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Pareto Analysis and Failure Mode and Effect Analysis (FMEA) of Central Melaka Power Distribution Plant Maintenance Strategies

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Abstract

This study explores the creation and use of a successful maintenance plan for the Melaka electricity distribution facility. The streamlining of maintenance activities is crucial because power distribution plays a crucial role in guaranteeing that consumers receive an uninterrupted supply of electricity. The study takes a methodical approach, integrating qualitative and quantitative techniques to determine the state-of-the-art maintenance procedures, evaluate their efficacy, and suggest improvements. The study determines areas where the current maintenance regime needs to be improved by thoroughly analyzing historical maintenance data, equipment reliability, and failure patterns. The goal of the suggested maintenance plan is to improve the Melaka power distribution plant's dependability, effectiveness, and safety. The strategy's alignment of maintenance activities with asset criticality, operational requirements, and business objectives guarantees cost-effective maintenance practices and appropriate resource allocation. Pareto analysis has been performed to assess the criticality and the most frequent maintenance issues that arose in the plant. Failure Mode and Effect (FMEA) has been deployed in strategizing the most appropriate strategies based on severity, detectability and occurrence. The outcome of the framework proposed is to enhance plant reliability, reduce maintenance cost and improve asset lifecycle. Remote Terminal Unit (RTU) as a critical element in power distribution plant maintenance has been highlighted in the assessment in this study.

Keywords

Pareto Analysis, Power Distribution Plant, FMEA, Maintenance Strategy

1. Introduction

This study explores the creation and use of a successful maintenance plan for the Melaka electricity distribution facility. The streamlining of maintenance activities is crucial because power distribution plays a crucial role in guaranteeing that consumers receive an uninterrupted supply of electricity. The study takes a methodical approach, integrating qualitative and quantitative techniques to determine the state-of-the-art maintenance procedures, evaluate their efficacy, and suggest improvements. The study determines areas where the current maintenance regime needs to be improved by thoroughly analyzing historical maintenance data, equipment reliability, and failure patterns [1]. To predict equipment failures and prioritize maintenance operations, it makes use of modern reliability-centered maintenance (RCM) approaches and predictive maintenance instruments like vibration analysis, thermography, and oil analysis. Furthermore, the study also highlights how crucial it is to incorporate a condition-based maintenance (CBM) strategy that makes use of Internet of Things (IoT) and real-time monitoring systems. This makes it easier to perform preventative maintenance, which lowers downtime and lengthens the life of important assets. Additionally, the study emphasizes how important it is to train and upskill maintenance staff to help them adjust to new technology and procedures. In summary, the goal of the suggested maintenance plan is to improve the Melaka power distribution plant's dependability, effectiveness, and safety. The strategy's alignment of maintenance activities with asset criticality, operational requirements, and business objectives guarantees cost-effective maintenance practices and appropriate resource allocation. By putting this plan into practice, it should be possible to satisfy the growing demands of the quickly expanding region by reducing equipment failures, minimizing operating disruptions, and improving overall plant performance [2].

2. Literature Review

Over the past few decades, the Malaysian state of Melaka has seen tremendous growth in both the industrial and residential sectors. Due to this expansion, there is a greater need than ever for a steady and dependable supply of electricity, which makes Melaka's power distribution plant an essential piece of infrastructure. This plant's smooth functioning is crucial for both supplying the region's industrial and commercial sectors with electricity and for satisfying the energy needs of its residents. Power distribution system maintenance is a difficult and varied undertaking. It entails a variety of tasks, including overhauls, corrective actions, and preventive measures in addition to routine inspections [3]. Traditionally, many power distribution facilities, including the Melaka plant, have used the time-based maintenance approach, which is based on set intervals for maintenance activities. Unfortunately, this strategy frequently results in higher maintenance costs, more downtime, and wasteful use of resources. According to technological improvements and an increasing awareness of asset reliability and failure patterns, there has been a paradigm shift in maintenance techniques in recent years toward more proactive and predictive approaches [4]. Predictive maintenance, condition-based maintenance, and reliability-centered maintenance (RCM) are becoming the go-to approaches because they can lower operating hazards, increase equipment longevity, and improve maintenance procedures [5]. The electricity distribution plant in Melaka has not adopted these complex maintenance procedures despite their acknowledged benefits. A thorough investigation is required to evaluate the existing maintenance procedures, spot any weaknesses and areas for development, and create a customized maintenance plan that is in line with the unique requirements and difficulties faced by the Melaka power distribution facility. In addition, the growing intricacy of the power distribution network, in conjunction with deteriorating infrastructure and labor shortages, highlights the necessity of implementing a methodical approach to maintenance strategy deployment [6].

