliance**: Utilities must meet reliability steroid penalties, reinforcing compliance and operational stability.

Reliable power distribution is critical to economic, environmental, and soeing, directly impacting economic growth, public safety, and quality of life.

Studies on Reliability in Power Distribution Systems

2. Power Outage-Dependent Failures in Substations

Sub stations are essential in distributing electricity from high-voltage lines to lower-voltage systems. Patel and Gupta identified primary causes of substation outages, including equipment aging, environmental factors, and operational errors, stressing the importance of routine maintenance and advanced monitoring to prevent failures. Shi et al. demonstrated that smart technologies, such as sensors and automated controls, significantly reduce substation failures, enhancing overall network reliability.

3. Reliability Assessment for Distribution Feeders

Distribution feeders directly impact the quality of power delivered to consumers. Sharma et al. compared deterministic and probabilistic reliability assessment methods, finding that probabilistic approaches better reflect the stochastic nature of failures. Khan et al. introduced a dynamic reliability assessment model using real-time data and machine learning, allowing for proactive maintenance and reducing the likelihood of feeder outages.

4. Importance of Reliability in Power Distribution

Reliability in distribution systems ensures uninterrupted power, which boosts customer satisfaction and economic output. Kumar et al. emphasized that outages have economic consequences, particularly for industries dependent on continuous power. Chen et al. noted that reliability is crucial for smart grid development, where technologies like automatic line switches and fault detection systems enhance grid stability, supporting renewable energy integration.

Table 2.1: Key Findings from Literature on Power System Reliability

Study	Methodology	Key Findings

Shokrollahi et al. in [3]	Probabilistic Risk Assessment	Highlighted the need for improved redundancy
Manadhar et al. [14]	Failure Mode and Effect Analysis	Identified common failure points in distribution systems
Zhai et al. [9]	Simulation Modelling	Emphasized the benefits of predictive maintenance

Methodology

To ensure a thorough survey on power distribution reliability, this study used a structured approach, focusing on publicly available resources, including scholarly books, conference papers, articles, and standards. Databases such as Scopus, IEEE Explore, Science Direct, Springer, Taylor & Francis, and Wiley were searched using key terms like "Power Distribution Systems," "Reliability Assessment," "Smart Distribution Technologies," and "Electric Power Reliability." Priority was given to high-quality sources, especially publications from ISI, Q1, and Q2 journals, and IEEE conference materials. Relevant insights were also verified with international energy industry data and IEEE standards.

Table 3.1 lists keywords, topics, and databases searched, while **Figure 2.1** illustrates the review process flowchart. Covering materials from 2015 to 2024, this review aims to explore major global blackouts, cascade events, and reliability challenges in electric power distribution, providing insight into ongoing research in this area.

Table 3.1: Terms and searched databases used in the review methodology.

Sector	Electric Power System (EPS)
General Topic	Power system reliability, frequent
Discipline	Power distribution reliability
Very specific topic	Reliability assessment of power distribution systems
Keywords I	Power distribution systems, reliability assessment, cyber-induced failures, smart distribution technologies,
Keywords II	33KV feeders, electric power reliability, distribution feeders, resilience, network performance
Language English (En)	Language English (England)
Availability	Online available only
Databases	IEEE, MDPI, Scopus, Science Direct, Springer, Wiley, and Taylor and Francis
Publication type	Publication type Research articles, Books, Conference papers and Standards

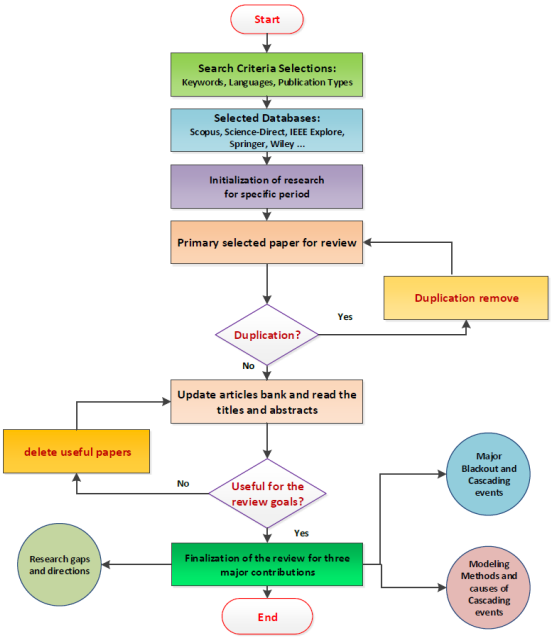

Figure 2.1: The flowchart of the review methodology used.

