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Risk-based predictive maintenance of medium voltage network switching equipment using analytical hierarchy process as an analytical tool

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Abstract
Predictive maintenance has become crucial for enhancing the reliability and efficiency of electrical systems, especially for Medium Voltage Network (MVN) switching equipment, which plays a key role in electricity distribution. This study aimed to develop a risk-based predictive maintenance model for MVN switching equipment using the Analytical Hierarchy Process (AHP) for maintenance prioritization, along with Z-score and Monte Carlo simulation methods to evaluate risk likelihood and impact. The Z-score method assessed the probability of risks occurring, revealing a probability exceeding 90% for specific equipment, such as UP2D.2025.C4, at 93.12%. The Monte Carlo simulation assessed the potential impact of these risks, showing severe consequences for various types of equipment. For example, UP2D.2025.C1 had a mean of 28.51 and a standard deviation of 3.50, while UP2D.2025.C8 had a standard deviation of 33.17, with an impact of over 61.53%. AHP was used to assign priority weights to components based on criteria such as equipment age, operational condition, and failure history. The analysis indicated that the Lightning Arrester had the highest maintenance priority at 26.04%, followed by the Fuse Cutout at 20.62% and the Pole-Mounted Circuit Breaker at 11.15%. This research was expected to significantly contribute to the development of more efficient and effective maintenance strategies for electrical systems, particularly in the electricity distribution sector.

Keywords:
Analytical hierarchy process;
Monte Carlo;
Risk management;
Switching equipment;
Z-score;

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INTRODUCTION

In electrical distribution systems, switching equipment plays a crucial role in determining system reliability, especially for companies like Indonesian State Electricity Company (PLN), which is responsible for ensuring the efficient distribution of electricity across Indonesia, which is evaluated using the System Average Interruption Duration Index (SAIDI) and the System Average Interruption Frequency Index (SAIFI) [1]. In medium-voltage network terminology, switching equipment is used to connect, distribute, and disconnect electrical current via a spring mechanism, with SF6 serving as the insulating medium for 630 A/24 kV [2]. The purpose of establishing this unit is to improve customer service, enhance the quality of power distribution, boost the performance of the SAIDI and SAIFI indicators, minimize outages by reducing recovery time, and lower electrical energy losses. Currently, a significant number of switching equipment units, including Load Breaker Switches and Reclosers, are distributed across the entire operational area of the Indonesian State Electricity Company, playing a critical role in the efficient and reliable functioning of the electrical distribution network.

These switching devices are integrated with the Supervisory Control and Data Acquisition (SCADA) system, which facilitates data exchange among network nodes. SCADA plays a vital role in the management of modern power systems by enabling real-time monitoring, control, and efficient operation [3]. Through SCADA, the Indonesian State Electricity Company can improve the reliability, efficiency, and safety of energy distribution, while enhancing operational management [4].

Thus, switching equipment will always be ready to act without delay. Switching equipment, which comes in volumes ranging from high to very high, and real-time monitoring in the absence of skilled professionals are hurdles that need to be addressed right now. Poor or nonexistent maintenance and outdated work instructions lead to operational inefficiencies. These problems can cause disturbances in the medium-voltage network, affecting the continuity of electrical system operations [5]. Such anomalies may include errors in fault-current detection, operational failures, or damage to insulation components, which can ultimately result in unplanned power outages, reduced system reliability, and increased maintenance and recovery costs [6]. In this case, the company's risk management must consider the potential risks associated with uncertainty in switching equipment as part of a broader strategy [7]. Research on equipment risk provides valuable insights into how the system relies on timely maintenance and the expertise of its personnel. Effective risk management involves identifying, analyzing, and evaluating risks arising from equipment malfunctions or failures, and their impact on overall electrical system operations [8][9].

This approach aims not only to prevent disruptions but also to minimize the financial and operational impacts of equipment failure, while ensuring the company's smooth, continuous operation [10]. Given the potential impact of system disturbances and the uncertainties caused by irregular maintenance, this research is crucial in addressing these challenges [11]. Lightning arrester, fuse cutout, potential transformer, pole-mounted circuit breaker, control cable, power supply cable, live line connector, earth wire, power supply module, modem, remote terminal unit, and 12V 17Ah battery are some of the switching equipment criteria that have been considered for use in this experimental research [12].

Several prior studies have designed and introduced an approach for scheduling the maintenance of switching devices in medium voltage network systems by utilizing the concept of Reliability-Centered Maintenance (RCM) [13], The analysis of device failure patterns and the assessment of potential risks [14], combination of AHP and TOPSIS methods to assess the risk levels of equipment [15], risk assessment to identify high-risk components followed by the application of AHP [16], implement a risk-based maintenance (RBM) [17], Experts identify risk components and their weights using a qualitative study Delphi [18], risk identification based on safety compliance and human perception without risk-based predictive maintenance prioritization [19], integration of House of Risk and Fuzzy AHP for risk identification and mitigation prioritization in supply chain systems [20].