This study is to investigate the implementation of an optimal maintenance approach for the Melaka power distribution plant considering these factors. The study aims to improve the sustainability, efficiency, and dependability of the power distribution infrastructure by bridging the gap between traditional and advanced maintenance techniques and utilizing technological breakthroughs. This will support the ongoing expansion and development of the region. Since power distribution plants are the foundation of the electrical supply chain, it is essential to maintain and improve their longevity to meet population energy needs and promote economic growth [7]. Deploying maintenance strategies is essential to accomplishing these goals because it offers a disciplined framework for controlling and maintaining power distribution facilities' equipment and infrastructure [8]. Throughout the years, the literature on maintenance techniques in the power industry has changed significantly, with an increasing focus on initiative-taking, data-driven, and sustainable approaches to maintenance management [9].

For efficient maintenance planning and risk mitigation techniques in power distribution facilities, it is essential to comprehend the failure mechanisms of both mechanical and electrical systems [10]. The following are a few typical failure modes linked to electrical and mechanical issues or upkeep at power distribution plants:

2.1. Mechanical Failure Modes

Mechanical failure mechanisms in power plant distribution systems provide serious difficulties that might impair system dependability and cause operations to be disrupted. One typical mechanical failure mode is bearing failure, which occurs when problems like wear, contamination, or a lack of lubrication affect the bearings that support spinning shafts and other components [11]. Increased vibration levels, device failure, and catastrophic damage can result from this. In addition, common problems include tooth failure and gear wear, which are frequently brought on by overloading, improper lubrication, or misalignment and can reduce performance and result in equipment failures [12]. Risks include structural decay and corrosion, which erode the integrity of infrastructure and raise the possibility of failures. Furthermore, as they can result in fluid loss, pollution, and decreased system performance, seal and gasket leaks are a cause for concern [13]. It takes initiative-taking measures to address these mechanical failure modes. Initiative-taking maintenance techniques, like routine inspections, condition monitoring, and timely replacements, are necessary to address these mechanical failure mechanisms and maintain the dependability and lifespan of power plant distribution systems.

2.2. Electrical Failure Modes

Electrical failure modes in power plant distribution systems refer to a variety of potential problems that could impair system reliability and cause operations to be disrupted. Insulation breakdown is a common failure event that results in short circuits or arcing because dielectric materials are unable to tolerate electrical stress. Another frequent problem is overloading of electrical circuits and components, which is caused by high current flow and overheating from increased loads or insufficient cooling [14]. Arc flash events are extremely dangerous. They happen when an electric arc forms between wires or against the ground, generating a great deal of heat and light and damaging equipment and causing significant injury. Distribution networks are also hampered by power quality problems and voltage variations, which impair equipment functionality [15]. To guarantee the dependability and security of power plant distribution systems, addressing these electrical failure types necessitates a comprehensive maintenance strategy that includes insulation testing, load monitoring, arc flash mitigation techniques, and power quality monitoring.

3. Methodology

A thorough approach to comprehending the complexities of the distribution system and creating efficient maintenance strategies suited to its unique requirements is part of the research technique for maintenance strategy implementation on Melaka's power plant distribution. Using a mixed-methods approach, this study aims to close the gap between theoretical frameworks and real-world application. Firstly, a comprehensive examination of the literature will be done to learn more about current maintenance approaches and how they relate to power plant distribution systems. After that, quantitative techniques like survey data collecting and maintenance record analysis will be used to evaluate the distribution system's current condition and indicate areas that require improvement. The use of qualitative techniques, such as stakeholder and maintenance staff interviews, will yield insightful viewpoints on the opportunities and difficulties associated with implementing maintenance strategies. The integration of both quantitative and qualitative data would facilitate the creation of a comprehensive maintenance plan tailored to the needs of Melaka's power plant distribution system.