The items that have been published online mostly between 20015 and 2024 are covered by this review. It ought to be noted that the paper's topic is overly narrow, and we attempt to examine the main blackouts that occur worldwide. The study also makes an effort to explain the causes of these laudable power outages and cascade catastrophes. Additionally, the examination of the gathered data reveals a significant amount of study being done on the subject of reliable electric power distribution

3.1 Assessment Frameworks for Reliability Evaluation

Evaluating power distribution reliability involves various frameworks that address system reliability amid frequent outages, smart technologies, and automatic line switches [31].

Load and Generation Analysis

In power system management, load and generation analysis is critical for determining the required generating capacity. This process is divided into static and operational requirements: static capacity focuses on long-term demand projections and infrastructure planning, while operational capacity addresses short-term needs to meet real-time load demands. The static reserve accounts for maintenance, unplanned outages, and growth, emphasizing the importance of accurate load estimation for efficient network design and expansion. However, this must be balanced against cost efficiency to avoid unnecessary redundancy's, such as deterministic approaches [23].

- **Generating Capacity**: Installed capacity meets maximum anticipated demand plus a reserve margin.
- **Operating Capacity**: A combination of demand and a backup reserve, often one or more large units, ensures operational reliability.
- **Network Capacity Planning**: Circuits are added based on redundancy levels, typically following (n-1) or (n-2) criteria.

These methods have limitations, as they overlook the probabilistic nature of system performance, consumer demand variability, and component failure risks. Key probabilistic considerations include [32].

- Generator forced outage rates vary by type and size, making fixed reserve percentages unreliable.

- Overhead line failure rates, affected by physical and environmental factors, may require more than minimum circuit standards.
- Load forecasting inaccuracies contribute to decision-making uncertainties, complicating planning and operations.

1. **Exploration of Alternatives**
   In planning, multiple options are considered, prioritizing those that are technically and financially feasible based on experience. The current network solution serves as a baseline for assessing alternatives. Options that don't meet set criteria are discarded. Utility practices involve regularly comparing current performance with standards and projecting future performance, especially with changes in setup, operations, security, and network extensions.
   Predictive Reliability Assessment (PRA) can enhance expansion planning by quantifying the reliability impact of new programs and expansions. PRA often evaluates equipment upgrades, substation expansions, feeder automation, load transfers, and optimal locations for dispatch centers. While remote monitoring could improve reliability, it may be cost-prohibitive in low-demand rural areas. However, placing auto-recloses and distributed generators can boost reliability by adding backup reserve.

Evaluation of Alternative Systems

Network planning often begins with the current network as a reference. Alternatives are evaluated using the NetBas/Levsik program by Powel Company, a comprehensive utility management software. Powel NetBas supports distribution and transmission tasks with tools for asset management, GIS, planning, engineering, and real-time operations analysis. Its customized data model optimizes grid documentation and includes GIS-based features like statistics and search functions.

Key analysis components include:

- **Load Flow Analysis:** Assesses voltage drops, power flows, and losses to determine steady-state operation and identify system improvements.
- **Short Circuit Analysis:** Evaluates short circuit currents to optimize switchgear and network protection design.
- **Reliability Analysis:** Measures outage frequency, duration, and costs to identify the most reliable solutions.
- **Risk Analysis:** Examines the likelihood and impact of risks, prioritizing them based on economic, safety, environmental, and reputational factors.
- **Power Quality Analysis:** Analyzes voltage, current, frequency, and harmonics to maintain optimal power quality.

Alternatives meeting technical criteria proceed to economic analysis, while non-compliant options are revised or discarded. Both technical and economic evaluations guide the final selection.

2. **Cost-Benefit Analysis**

After identifying technically feasible alternatives, the next step is evaluating their costs. This includes investment, system loss, outage costs (CENS), and ongoing operation and maintenance expenses. A detailed development plan should outline the type, amount, and timing of expenditures to minimize costs while maximizing social benefits. This analysis aids in selecting the most cost-effective option and informs recommendations for future system implementation [14].

Evaluation of Reliability: Metrics and Indices

Distribution reliability is crucial for customer satisfaction and operational efficiency. It measures a system's ability to function without failure over a specified period under defined conditions. As the primary customer interface, the distribution system's reliability directly impacts customer perceptions [39].