The integration of the Analytical Hierarchy Process with risk management to assess impact and likelihood offers an innovative approach to mitigating anomalies in medium-voltage network switching equipment [21]. This approach aims to establish a structured predictive maintenance system while simultaneously prioritizing maintenance tasks that are both effective and cost-efficient, all while supporting the implementation of sustainable risk management strategies [22].

To date, no in-depth scientific research has been conducted on the prioritization of maintenance and risk management for switching equipment, which plays a critical role as a control device in distribution systems. Determining the priority of this equipment based on the likelihood and impact of failure is crucial, given its vital role in maintaining the smooth operation of the energy distribution system [6]. By adopting a hierarchical approach to risk management, companies can more effectively identify critical equipment that requires closer monitoring while reducing potential losses from equipment damage or failure [23]. This approach offers an opportunity to establish a more structured, proactive, and measurable maintenance system, providing long-term solutions to enhance the reliability and efficiency of energy distribution [24].

MATERIALS AND METHODS

Materials

This research analyzes 12 criteria related to the switching equipment at East and North Kalimantan Distribution Control Unit's Medium Voltage Network (MVN). These criteria include Lightning Arrester, Fuse Cutout, Potential Transformer, Pole-Mounted Circuit Breaker, Control Cable, Power Supply Cable, Live-Line Connector, Grounding Wire, Module Power Supply, Modem, Remote Terminal Unit, and

Battery. A comparative analysis is conducted on these components. Figure 1 shows the installation diagram of the switching equipment, and Figure 2 illustrates the general configuration of the Control Panel.

Methods

This paper uses a mixed-methods approach, combining qualitative and quantitative methods for a comprehensive analysis. The quantitative approach provides measurable data, ensuring empirical validation. The combination enhances the depth, validity, and reliability of the analysis. The research follows a systematic process outlined in a flowchart, starting with problem formulation and then a literature review. Data collection strengthens validity, risk management addresses issues, and the Analytical Hierarchy Process (AHP) is used to prioritize solutions. The research flow is shown in Figure 3.

Risk Management Process

This study uses ISO 31000:2018-based risk management, focusing on Risk Assessment and Risk Treatment. Risk Assessment involves Risk Identification, which identifies potential risks, impact locations, events, causes, and consequences to create a risk register for further analysis and mitigation, as shown in Figure 4. Risk Analysis evaluates the probability, impact, and interrelations of identified risks to guide mitigation decisions. Risk Evaluation prioritizes these risks to support strategic decision-making, while Risk Treatment selects and implements the most effective strategies for efficient risk management. With the following equation [25][26].

$$Risk = Probability\ x\ Impact \quad (1)$$

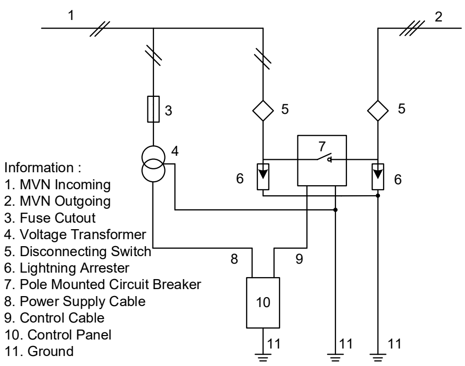

Figure 1. Installation diagram of the switching equipment

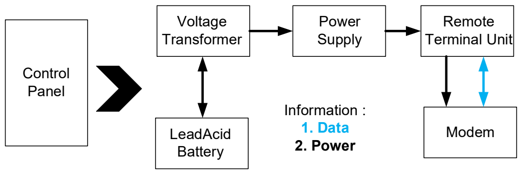

Figure 2. General configuration of the Control Panel

Method of Likelihood Level

This study adopts a quantitative approach to systematically analyze data and provide a clear depiction, as shown in Table 1. The Z-score model is an analytical tool used to measure and assess the likelihood of specific events, such as bankruptcy or financial failure, based on relevant financial ratios [27]. This method reveals relationships between variables and provides insights into data patterns. Using the Z-score, the study evaluates an entity's stability or risk, supporting data-driven managerial and financial decision-making [28].