3.1. Methods of Maintenance Strategy

In the realm of maintenance strategy implementation in a power distribution facility, the combination of Failure Mode and Effects Analysis (FMEA) Pareto Analysis as shown in **Figure 1** and **Figure 2**. with Pareto Analysis presents a robust methodology for enhancing maintenance operations [16]. FMEA is employed to systematically recognize potential failure modes in the components of the facility and evaluate their impact on operational performance. This systematic approach aids in prioritizing the most critical failure modes based on severity, occurrence, and detection ratings, resulting in a Risk Priority Number (RPN) assigned to each failure mode. Following the prioritization of failure modes, Pareto Analysis is utilized to pinpoint the vital few important failures/problems that are responsible for many issues, in alignment with the 80/20 principle [17]. This analytical method brings to light the most crucial concerns that, if addressed, can lead to substantial enhancements in both reliability and effectiveness. By concentrating on these pivotal areas, resources can be efficiently allocated to achieve maximum impact. This approach guarantees that decision-making is thorough and well-balanced, considering all pertinent factors. The integration of FMEA and AHP

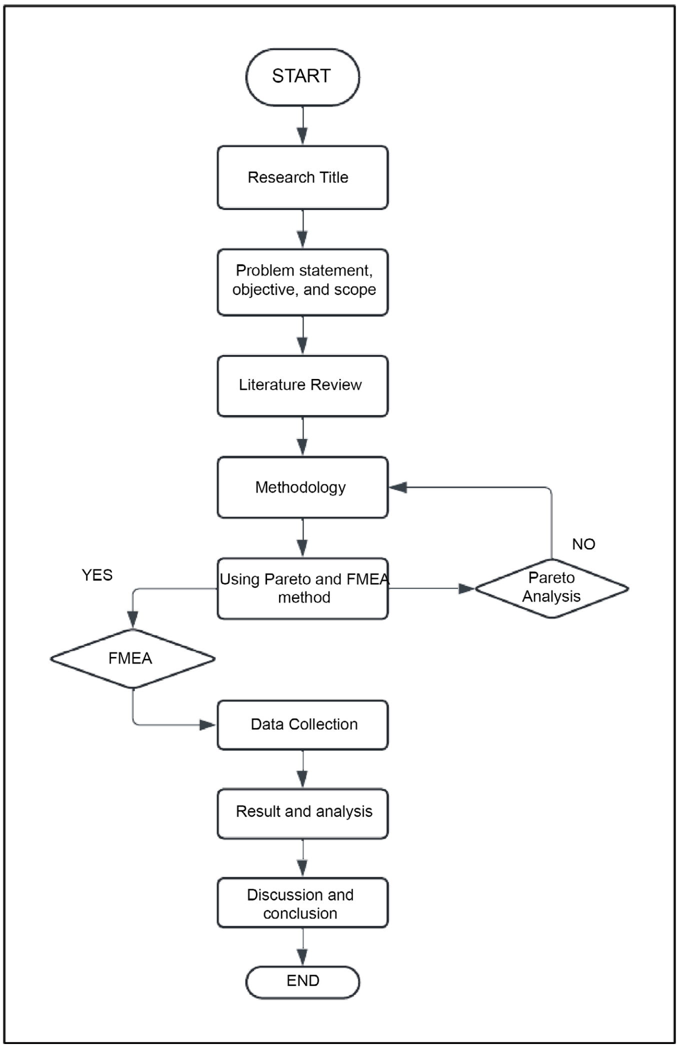

Figure 1. Flowchart for methodology.

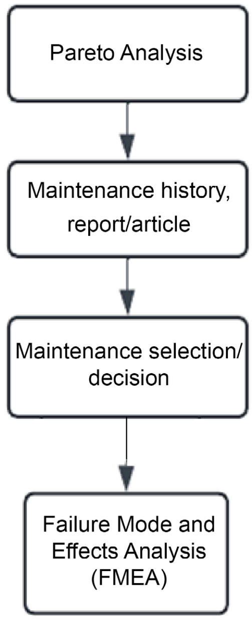

Figure 2. Flowchart for Pareto Analysis and Failure Mode and Effect Analysis (FMEA).

with Pareto Analysis promotes a data-centric, prioritized strategy for maintenance activities [18]. This consolidated approach empowers power distribution facilities to diminish risks, elevate system dependability, minimize downtime, and optimize maintenance assets, ultimately leading to a more effective and resilient operation.