Reliability is assessed using indices widely adopted by utilities to monitor regional or circuit performance. Regulators often mandate reporting these indices, with a shift toward performance-based rates that reward or penalize utilities based on reliability performance. Commercial and industrial customers also consider these indices when choosing facility locations, highlighting the growing importance of reliability in modern utility management [40].

Understanding Power Quality, Reliability, and Availability

Power quality, reliability, and availability are interconnected concepts, each focusing on different aspects of electrical supply performance.

- **Power Quality** refers to maintaining an ideal sinusoidal voltage waveform with constant frequency and amplitude. Issues like amplitude fluctuations, frequency deviations, transients, and harmonics can impair power quality. For customers, power quality problems disrupt appliance functionality, while utilities consider deviations from standards like RMS voltage and harmonics as key indicators.
- **Reliability** is a subset of power quality, emphasizing the system's ability to minimize customer interruptions, particularly those causing voltage drops to zero.
- **Availability** is a subset of reliability, focusing on the proportion of time a voltage source remains uninterrupted and the likelihood of experiencing an outage.

The relationship among these terms is hierarchical, with power quality encompassing reliability and reliability including availability. Each aspect addresses specific performance benchmarks critical to both customer satisfaction and system operation [20].

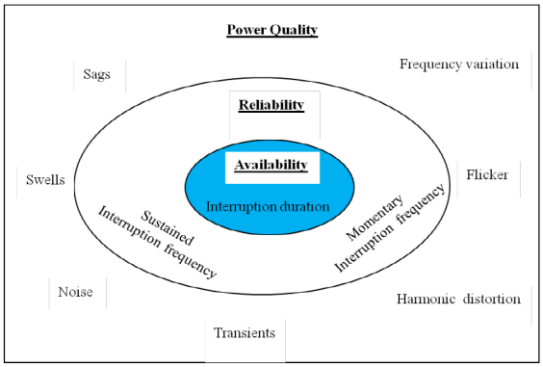

Figure 4.1: Hierarchy of power quality, reliability and availability [36]

Power Quality

Ideal power quality is defined by a flawless sinusoidal voltage source, free from waveform distortion, amplitude fluctuations, or frequency variations. Achieving near-perfect quality may necessitate substantial utility investment in accommodating equipment with heightened power quality requirements. Conversely, utilities may opt for cost-saving measures, shifting responsibility for power quality issues to customers. However, neither extreme is ideal, as utilities must strike a balance between cost and the level of power quality provided to customers [41].

The frequency of power quality concerns is escalating due to the widespread use of sensitive electronic equipment and automated processes. These concerns encompass various issues including interruptions, sags, swells, transients, noise, flicker, harmonic distortion, and frequency variations [42]

Reliability

Distribution reliability primarily concerns equipment outages and customer interruptions. Under normal operating conditions, all equipment (except standby) is energized, ensuring uninterrupted service to all customers. However, both scheduled and unscheduled events can disrupt normal operations, leading to outages and interruptions [36]. Unscheduled events may result from human error or equipment failures, while scheduled events involve periodic maintenance aimed at ensuring equipment reliability. Customers are typically notified in advance of scheduled maintenance to minimize inconvenience. Various indicators are utilized to assess reliability in transmission and distribution systems. Regulations may aim to compensate customers for prolonged interruptions, manage restoration times effectively, and incentivize utilities to reduce both the total number and duration of interruptions, thereby discouraging increases in such occurrences [43].

Availability

Availability refers to the probability of a system being energized, while unavailability denotes the likelihood of it not being energized. It is a fundamental aspect of reliability and is commonly expressed as a percentage or per unit. Unavailability can be directly calculated from interruption duration data. For example, if a customer experiences 9 hours of interrupted power in a year (out of 8760 hours), the unavailability would be calculated by dividing 9 by 8760, resulting in 0.10%. Subtracting this value from 100% yields the availability, which in this case would be 99.90%. With the increasing demand for highly reliable power supply, particularly due to the proliferation of ultrasensitive loads[44], [45].

2. **Reliability Analysis**

Reliability analysis is vital for planning engineers to ensure quality service and identify cost-effective expansion plans that balance investment and loss costs [16]. Two primary approaches are used:

1. **Simulation Methods**: Employ statistical distributions, such as Monte Carlo simulations, which require extensive iterations to achieve precise results.
2. **Analytical Methods**: Use mathematical models and statistical data like failure rates and repair times to compute reliability indices, particularly for simple radial systems [46], [47].