Method of Impact Level

The Monte Carlo simulation solves complex problems with uncertainty by creating a system model (Table 2) and using random variables in the equation below [29]. Random samples are generated, and experiments are run multiple times for reliable results. These results are analyzed using statistics and compared with other methods for accuracy [30]. The final step involves verifying and validating the results and optimizing for greater efficiency. Monte Carlo simulations are useful in fields such as medical physics and radiotherapy planning because they can handle multiple random variables [31][32].

$$Z = \frac{(X - \mu)}{\sigma} \quad (2)$$

Table 1. Criteria for the Likelihood of Corporate Risk [33]

Probability Level	Probability	Qualitative Description	Previous Incident
E Frequent	>90%	Almost certain to occur	Occurred more than once in the last 6 months
D Likely	70% - 90%	High probability of occurring	Occurred once in the last 6 months
C Occasional	>30% - <70%	Equal probability of occurring and not occurring	Occurred once in the last year
B Seldom	10% - 30%	Low probability of occurring	Did not occur in the last year
A Unlikely	< 10%	Almost certain not to occur	Never occurred in the last year

Table 2. Criteria for the Impact of Corporate Risk [26][31]

Category	Impact Level	Target Deviation
Operational Achievement (for Financial Performance, referring to the Financial and Market Category)	Negligible Minor Moderate Significant Severe	< 1 % 1 % - 5 % 5 % - 10 % 10 % - 20 % > 20 %

$$N = \left(\frac{3x\sigma}{\varepsilon}\right)^2 \quad (3)$$

$$EXP = (NORMINV(RAND(), mean, SD) \quad (4)$$

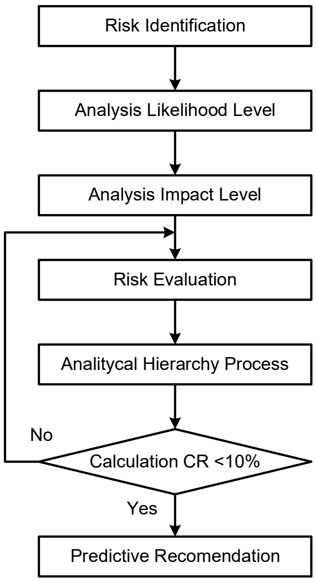

Figure 3. Methodology study

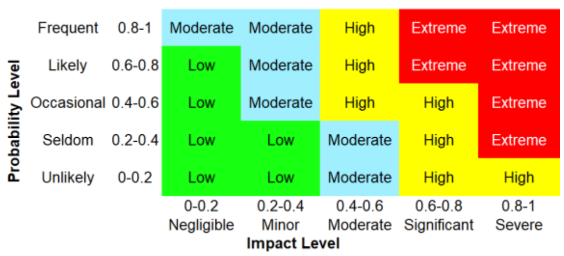

Figure 4. Risk Matrix of Risk Level and Risk Appetite [33]

Method of Analytical Hierarchy Process

The Analytical Hierarchy Process (AHP) is a decision-making method that combines quantitative and qualitative analysis to select the best alternatives using decomposition, pairwise comparison, and priority synthesis, despite relying on subjective input [34]. This study uses AHP to determine maintenance priorities for East and North Kalimantan Distribution Control Switching Unit's Equipment, focusing on critical system components based on their maintenance needs [35]. The process involves defining the situation, creating a hierarchical model with levels for the problem, criteria, and alternatives, and using criteria to identify alternatives based on the problem analysis, as shown in Figure 5 [36]. After constructing the hierarchy, pairwise comparisons are used to assess the importance of elements at each level, helping prioritize them through a structured evaluation matrix shown in Table 3 [37].

To ensure accuracy, the evaluation checks the matrix's consistency using a consistency index (CI) calculated from the largest eigenvalue [38, 39, 40]. In the equation, m represents the number of independent rows, S is the pairwise comparison matrix, and v is the matrix eigenvector, used to calculate the Consistency Index (CI) for assessing decision validity in AHP. The Consistency Ratio Index (RI) is the average CI from random simulations of paired comparison matrices, with the recommended upper threshold for the Consistency Ratio (CR) being 0.1 or less [41].

RESULTS AND DISCUSSION

The Number of Anomalies in Switching Equipment

The evaluation using the SRIKANDI application of the Indonesian State Electricity Company in 2024 revealed nearly 400 incidents of ground wire disturbances, along with fewer issues in other equipment like circuit breakers and fuse cutouts, suggesting problems with material quality, environmental factors, or external influences, while communication equipment had fewer frequent issues, indicating potential remote monitoring system problems. Additionally, 12V 17AH batteries experienced disruptions due to reduced storage capacity or charging system failures, as shown in Figure 6, highlighting the need for mitigation strategies and further risk evaluation, particularly for high-risk equipment such as ground wires.