3.2. Pareto Analysis

Using Pareto Analysis to develop a maintenance strategy for a power distribution plant entails several organized processes to ensure that maintenance activities are prioritized effectively. The first step in identifying all potential failure modes and their frequencies is data gathering; maintenance records, failure logs, and performance reports are acquired. The impact of each failure mode on plant operations is then ascertained by classifying and quantifying this data, considering aspects like downtime, repair costs, and safety concerns. Plotting the failure modes on a Pareto chart is how the Pareto Principle is implemented after the data has been organized. The cumulative impact of each failure mode is usually shown in this chart in descending order. The horizontal axis lists the failure modes, while the vertical axis shows the frequency or impact (such as cost, downtime) of failures. Next, the research pinpoints the key few, which are typically about 20% of the failure modes and account for 80% of the issues. The maintenance approach concentrates on these high-impact failure types in accordance with this prioritization. Preventive maintenance, more frequent inspections, or component upgrades for the most important portions are some possible courses of action. By focusing on the most important problems, this targeted strategy makes sure that maintenance resources are used effectively, improving reliability, lowering unplanned failures, and maximizing maintenance costs [19].

3.3. Failure Mode and Effects Analysis (FMEA)

A methodical technique called Failure Mode and Effect Analysis (FMEA) is employed to determine probable failure modes in a system, product, or process and evaluate the consequences of those failures. By disassembling complex systems into their component parts and examining the potential failure modes of each part, Failure Mode and Effect Analysis (FMEA) assists companies in anticipating problems and improving dependability. Failure modes can be determined for each equipment and the system behavior can be then examined from the viewpoint of reliability via failure modes and effects analysis (FMEA) [20]. Failure modes are failure of one or a combination of network equipment that cause the system to malfunction or collapse. FMEA, on the other hand, is a procedural method to analyze failure modes and their effects on reliability. These steps include defining the system, identifying potential failure modes in the system, determining the effects and consequences of the occurrence of each failure mode, ranking the negative effects, determining all potential sources of failure modes, determining tracking methods, identifying potential sources of failure modes, and eventually using methods to eliminate the root of the failure or reduce the sensitivity of the system performance to the failures.

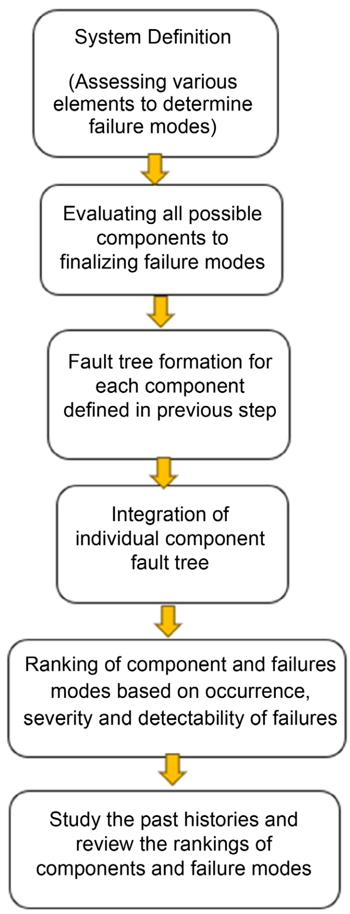

Figure 3. The process of identifying and estimating equipment failure rates.

Figure 3 illustrates the mechanism for identifying the failure mode and estimating its rate. As shown in **Figure 3**, in the first step (failure tree), it is necessary, for example for a power transformer, to include the components such as bushing, coil, tank, pulse changer, oil, cooler, and core. A failure tree must be drawn for each of these components separately. Finally, by selecting an appropriate estimation model, the failure rate is calculated and incorporated in the reliability assessments, maintenance planning, and related applications.

4. Results

It is predicted that a power distribution plant's maintenance strategy deployment that incorporates FMEA (Failure Modes and Effects Analysis) and Pareto Analysis will result in notable increases in system reliability and operational efficiency. By methodically identifying possible failure modes and assessing their effects, FMEA makes it possible to rank maintenance jobs according to Risk Priority Numbers (RPNs). The maintenance crew can concentrate on the most important 20% of failure modes, which account for 80% of the issues, by doing Pareto Analysis on these RPNs. This combination strategy guarantees that maintenance funds are allocated to the most critical locations, which lowers downtime, maximizes maintenance savings, and improves the power distribution plant's overall performance.