Key reliability indices include failure rate (λ), average outage time (r), and annual outage time (U). While radial systems are straightforward to analyze, meshed or parallel networks require more complex evaluations.

Markov Chain Model

the Markov model, a widely used analytical approach, is efficient and effective for reliability analysis. It calculates reliability in radial distribution networks using the duration-frequency technique and stationary Markov processes, focusing on:

- **Failure Frequency (λ)**
- **Repair Time (r)**

Components are represented in two states: operational (1) or failed (0), as shown in state model diagrams. Analytical methods, favored for their efficiency, dominate over simulation techniques, which are computationally intensive and reserved for specific cases [50].

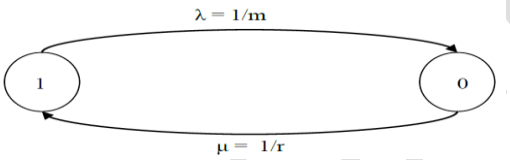

Figure 4.2: Transition diagram of component states

Where, λ = fault frequency, m = mean time to failure, μ = repair frequency, r = mean time to repair.

Where, $\lambda = \frac{number\ of\ outages\ on\ component\ in\ a\ given\ period}{total\ time\ component\ is\ in\ operation}$……..Eq. 4.1

Figure 4.3 presents the anticipated functional and outage durations for a component, known as the state cycle.

transition rates [50].

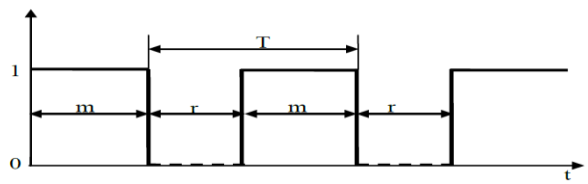

Figure 4.3: Average state cycle

The average function time, m, is given by; m = $^1/_\lambda$

Where, m = MTTF, mean time to failure = $^1/_\lambda$

r = MTTR, mean time to repair = $^1/_\mu$

$m + r$ = MTBR, mean time between failures = T = $^1/_f$

f = cycle frequency = $^1/_{\mathrm{T}}$

T = $cycle\ time\ ^1/_f$

The probability of component to be in either one of the two states are as shown in the figure:

$P_0 = \frac{r}{m+r} = \frac{\lambda}{\lambda+\mu} = \frac{r}{\mathrm{T}} = \frac{f}{\mu} = \frac{\sum(down\ time)}{\sum(down\ time)+\sum(up\ time)}, where\ f = \mu \cdot P_0$ …….Eq. 4.2

$P_0 = \frac{m}{m+r} = \frac{\mu}{\lambda+\mu} = \frac{m}{\mathrm{T}} = \frac{f}{\lambda} = \frac{\sum(up\ time)}{\sum(down\ time)+\sum(up\ time)}, where\ f = \lambda \cdot P_1$ …….Eq. 4.3

$f = P_0 \cdot \lambda = f = P_1 \cdot \mu$……....Eq. 4.4

Where, P_0 = probability for a component to be in state 0 (down)

P_1= probability of a component to be in state 1 (up)

f = cycle frequency (frequency to be in or out)

Series System

A radial system comprises various components like breakers, lines, switches, transformers, and end-users [4]. In this configuration, components are interconnected in series, where the system operates under the principle that "a chain is only as strong as its weakest link." in Figure 4.4. [51]:

Figure 4.4: Series structure

• **Average failure rate of the system;**

$\lambda_B = \lambda_1 + \lambda_2 = \sum_{i=1}^{2} \lambda_i$…….. Eq. 4.5

Average Outage time of the system:

$r_B = \frac{\lambda_1 r_1 + \lambda_2 r_2 + \lambda_1 \lambda_2 r_1 r_2}{\lambda_1 + \lambda_2} = \frac{\sum \lambda_i r_i}{\sum \lambda_i} = \frac{\cup_B}{\lambda_B}$ ……Eq. 4.6

$If = \lambda_1 \lambda_2 r_1\ r_2 \ll \lambda_1 r_1\ or\ \lambda_1 r_1\ r_2$

• **Average Annual Outage time**

$\cup_S = f_s \cdot r_s = \lambda_s \cdot r_s$ ……Eq. 4.7

Where the failure is rate at node i, is the outage time at node i.