$$\lambda_{max} = \sum_{i=1}^{m} \frac{(S.v)_j}{M.V_j}, \quad (5)$$

$$C1 = \frac{\lambda_{max} - m}{m - 1} \quad (6)$$

$$CR = \frac{CI}{RI} \quad (7)$$

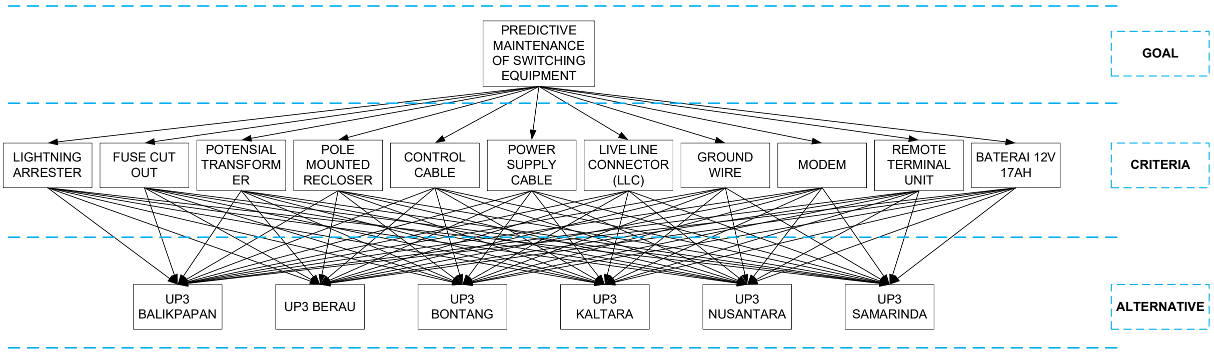

Figure 5. AHP Hierarchy for Medium Voltage Network Switching Equipment

Table 3. Saaty's Nine-Point Scale [33][37]

Saaty's Scale	Definition
1	Equally important to each other
3	Slightly more important than the other
5	More important than the other
7	Much more important than the other
9	Absolutely more important than the other
2,4,6,8	Values between two close ratings

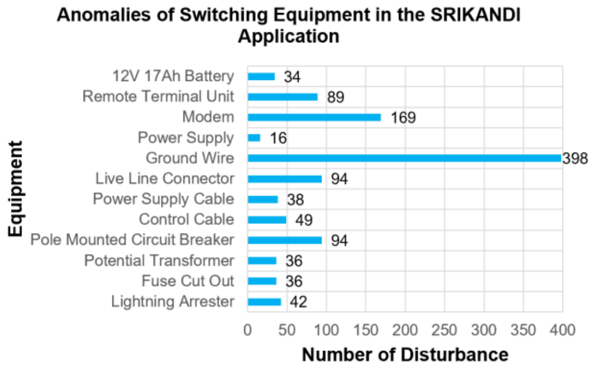

Figure 6. The number of disturbances in the MVN switching equipment in the SRIKANDI APP

Risk Identification

The process results in a detailed outline, as shown in Table 4, for determining risk criteria for MVN switching equipment at the Indonesian State Electricity Company. It involves extensive communication with stakeholders and systematic risk analysis across three key areas: Objectives, Proposed Activities, and Decisions. Each category plays a significant role in risk mitigation. The Objectives category focuses on operational safety and system disruptions, while the Proposed Activities category evaluates cost-effective risk mitigation alternatives. Decisions reflect the company's commitment to minimizing financial and reputational losses, providing a comprehensive framework for risk management.

Z-Score Analysis in Determining the Likelihood Level

Table 5 presents the Risk Analysis Results using Z-Scores, which help assess the likelihood of events exceeding a particular value (X). The Z-Score measures how many standard deviations X is from the mean, helping identify whether a value is normal or extreme. It involves three components: the analyzed value (X), the mean (μ), and the standard deviation (σ). The Z-Score is useful for determining event probabilities, particularly in risk management, by calculating the probability of events greater than X based on the normal distribution.

The Z-Score risk analysis reveals significant variation in the likelihood of events exceeding a specified value, X. Most risks with negative Z-Scores, such as UP2D.2025.C4, UP2D.2025.C5, and UP2D.2025.C7, indicate that X is below the mean but still have high probabilities (over 90%) of extreme events, suggesting substantial potential impacts. Risks with lower probabilities, such as UP2D.2025.C2, UP2D.2025.C9, and UP2D.2025.C12, are classified as "Likely" risks but also have negative Z-Scores, indicating values below the mean. Overall, Z-Score calculations and event probabilities help prioritize risks for mitigation, with those exceeding 70% requiring more immediate attention.