4.1. Results Pareto Analysis of Protection and Automation

In the deployment of maintenance strategies for power distribution plants, understanding and prioritizing Protection and Automation data through tools like Failure Mode and Effects Analysis (FMEA) and Pareto analysis are crucial steps. The Failure Mode and Effect Analysis (FMEA) methodology facilitates a methodical process for recognizing possible failure modes in the Automation and Protection systems, evaluating their impact, and estimating the probability of their occurrence. With the help of this technique, maintenance staff can proactively fix vulnerabilities before they become serious malfunctions. Pareto analysis highlights the most important factors that could lead to possible failures, which is a supplement to FMEA. The bulk of risks or failures may be attributed to a critical few variable, thus maintenance resources can be spent effectively and efficiently. Pareto analysis is useful in identifying the most frequent failure modes or problems that could jeopardize the power distribution system's dependability and safety when applied to data related to protection and automation. By offering an organized method for allocating resources and prioritizing tasks according to the protection and automation systems' level of criticality, the combination of FMEA and Pareto analysis improves the process of implementing maintenance strategies. This strategy improves overall system longevity and performance while reducing the chance of unplanned downtime. Power distribution plants can ultimately guarantee the highest levels of operational efficiency, safety, and dependability by utilizing these approaches. **Table 1** tabulates the number of fault for protection and automation; meanwhile **Table 2** tabulates cumulative number of faults for protection and automation. **Figure 4** depicts Pareto analysis of protection and automation.

Table 1. Number of fault for protection and automation.

No	Fault Category	Number of Fault
1	Backup Relay	6
2	Battery bank & accessories	16
3	BCU/BLR/IOIED	17
4	Charger	8
5	Communication	10
6	Communication/lntertrip scheme	6
7	Control Relay	4
8	CT Circuit	3
9	Disturbance recorder	10
10	Fascia/Atarm/SCADA/SCS Indication	7
11	Gateway	70
12	HMVSLOI	12
13	Instrument meter	5
14	Main Relay	12
15	Panel	3
16	Panel Inspection	8
17	Pole Discordance Scheme	5
18	Primary Aux Component failure	3
19	Protection Aux component failure	3
20	Proxy Server	9
21	RTCC panel	4
22	RTU	87
23	Scheme failure	5
24	SLC/Base	41
25	Special scheme IED	1
26	Supervision Relay	2
27	VT circuit	6
28	Scheme Drawings	3
	Total Number of Faults	366

Table 2. Cumulative number of faults for protection and automation.

No	Fault	Number of Fault	Relative Number (%)	Cumulative number of faults	Cumulative relative number (%)
1	RTU	87	23.77	87	23.77
2	Gateway	70	19.13	157	42.9
3	SLC/Base	41	11.2	198	54.1
4	BCU/BLR/IOIED	17	4.64	215	58.74
5	Battery bank & accessories	16	4.37	231	63.11
6	HMI/SLOI	12	3.28	243	66.39
7	Main Relay	12	3.28	255	69.67
8	Communication	10	2.73	265	72.4
9	Disturbance recorder	10	2.73	275	75.14
10	Proxy Server	9	2.46	284	77.6
11	Charger	8	2.19	292	79.78
12	Panel Inspection	8	2.19	300	81.97
13	Fascia/Alarm/SCADA/SCS Indication	7	1.91	307	83.88
14	Backup Relay	6	1.64	313	85.52
15	Communication/Intertrip scheme	6	1.64	319	87.16
16	Panel inspection	6	1.64	325	88.8
17	Instrument meter	5	1.37	330	90.16
18	Pole Discordance scheme	5	1.37	335	91.53
19	Scheme failure	5	1.37	340	92.9
20	Control Relay	4	1.09	344	93.98
21	RTCC Panel	4	1.09	348	95.08
22	CT Circuit	3	0.82	351	95.9
23	Panel	3	0.82	354	96.72
24	SLC/Base	3	0.82	357	97.54
25	Primary Aux Component failure	3	0.82	360	98.36
26	Protection Aux component failure	2	0.55	362	98.91
27	Supervision Relay	2	0.55	364	99.73
28	Special scheme IED	1	0.27	365	100