Parallel System

In this scenario, the failure modes of the load point involve overlapping outages, meaning that two or more components must simultaneously fail to interrupt a load point, as depicted in Figure 4.5.

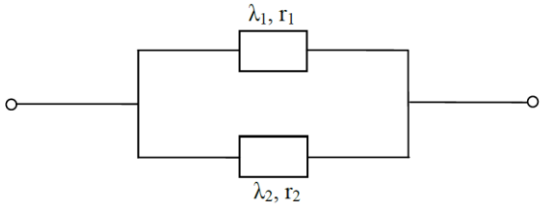

Figure 4.5: Parallel structure

Average Failure rate of the system:

$\lambda_P = \frac{\lambda_1\lambda_2(r_1+r_2)}{1+\lambda_1 r_1+\lambda_2 r_2} = \lambda_2\lambda_1\lambda_2(r_1+r_2)$……Eq. 4.8

Where, $\lambda_1 r_1 and\ \lambda_2 r_2\ usualyy\ \ll 1$

• **Average Outage time of the system:**

$r_P = \frac{r_1 r_2}{r_1+r_2}$ ……...Eq. 4.9

• **Average Annual Outage time of the system:**

$\cup_P + \lambda_P r_P$ ……Eq. 4.10

These indices are sufficient for evaluating simple radial systems. However, for more complex distribution systems, which may include both radial and meshed configurations, more comprehensive indices must be utilized [4].

The RELRAD Model

To evaluate the cost-effectiveness of reliability improvements, indices like expected annual non-delivered power (NDP) and energy (NDE) are crucial [10]. Traditional methods, such as failure mode or minimum cut set analysis, offer quick results but may struggle with accurately modeling repair times.

To address these complexities, the Norwegian Electric Power Research Institute (EFI) developed the

Reliability Evaluation of Radial Distribution Network (RELRAD) model. This analytical approach complements the minimum cut set method by evaluating fault contributions from all network components and their impact on load point outages, rather than focusing solely on individual load points [10], [52].

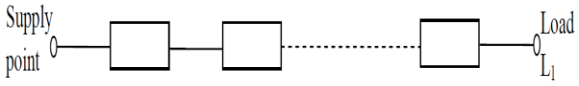

Figure 4.6: Minimum cut set for load point L1

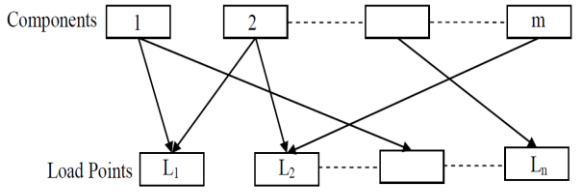

Figure 4.7: Analytical techniques (RELRAD approach)

The positioning of circuit breakers significantly impacts the duration of outages at system load points. [54].

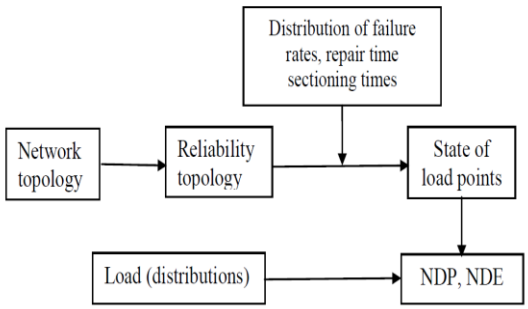

Figure 4.8: Model for reliability analysis

The logic delineating the relationship between components and their contribution to fault-related reliability across various load points is formulated prior to commencing the reliability assessment [55].