Table 4. Risk Criteria for Switching Equipment in Medium-Voltage Networks

Equipment Name	Risk ID	Target/Risk Source	Risk Description
Lightning Arrester	UP2D.2025.C1	Enhance the distribution system's protection against lightning-induced disturbances.	Failure of the insulation system
Fuse Cutout	UP2D.2025.C2	Improve the reliability of protection systems against overcurrent disturbances in the medium-voltage network (JTM)	Incorrect fuse rating selection
Potential Transformer	UP2D.2025.C3	Ensure the accuracy of voltage measurements for control and monitoring of the distribution system.	Partial discharge
Pole-Mounted Circuit Breaker	UP2D.2025.C4	Improve control of overcurrent and distribution system disturbances in remote locations or areas with difficult access.	Failure of the spring charging mechanism
Control Cable	UP2D.2025.C5	Ensure stable and uninterrupted transmission of control signals for a more reliable power distribution system.	Insulation degradation
Power Supply Cable	UP2D.2025.C6	Ensure a continuous, stable power supply from the source to the distribution system.	Loose connections
Live Line Connector	UP2D.2025.C7	Enhance the efficiency and safety of cable connections under operational load conditions.	Corrosion on galvanic components
Ground Wire	UP2D.2025.C8	Improve grounding systems to prevent overcurrent disturbances or fire hazards due to leakage currents.	Increase in soil resistivity
Power Supply	UP2D.2025.C9	Ensure power supply stability for the distribution system and associated control devices.	High ripple voltage
Modem	UP2D.2025.C10	Enhance the reliability of communication data in the medium-voltage distribution system by using efficient, stable modems.	High latency
Remote Terminal Unit	UP2D.2025.C11	Improve the efficiency of system control and monitoring through Real-Time Units (RTUs), functioning as intermediary links between the distribution system and central control	Firmware failure
12V 17Ah Battery	UP2D.2025.C12	Ensure backup power stability for control devices during emergencies.	Thermal degradation

Monte Carlo Simulation Analysis in Determining the Impact Level

After using the Z-Score method to calculate the likelihood level, the next step is to assess the impact level through a Monte Carlo simulation. This simulation is widely used in both academia and industry to model uncertainty and risk, particularly in project management for estimating variables like cost and time. A crucial factor in ensuring accurate results is selecting the correct distribution function, as it directly affects the simulation's reliability. The following section outlines the common stages of the Monte Carlo simulation process.

The Monte Carlo simulation analyzes various risks, using parameters such as Iterations, Mean, Standard Deviation, Error, Median, and Impact > X to provide insights into risk distribution. More iterations lead to improved accuracy, with higher standard deviations indicating greater variability and uncertainty. The mean indicates the central tendency of the data, with lower values indicating lower risk and higher values indicating greater risk. The Error reflects the uncertainty in estimates, with larger values indicating higher uncertainty. Meanwhile, the Median shows the central clustering of values, while the Impact > X value highlights the likelihood and severity of extreme events.

Table 5. Risk Analysis Results Using Z-Score

Risk ID	X	*MEAN* (μ)	*STD.DEV* (σ)	*Z-Score* (Z)	*Likelihood* > X	Corporate Risk
UP2D.2025.C1	2	3.50	2.06	-0.73	76.65 %	Likely
UP2D.2025.C2	2	3.00	2.18	-0.46	67.71 %	Likely
UP2D.2025.C3	2	3.00	1.86	-0.54	70.42 %	Likely
UP2D.2025.C4	2	7.83	3.93	-1.48	93.12 %	Frequent
UP2D.2025.C5	2	4.08	1.75	-1.19	88.25 %	Frequent
UP2D.2025.C6	2	3.17	2.11	-0.55	70.99 %	Likely
UP2D.2025.C7	2	7.83	4.14	-1.41	88.25 %	Frequent
UP2D.2025.C8	20	33.17	16.32	-0.81	79.01 %	Likely
UP2D.2025.C9	1	1.33	0.95	-0.35	63.74 %	Likely
UP2D.2025.C10	10	14.08	7.02	-0.58	71.97 %	Likely
UP2D.2025.C11	5	7.42	3.76	-0.64	73.97 %	Likely
UP2D.2025.C12	2	2.83	2.03	-0.41	65.91 %	Likely