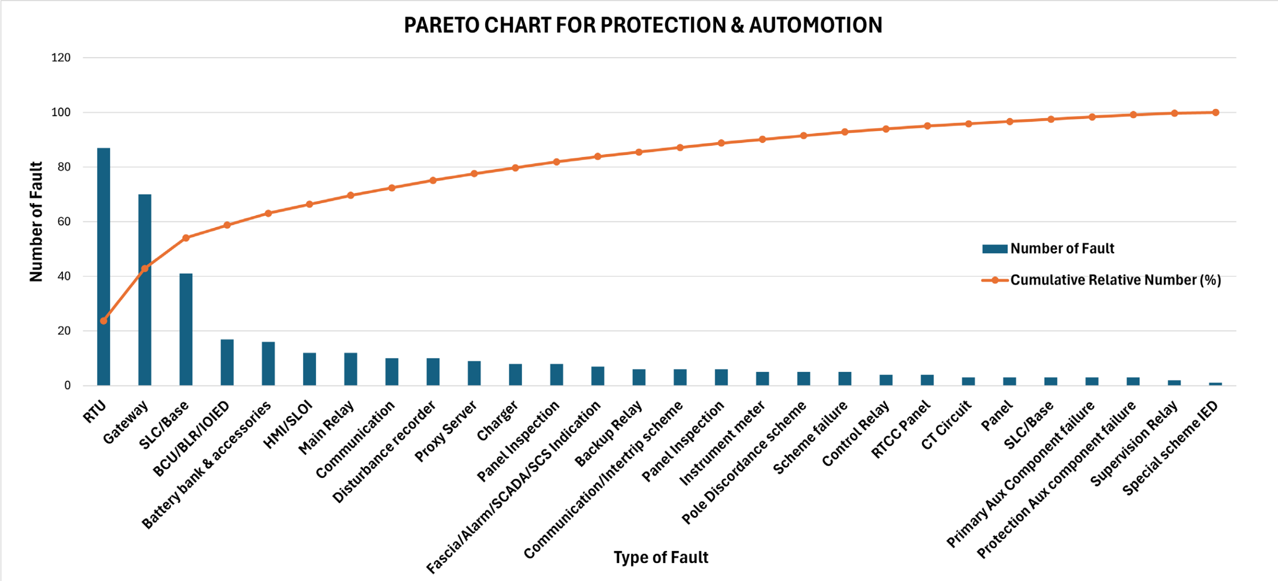

Figure 4. Pareto analysis of protection and automation.

4.2. Results Pareto Analysis of High-Voltage Direct Current (HVDC)

High-Voltage Direct Current (HVDC) systems are essential for transporting electricity over long distances with low losses in the field of power distribution. However, a strong maintenance plan is necessary to guarantee the dependability and effectiveness of HVDC systems. The application of Failure Modes and Effects Analysis (FMEA) in conjunction with Pareto analysis is a useful method for creating such a plan. Pareto analysis is used to rank failure modes according to how they affect system dependability and performance after they have been found. Maintenance teams can direct their resources and efforts where they are most needed by using Pareto analysis, which identifies the critical few failure modes that account for the bulk of system failures. Targeted maintenance plans can be developed by utilizing FMEA Pareto analysis for HVDC systems in the context of maintenance strategy implementation on power distribution plants. Maintenance efforts can be improved to improve system dependability, reduce downtime, and guarantee a continuous supply of energy by focusing on the most significant failure scenarios first. In addition to increasing overall system safety and operational efficiency, this proactive strategy also lowers costs. As per Table 3 is the tabulated for faults category with their corresponding number of faults for HVDC. Meanwhile Table 4 tabulates Cumulative Number of Fault of HVDC and Figure 5 depicts the Pareto Analysis of HVDC respectively.

Table 3. Number of Fault for HVDC.

No	Fault	Number of Fault
1	AC Filter-Air Core Reactor	2
2	AC filter-Aux relay	1

Continued

3	AC Filter-Capacitor Can	5
4	AC Filter-Connector	4
5	AC Filter-CT Circuit	2
6	AC Filter-Earth Tape	2
7	AC Filter-Fascia	1
8	AC Filter-Fittings	1
9	AC Filter-HMI	1
10	AC Filter-Housing	2
11	AC Filter-Measuring Module	2
12	AC Filter-Post Insulator	3
13	AC Filter-Simadyn D	14
14	AC Filter-Trip Circuit	3
15	BCU/SU200	19
16	Building-Aircond	2
17	Building-Battery Room	9
18	Building-Ceiling	2
19	Building-Checquered Plate	1
20	Building-Door	2
21	Building-Exhaust fan	1
22	Building-Fire Alarm Panel Faulty	1
23	Building-Fire Fighting Fitting	4
24	Building-Floor	1
25	Building-Handrail	1
26	Building-Hoist Crane	1
27	Building-Lighting	1
28	Building-Roller Shutter	1
29	Building-Roof	2
30	Building-Settlement	1
31	Building-Structure	1
32	Building-Switch	1
33	Building-Toilet	3
34	Building-Wall	1
35	Building-Water Pump	1
36	Building-Water Supply Fitting	1
37	Building-Water Tank	4
38	Building-Window	1
39	Building-Wiring	3