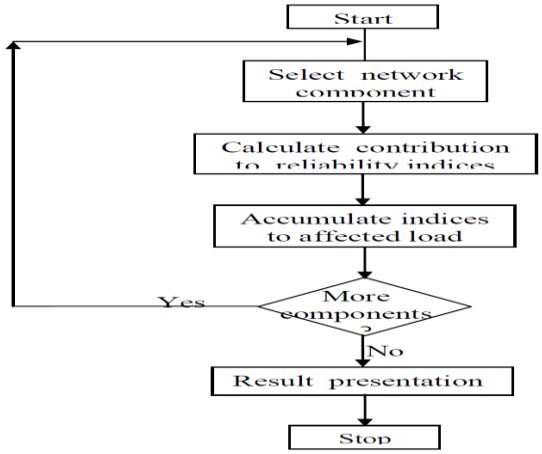

Figure 4.9: Flow chart for calculation of reliability indices

- **Customer Impact**: Outages are quantified through metrics like non-delivered power (NDP) and energy (NDE) to assess customer inconvenience. Scheduled outages, while planned, can incur significant costs, often exceeding those of forced outages.
- **Reserve Options**: The model considers network reserve options, such as normally open ring connections, mobile reserve cables, generating units, and other external supplies.
- **Automation**: Automatic sectioning devices or remotely controlled disconnectors reduce sectioning times and improve reliability.

Reliability Indices

Core Metrics

1. **Reliability Function (R(t))**
   Measures the likelihood of uninterrupted service (t) =Total operating hours - Downtime Total operating hours (t) = \franc{\text{Total operating hours - Downtime}} {\text{Total operating hours}} R (t)=Total operating hours Total operating hours - Downtime
2. **Failure Rate (λ)**
   Evaluates equipment failure frequency: λ=Total failures Operational exposure time λ = \franc{\text{Total failures}}{\text{Operational exposure time}}λ=Operational exposure time Total failures
3. **Mean Time Between Failures (MTBF)**
   The average duration between failures for repairable systems: MTBF=Total operational time Failures MTBF = \franc{\text{Total operational time}}{\text{Failures}}MTBF=Failures Total operational time
4. **Mean Time to Repair (MTTR)**
   Time needed to restore functionality: MTTR=Total downtime Failures MTTR = \franc{\text{Total downtime}}{\text{Failures}}MTTR=Failures Total downtime

Availability (A)
Probability of maintaining intended operation:

A=Uptime + Downtime
A = \franc {\text{Uptime}}{\text{Uptime + Downtime}
A=Uptime + Downtime Uptime

Customer-Based Indices

- **System Average Interruption Duration Index (SAIDI)**: Average interruption duration for customers. SAIDI=∑ (Outage duration × Affected customers) Total customers SAIDI = \ franc {\sum (\text{Outage duration} \times \text{Affected customers})} {\text{Total customers}} SAIDI=Total customers∑(Outage duration ×Affected customers)
- **System Average Interruption Frequency Index (SAIFI)**: Average number of interruptions per customer. SAIFI=∑(Failure rate ×Affected customers)Total customers SAIFI = \franc{\sum (\text{Failure rate} \times \text{Affected customers})}{\text{Total customers}}SAIFI=Total customers∑(Failure rate×Affected customers)
- **Customer Average Interruption Duration Index (CAIDI)**: Average restoration time after outages. CAIDI=SAIDISAIFICAIDI = \franc{\text{SAIDI}}{\text{SAIFI}}CAIDI=SAIFISAIDI
- **Momentary Average Interruption Frequency Index (MAIFI)**: Frequency of momentary outages (under 5 minutes).
- **Average System Availability Index (ASAI)**: Measures system availability: ASAI=Total operational hours - Outage hours Total operational hours ASAI = \franc{\text{Total operational hours - Outage hours}}{\text{Total operational hours}}ASAI=Total operational hoursTotal operational hours - Outage hours

B. Reliability Modeling and Smart Technology

Reliability Modeling Methods

- **Probabilistic Risk Assessment (PRA)**
  i. Fault Tree Analysis (FTA): Identifies failure points.
  ii. Event Tree Analysis (ETA): Assesses the consequences of initiating events.
- **Monte Carlo Simulations**
  i. Stochastic modeling for variable input analysis.

C. Smart Distribution Technologies

1. **Real-Time Monitoring**

   i. SCADA systems and IoT-enabled sensors improve reliability evaluation.

2. **Predictive Maintenance**
   i. **Condition-Based Monitoring (CBM)**: Prevents failures through analytics.
   ii. **Reliability-Centered Maintenance (RCM)**: Optimizes maintenance strategies.

D. Automatic Line Switches (ALS)

a. **Performance Metrics**: Evaluate fault isolation and service restoration.
b. **Placement Optimization**: Algorithms like Genetic Algorithms (GA) and Particle Swarm Optimization (PSO) determine optimal switch locations [62].

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3. **ASSESSMENT OF RELIABILITY**

Power reliability denotes the power system's capacity to fulfill its intended functions under specified conditions for a designated duration without encountering failures. In the contemporary competitive landscape, the significance of distribution reliability has amplified as the distribution system directly caters to the customer [11].