Table 6. Risk Analysis Results Using the Monte Carlo Simulation

RISK ID	X	Iteration (N)	Mean	Std.Dev. P (σ)	Error (ε)	Median	*Impact* > X	Corporate Risk
UP2D.2025.C1	2	28,513	3.50	1.97	3.50%	3.507156523	0.9381029986	Severe
UP2D.2025.C2	2	12,573	3.00	2.08	5.57%	3.005623326	0.8757029158	Severe
UP2D.2025.C3	2	9,207	3.00	1.78	5.57%	2.992792018	0.8740990023	Severe
UP2D.2025.C4	2	6,031	7.83	3.76	14.52%	7.844130472	0.9944332311	Severe
UP2D.2025.C5	2	4,434	4.08	1.68	7.57%	4.124336235	0.9642224985	Severe
UP2D.2025.C6	2	10,620	3.17	2.02	5.88%	3.207199103	0.9008998879	Severe
UP2D.2025.C7	2	6,690	7.83	3.96	14.52%	7.892522563	0.9961615201	Severe
UP2D.2025.C8	20	5,800	33.17	15.62	61.53%	33.11351085	0.9822702171	Severe
UP2D.2025.C9	1	12,244	1.33	0.91	2.47%	1.322317915	0.8305794787	Severe
UP2D.2025.C10	10	5,958	14.08	6.72	26.12%	13.92917133	0.9286114223	Severe
UP2D.2025.C11	5	6,157	7.42	3.6	13.76%	7.417504135	0.9417504135	Severe
UP2D.2025.C12	2	12,418	2.83	1.95	5.25%	2.802045591	0.8502556989	Severe

Risk Evaluation

This study evaluates risks in data-driven decision-making to determine appropriate actions based on risk levels. The goal is to develop strategies to manage uncertainties and minimize potential impacts. Table 7 shows the risk evaluation for switching equipment in medium-voltage networks, highlighting potential disruptions and their impacts. The evaluation includes key factors such as Risk ID, Likelihood of Risk, Impact of Risk, and Risk Matrix, which help prioritize mitigation efforts. All identified risks are classified as "Extreme," underscoring the need for immediate attention and intensive mitigation measures, including regular maintenance and technological upgrades.

The Analytical Hierarchy Process Analysis

The Analytical Hierarchy Process (AHP) is used for decision-making in complex situations with multiple criteria and alternatives. In this study, AHP is used to assess different types of switching equipment for the Medium Voltage Network to improve energy flow regulation and power distribution reliability. Table 8 shows the assigned priority values for each piece of equipment. To account for varying opinions among respondents, the researcher applies the geometric mean formula in the AHP analysis, combining individual assessments into a single representative value. This approach ensures more accurate and consistent decision outcomes.

After determining the priorities for each piece of equipment in the first stage, the next step is to calculate the eigenvalues, which help determine how much each piece of equipment contributes to the overall system. These eigenvalues are crucial for understanding the relative weight or significance of each piece of equipment, directly influencing decisions related to planning and resource management. The eigenvalue calculations provide a foundation for data-driven decision-making and are presented in Table 9 to support further analysis.

Once the eigenvalues are computed, the next step is to determine the maximum alpha value for each piece of equipment, which assesses how much each component contributes to overall performance based on established priorities. Identifying these values is essential for optimizing resource allocation and maximizing system efficiency. The results are shown in Table 10. Using the Analytic Hierarchy Process (AHP), the priorities for each piece of equipment are determined, yielding a ranking that reflects their relative importance. These results are presented in detail in Table 11. This process involves expert judgment, pairwise comparisons between equipment, principal eigenvector calculations to determine priority weights, and consistency testing of the judgment matrix. These steps ensure that maintenance decisions are made objectively, validly, and based on accountable data. The next step is to evaluate the results' consistency by determining the values shown in Table 12, ensuring the priorities are reliable for accurate decision-making.

Based on the Random Index (RI) value in Table 12, the Consistency Ratio (CR) is 0.081, indicating consistency, as it is below the 10% threshold suggested by Thomas Saaty. According to the AHP data, the Lightning Arrester is the highest-priority maintenance item, as it protects the electrical system from lightning strikes and significant damage. The next priority is the fuse cutout, which disconnects current during overcurrent faults. Following this are the Transformer, Pole Mounted Circuit Breaker, and Grounding Wire, which work together to maintain system stability, with the Grounding Wire ensuring safe current flow.

Table 7. Risk Evaluation for Switching Equipment in Medium-Voltage Networks

RISK ID	Likelihood		Impact		Risk	Matrix
	Value	Risk	Value	Risk		
UP2D.2025.C1	0.7665	Likely	0.9381029986	Severe	0.719056	Extreme
UP2D.2025.C2	0.6771	Likely	0.8757029158	Severe	0.592938	Extreme
UP2D.2025.C3	0.7042	Likely	0.8740990023	Severe	0.615541	Extreme
UP2D.2025.C4	0.9312	Frequent	0.9944332311	Severe	0.926016	Extreme
UP2D.2025.C5	0.8825	Frequent	0.9642224985	Severe	0.850926	Extreme
UP2D.2025.C6	0.7099	Likely	0.9008998879	Severe	0.639549	Extreme
UP2D.2025.C7	0.8825	Frequent	0.9961615201	Severe	0.879113	Extreme
UP2D.2025.C8	0.7901	Likely	0.9822702171	Severe	0.776092	Extreme
UP2D.2025.C9	0.6374	Likely	0.8305794787	Severe	0.529411	Extreme
UP2D.2025.C10	0.7197	Likely	0.9286114223	Severe	0.668322	Extreme
UP2D.2025.C11	0.7397	Likely	0.9417504135	Severe	0.696613	Extreme
UP2D.2025.C12	0.6591	Likely	0.8502556989	Severe	0.560404	Extreme

Table 8. The priority of maintenance for Switching Equipment in Medium-Voltage Networks.