Continued

40	Capbank-Air Core Reactor	2
41	Capbank-Capacitor Can	5
42	Capbank-Connector	2
43	Capbank-Earth Tape	1
44	Capbank-Fittings	2
45	Capbank-Housing	3
46	Capbank-Post Insulator	1
47	Compound-Superfluous Material at site	1
48	Converter Tx-Aux Relay	1
49	Converter Tx-Backup relay	2
50	Converter Tx-Fascia	7
51	Converter Tx-HMI	3
52	Converter Tx-LED Indication	1
53	Converter Tx-Main Relay	2
54	Converter Tx-OP2	1
55	Converter Tx-Tripping Relay	1
56	Converter Tx-Tx Guard relay	1
57	DC Filter-Air Core Reactor	1
58	DC Filter-Capacitor Can	2
59	DC Filter-Connector	1
60	DC Filter-CT Circuit	3
61	DC Filter-Earth Tape	2
62	DC Filter-Fittings	2
63	DC Filter-Housing	2
64	DC Filter-Measuring Module	2
65	DC Filter-Post Insulator	1
66	DC Filter-Simadyn D	3
67	DC Protection	2
68	DC Protection-Aux Relay	1
69	DC Protection-communication	2
70	DC Protection CT Circuit	3
71	DC Protection-HMI	3
72	DC protection-Measuring Module	2
73	DC Protection-Simadyn D	1
74	DC Protection-Trip circuit	3
75	Others	7
76	Panel Inspection	1

Continued

77	Perimeter-Access Road	2
78	Perimeter-Drainage	1
79	Perimeter-Fencing	1
80	Perimeter-Guard House	1
81	Perimeter-Piping	1
82	Perimeter-Septic Tank	1
83	Perimeter-Water Supply Fittings	1
84	Perimeter-Water Tank	1
85	Pole control-Aux relay	1
86	Pole control-Communication	2
87	Pole control-CT Circuit	3
88	Pole control-HMI	3
89	Pole control-Measuring Module	1
90	Pole control-Simadyn D	2
91	Pole control-trip circuit	3
93	Primary Aux Component Failure	4
94	Protection Aux Component Failure	3
95	Schematic Drawings	3
96	Smoothing reactor	2
97	Switchyard-Cable Slab	1
98	Switchyard-Chainlink Fencing	2
99	Switchyard-Detachable Fencing	1
100	Switchyard-Oil Pit Grating	2
101	Switchyard-Oil Pit Minimum water level	1
102	Switchyard-Settlement	2
103	Switchyard-Signage	1
104	Switchyard-Spot Light	1
105	Switchyard-Stone Chipping	1
106	Switchyard-Street Lighting	1
107	Switchyard-Structure	1
108	Switchyard-Structure/Plinth	1
109	Switchyard-Water Pump	2
110	Thyristor Valve	5
111	Transformer-Bushing	1
112	Transformer-Bushing HV	2
113	Transformer-Conservator/Main Tank	3
114	Transformer-Conservator/Main tank/Cable box	2

Continued

115	Transformer-Conservator/Main tank/Cable box/Bushing	1
116	Transformer-Earth Tape	2
117	Transformer-Fans/Motors/Pumps	1
118	Transformer-Fittings	1
119	Transformer-Gauge	1
120	Transformer-Insulating oil	1
121	Transformer-Label	1
122	Transformer-Local Control Panel	1
123	Transformer-Main tank	1
124	Transformer-Multicore Cable	1
125	Transformer-OMS DGA	2
126	Transformer-Open bushing AIS insulation type	1
127	Transformer-Panel and Kiosk	2
128	Transformer-Radiator/ Valves	2
129	Transformer-Transformer Guard OLTC Oil Surge Relay	1
130	Transformer/VSR-Tap Changer	2
131	Valve Cooling	8
	Total Number of Faults	391

Table 4. Cumulative Number of Fault of HVDC.

No	Fault	Number of Fault	Relative Number (%)	Cummulative number of faults	Cummulative relative percentage (%)
1	Thyristor Valve	25	6.39	25	6.39
2	BCU/SU200	19	4.86	44	11.25
3	AC Filter-Simadyn D	14	3.58	58	14.83
4	AC Filter-HMI	13	3.32	71	18.16
5	Converter Tx-HMI	13	3.32	84	21.48
6	DC protection-HMI	13	3.32	97	24.81
7	Pole control-HMI	13	3.32	110	28.13
8	Transformer-Panel and Kiosk	11	2.81	121	30.95
9	Converter Tx-Main Relay	9	2.30	130	33.25
10	Valve Cooling	8	2.05	138	35.29
11	AC Filter-Fascia	8	2.05	146	37.34
12	Converter Tx-Fascia	7	1.79	153	39.13
13	DC Filter-Simadyn D	7	1.79	160	40.92