Maintainability of Each Feeder

To decrease the duration of power outages, it is imperative to assess the feasibility of executing successful repair actions on each feeder, a concept termed maintainability. Maintainability gauges the ease and speed with which a system can be reinstated to operational status following a failure. Ensuring maintainability entails facilitating swift repairs to uphold high availability, thereby reducing downtime of productive equipment and managing costs in critical availability scenarios [63]

.***Maintenance Strategies***

After evaluating the reliability and maintainability of feeders, exploring alternative maintenance strategies becomes crucial. Maintenance analysis demonstrates that maintenance predominantly revolves around component strategies to uphold the functionality of systems, plants, and power distribution networks. "Alternative strategies" encompass both enhanced component-focused and system-oriented approaches. Table 6 delineates the criteria utilized for maintenance measures across various strategies. [17].

Table 4.1: maintenance measure of different strategies [55].

Measures / ategies	**Inspection**	**Servicing**	**Repair**	**Renewal**
Corrective	-	-	In case of outage	In case of outage
Time-based	According to interval	According to interval	In case of outage	According to interval
Condition-based	Cyclic or Continuous (monitoring)	According to condition	In case of outage	According to condition
Reliability-centered	***'Strategies overall process' considering the importance of the network component to the system reliability***			
Risk-based (quantification of outage cost)	**Cyclic or Continuous (monitoring)**	**According to condition, importance and outage risk**	**In case of outage**	**According to condition, importance and outage risk**

Reliability Evaluation of Ganmo 33kv feeders and Maintenance Strategies

Balogun et al[15] evaluated the Ganmo 33kV feeders, identifying that dedicated feeders like KAM and UNILORIN exhibited higher reliability due to load demand. Reliability was lowest during May–October, attributed to vegetation and rainfall. Maintenance strategies suggested tailoring intervals based on feeder type, load demand, and reliability to enhance overall performance.

Case Study: Ede Town Distribution Feeders

Johnson et al[45], Analyzed reliability indices for Ede town's feeders, revealing significant discrepancies from international standards (e.g., SAIDI: 1884.99 hours vs. 2.5 hours). Findings highlighted the unreliability of power systems and the need for targeted improvements in feeder performance.

Traditional vs. Fuzzy Logic-Based Reliability Assessments

Shokrollahi 2017 in [3] as outlined in [2], utilized fuzzy logic to address uncertainties in traditional reliability metrics. Simulations on IEEE RBTS Bus 2 demonstrated how incorporating risk factors can enhance system reliability assessments.

Dynamic Simulation and Risk Assessment
GoldSim's in [64] dynamic simulation capabilities were highlighted for accurately modeling evolving system conditions, while Parhizkar et al. reviewed probabilistic risk assessment methods, emphasizing the integration of dynamic and probabilistic approaches for complex systems.

Recent Advances in Smart Distribution Systems
Recent studies, such as those by Billinton et al[50], showcased tools like Monte Carlo simulations and MATLAB for improving smart grid reliability. These technologies enhance system resilience and efficiency through advanced analytics.

Performance Metrics for Automatic Line Switches (ALS)
Key ALS metrics include fault detection/isolation times, composite reliability indices (e.g., EENS), and cost-benefit analyses (e.g., ROI). Research demonstrates ALS significantly enhances reliability by reducing outage durations and optimizing maintenance.

Tools for Analyzing Smart Distribution Systems

1. **Simulation Software**: MATLAB and Simulink are extensively used for dynamic simulation and optimization of power systems, enabling scenario testing for faults and renewable energy integration without affecting actual infrastructure[1], [74].
2. **ETAP**: This tool offers modules for reliability analysis, power flow, and fault analysis, providing real-time and predictive simulations to optimize smart distribution system performance[11].
3. **PSCAD**: Ideal for transient analysis, PSCAD models the impact of distributed generation and smart grid devices on system reliability and stability[75].
4. **CYME**: Supports planning and operation of electrical distribution systems with advanced reliability analysis, load flow studies, and fault management, aiding in evaluating smart grid technologies.