Equipment Name	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
Lightning Arrester (C1)	1.00	3.16	3.16	5,00	8.89	8.89	5.00	3.00	8.78	8.78	7.00	8.64
Fuse Cutout (C2)	0.32	1.00	3.00	3,00	9.00	9.00	3.00	5.00	9.00	9.00	7.00	9.00
Potential Transformer (C3)	0.32	0.33	1.00	3,00	8.89	8.89	7.00	3.00	5.17	5.17	3.00	5.17
Pole Mounted Circuit Breaker (C4)	0.20	0.33	0.33	1,00	8.56	8.56	8.56	3.16	3.16	5.00	3.44	3.44
Control Cable (C5)	0.11	0.11	0.11	0,12	1.00	0.31	0.31	0.11	0.20	0.32	0.14	0.32
Power Supply Cable (C6)	0.11	0.11	0.11	0,12	3.19	1.00	0.33	0.11	0.33	0.33	0.20	0.33
Live Line Connector (C7)	0.20	0.33	0.14	0,12	3.19	3.00	1.00	0.20	0.50	0.50	0.33	0.50
Ground Wire (C8)	0.33	0.20	0.33	0,32	9.00	9.00	5.00	1.00	2.00	5.00	2.00	2.00
Power Supply (C9)	0.11	0.11	0.19	0,32	5.00	3.00	2.00	0.50	1.00	2.00	0.48	2.00
Modem (C10)	0.11	0.11	0.19	0,20	3.16	3.00	2.00	0.20	0.50	1.00	0.48	0.48
RTU (C11)	0.14	0.14	0.33	0,29	7.00	5.00	3.00	0.50	2.08	2.08	1.00	2.00
12V 17Ah Battery (C12)	0.12	0.11	0.19	0,29	3.16	3.00	2.00	0.50	0.50	2.08	0.50	1.00
TOTAL	**3.08**	**6.06**	**9.11**	**13,77**	**70.04**	**62.66**	**39.21**	**17.28**	**33.22**	**41.26**	**25.57**	**34.88**

Table 9. The eigenvalue for Switching Equipment in Medium-Voltage Networks

Equipment Name	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	Mean
Lightning Arrester (C1)	1.00	3.16	3.16	5.00	8.89	8.89	5.00	3.00	8.78	8.78	7,00	8.64	**0.26**
Fuse Cutout (C2)	0.32	1.00	3.00	3.00	9.00	9.00	3.00	5.00	9.00	9.00	7,00	9.00	**0.21**
Potential Transformer (C3)	0.32	0.33	1.00	3.00	8.89	8.89	7.00	3.00	5.17	5.17	3,00	5.17	**0.14**
Pole-Mounted Circuit Breaker (C4)	0.20	0.33	0.33	1.00	8.56	8.56	8.56	3.16	3.16	5.00	3,44	3.44	**0.11**
Control Cable (C5)	0.11	0.11	0.11	0.12	1.00	0.31	0.31	0.11	0.20	0.32	0,14	0.32	**0.01**
Power Supply Cable (C6)	0.11	0.11	0.11	0.12	3.19	1.00	0.33	0.11	0.33	0.33	0,20	0.33	**0.02**
Live Line Connector (C7)	0.20	0.33	0.14	0.12	3.19	3.00	1.00	0.20	0.50	0.50	0,33	0.50	**0.03**
Ground Wire (C8)	0.33	0.20	0.33	0.32	9.00	9.00	5.00	1.00	2.00	5.00	2,00	2.00	**0.08**
Power Supply (C9)	0.11	0.11	0.19	0.32	5.00	3.00	2.00	0.50	1.00	2.00	0,48	2.00	**0.04**
Modem (C10)	0.11	0.11	0.19	0.20	3,16	3.00	2.00	0.20	0.50	1.00	0,48	0.48	**0.03**
RTU (C11)	0.14	0.14	0.33	0.29	7,00	5.00	3.00	0.50	2.08	2.08	1,00	2.00	**0.05**
12V 17Ah Battery (C12)	0.12	0.11	0.19	0.29	3,16	3.00	2.00	0.50	0.50	2.08	0,50	1.00	**0.03**