Techniques for Enhancing Smart Distribution Systems

1. **Monte Carlo Simulation**: Performs probabilistic reliability assessments by statistically evaluating system performance under variable conditions like renewable energy integration[16].
2. **Reliability Block Diagram (RBD)**: Models complex systems by breaking them into components to identify critical areas and improve design.
3. **Outage Management Systems (OMS)**: Streamlines outage response with real-time fault detection and repair coordination, enhancing efficiency and customer satisfaction.
4. **Geographic Information Systems (GIS)**: Maps and analyzes network spatial aspects, aiding in visualization, planning, and fault management when integrated with tools like SCADA[76].
5. **SCADA Systems**: Provides real-time monitoring and control, automating network elements to enhance reliability and reduce outage durations[77].

Case Studies

1. **Reliability Assessment of 33kV Feeders**: Analysis of feeders like those in TCN's Damaturu Work Centre revealed frequent outages caused by equipment failures, weather, and human errors. Reliability metrics like SAIFI and SAIDI exceeded thresholds, requiring significant improvements[45].
2. **Electric Power Distribution Feeder Reliability**: Statistical and computational tools, including ETAP and MATLAB, assessed feeder performance, simulated scenarios, and identified network vulnerabilities, emphasizing the need for targeted enhancements[17].

Impact of Power Outages on Distribution System Reliability

Frequent power outages significantly undermine the reliability of distribution systems, as reflected in metrics like SAIFI, SAIDI, and CAIDI. High values in these indices indicate more frequent and prolonged interruptions for consumers. Outages result from aging infrastructure, inadequate maintenance, equipment failures (e.g., transformers, circuit breakers), natural disasters (storms, floods, extreme weather), and human errors in operations or planning[16].

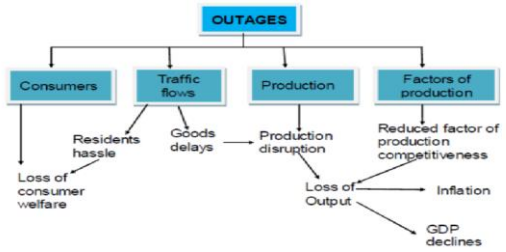

Figure 6.1: Summary Impact of Power Outages

Benefits and Challenges of Smart Distribution Technologies

Benefits:

1. Enhanced **grid reliability** through real-time monitoring and analytics, reducing outage frequency and duration. Smart meters and sensors quickly identify faults and isolate affected areas.
2. Improved **energy efficiency** with better load management and integration of renewable energy, reducing waste and operational costs.
3. **Consumer empowerment** via smart meters, providing insights into energy usage and enabling time-of-use pricing to stabilize the grid and lower costs.

Challenges:

1. **High initial investment** for upgrading infrastructure like smart meters and communication networks.
2. **Workforce training** required to manage and maintain advanced systems.
3. **Regulatory barriers** that can hinder adoption, requiring updated policies to support innovation and investment.

Role of Automatic Line Switches (ALS) in Enhancing Reliability

1. **Enhancing Reliability:**
   ALS detects and isolates faults automatically, minimizing outages and maintaining power for unaffected areas. This improves reliability metrics like SAIFI and SAIDI, particularly in rural areas where manual intervention is challenging.
2. **Analysis of ALS:**
   Optimal ALS placement requires network analysis, historical fault data, and load patterns. Integration with Distribution Management Systems (DMS) enhances real-time monitoring and decision-making, further reducing fault response times.

Results and Discussion

1. **Comparative Analysis:**
   Smart distribution systems outperform traditional grids with advanced fault detection, isolation mechanisms, and technologies like ALS, AMI, and DMS, leading to improved reliability and efficiency.
2. **Findings:**
   Simulations using tools like MATLAB and ETAP reveal the benefits of strategic ALS placement and DMS integration in reducing outage durations and improving fault management.

Recommendations:

- **Invest in smart technologies** like AMI, DMS, and ALS.
- Optimize **ALS placement** using simulations for maximum fault isolation.
- Regular **maintenance and upgrades** of infrastructure.

- Provide comprehensive **workforce training** for managing smart systems.

Conclusion and Future Directions

Addressing frequent outages requires integrating smart technologies, improving infrastructure resilience, and strategic planning. Key advancements include:

- Implementing **smart systems** for enhanced reliability and efficiency.
- Investing in **workforce training** and infrastructure upgrades.
- Focusing on **predictive maintenance** and optimizing ALS placement.

By adopting these strategies, utilities can significantly enhance grid reliability, reduce outages, and improve overall service quality. Future efforts should also prioritize cyber security and renewable energy integration.

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