Comparison of This Study with Previous Research

Previous studies [15, 42, 18] primarily focused on Risk-Based Maintenance (RBM) combined with the Analytical Hierarchy Process (AHP) for assessing risks and determining maintenance priorities, often using fuzzy logic or static models without integrating predictive analytics. In contrast, this study introduces a more advanced methodology by integrating AHP with Z-scores and Monte Carlo simulations, enabling predictive maintenance, forecasting future risks, and quantifying their impacts over time. This study also enhances risk analysis by using Z-score analysis to calculate failure probabilities in a more objective, quantitative manner and by adding a probabilistic dimension through Monte Carlo simulations, enabling risk prediction. Unlike previous studies, which relied heavily on expert judgment and historical data for maintenance task prioritization, this study uses predictive risk models to rank equipment based on both historical failure data and projected future failures. This dynamic, data-driven prioritization is a significant improvement over traditional methods, with components such as Lightning Arrester and Fuse Cutout being prioritized. In terms of practical impact, this study uses a predictive model to forecast potential failures before they occur, enabling better resource allocation and more effective mitigation strategies. It has been proven to reduce downtime, extend equipment lifespan, and significantly improve system reliability compared to reactive models.

$$GM = \sqrt[n]{X_1 X_2 \ldots . X_n} = exp\left(\sum_{i=1}^{n} \frac{In(X_1)}{n}\right) for\ x > 0 \quad (8)$$

Table 10. Alpha max value for Switching equipment in Medium-Voltage Networks

Equipment Name	Weight	Percentage	Alpha max
Lightning Arrester (C1)	0.26	26.04%	14.33
Fuse Cutout (C2)	0.21	20.62%	14.55
Potential Transformer (C3)	0.14	13.78%	14.19
Pole Mounted Circuit Breaker (C4)	0.11	11.15%	13.83
Control Cable (C5)	0.01	1.15%	12.91
Power Supply Cable (C6)	0.02	1.56%	12.39
Live Line Connector (C7)	0.03	2.74%	12.62
Ground Wire (C8)	0.08	8.13%	12.89
Power Supply (C9)	0.04	3.78%	13.08
Modem (C10)	0.03	2.65%	12.87
RTU (C11)	0.05	5.19%	13.04
12V 17Ah Battery (C12)	0.03	3.21%	13.19

Table 11. Maintenance priority percentages using the Analytical Hierarchy Process method

Number	Equipment Name	Percentage Priority
1	Lightning Arrester (C1)	26.04%
2	Fuse Cutout (C2)	20.62%
3	Potential Transformer (C3)	13.78%
4	Pole Mounted Circuit Breaker (C4)	11.15%
5	Ground Wire (C8)	8.13%
6	RTU (C11)	5.19%
7	Power Supply (C9)	3.78%
8	12V 17Ah Battery (C12)	3.21%
9	Live Line Connector (C7)	2.74%
10	Modem (C10)	2.65%
11	Power Supply Cable (C6)	1.56%
12	Control Cable (C5)	1.15%

Table 12. Analytic Hierarchy Process Consistency

Consistency Index (CI)	Random Index (RI)	Consistency Ratio (CR)
0.120355033	1.48	0.08132096827

CONCLUSION

Implementing a risk-based predictive maintenance model for Medium Voltage Network (MVN) switching equipment using the Analytical Hierarchy Process (AHP) provides a structured approach to prioritizing maintenance activities. By combining the Z-score method for risk assessment with Monte Carlo simulation for impact assessment, this study presents a comprehensive framework for maintenance decision-making. The AHP method, when integrated with risk assessment tools, helps identify high-priority components requiring immediate attention, ensuring efficient resource allocation and reducing the risk of system failures. However, while data from the SRIKANDI application provides valuable insights into disturbance frequencies, it cannot determine maintenance priorities in isolation. It lacks crucial factors such as potential impacts and major failures. Expert judgment is essential to account for factors such as equipment age, operational conditions, and failure history that are not captured in the application. This research highlights the importance of prioritizing critical equipment, including the Lightning Arrester and Fuse Cut Out, which are key to maintaining system reliability. By leveraging AHP, the study contributes to the development of more effective and cost-efficient maintenance strategies, leading to optimized scheduling, reduced downtime, and extended equipment lifespan. The findings of this study show that by focusing maintenance efforts on critical components, scheduling can be more targeted and strategic, while avoiding resource waste on less important equipment. Proper maintenance of these high-priority components is essential to minimize downtime and extend equipment lifespan, which ultimately contributes directly to operational cost efficiency and

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