Continued

14	DC Protection-Simadyn D	7	1.79	167	42.71
15	Pole Control-Simadyn D	7	1.79	174	44.50
16	Panel Inspection	6	1.53	180	46.04
17	AC Filter-Capacitor Can	5	1.28	185	47.31
18	Building-Roof	5	1.28	190	48.59
19	Capbank-Capacitor Can	5	1.28	195	49.87
20	DC Filter-Capacitor Can	5	1.28	200	51.15
21	Building-Floor	4	1.02	204	52.17
22	Primary Aux Component Failure	4	1.02	208	53.20
23	AC Filter-CT Circuit	3	0.77	211	53.96
24	AC Filter-Housing	3	0.77	214	54.73
25	AC Filter-Trip Circuit	3	0.77	217	55.50
26	Building-Wall	3	0.77	220	56.27
27	Capbank-Housing	3	0.77	223	57.03
28	DC Filter-CT Circuit	3	0.77	226	57.80
29	Dc Filter-Housing	3	0.77	229	58.57
30	DC protection-communication	3	0.77	232	59.34
31	DC Protection CT Circuit	3	0.77	235	60.10
32	DC Protection-Trip circuit	3	0.77	238	60.87
33	Others	3	0.77	241	61.64
34	Pole control-Communication	3	0.77	244	62.40
35	Pole control-CT Circuit	3	0.77	247	63.17
36	Pole control-trip circuit	3	0.77	250	63.94
37	Protection Aux Component Failure	3	0.77	253	64.71
38	Schematic Drawings	3	0.77	256	65.47
39	Transformer-Fans/Motors/Pumps	3	0.77	259	66.24
40	Transformer-Gauge	3	0.77	262	67.01
41	Transformer/VSR-Tap Changer	3	0.77	265	67.77
42	AC Filter-Air Core Reactor	2	0.51	267	68.29
43	AC Filter-Earth Tape	2	0.51	269	68.80
44	AC Filter-Fittings	2	0.51	271	69.31
45	AC Filter-Measuring Module	2	0.51	273	69.82
46	Building-Aircond	2	0.51	275	70.33
47	Building-Battery Room	2	0.51	277	70.84

Continued

48	Building-Ceiling	2	0.51	279	71.36
49	Building-Checquered Plate	2	0.51	281	71.87
50	Building-Door	2	0.51	283	72.38
51	Building-Handrail	2	0.51	285	72.89
52	Building-Hoist Crane	2	0.51	287	73.40
53	Building-Settlement	2	0.51	289	73.91
54	Building-Structure	2	0.51	291	74.42
55	Building-Window	2	0.51	293	74.94
56	Capbank-Air Core Reactor	2	0.51	295	75.45
57	Capbank-Earth Tape	2	0.51	297	75.96
58	Capbank-Fittings	2	0.51	299	76.47
59	Compound-Superflous Material at site	2	0.51	301	76.98
60	Converter Tx-Backup relay	2	0.51	303	77.49
61	Converter Tx-OP2	2	0.51	305	78.01
62	DC Filter-Air Core Reactor	2	0.51	307	78.52
63	DC Filter-Earth Tape	2	0.51	309	79.03
64	DC Filter-Fittings	2	0.51	311	79.54
65	DC Filter-Measuring Module	2	0.51	313	80.05
66	DC Protection-Aux Relay	2	0.51	315	80.56
67	DC protection-Measuring Module	2	0.51	317	81.07
68	Pole control-Measuring Module	2	0.51	319	81.59
69	Smoothing reactor	2	0.51	321	82.10
70	Switchyard-Settlement	2	0.51	323	82.61
71	Switchyard-Structure/Plinth	2	0.51	325	83.12
72	Transformer-Bushing	2	0.51	327	83.63
73	Transformer-Earth Tape	2	0.51	329	84.14
74	Transformer-Fittings	2	0.51	331	84.65
75	Transformer-Insulating oil	2	0.51	333	85.17
76	Transformer-Label	2	0.51	335	85.68
77	Transformer-Radiator/ Valves	2	0.51	337	86.19
78	AC filter-Aux relay	1	0.26	338	86.45
79	AC Filter-Connector	1	0.26	339	86.70
80	AC Filter-Post Insulator	1	0.26	340	86.96
81	Building-Exhaust fan	1	0.26	341	87.21

Continued

82	Building-Fire Alarm Panel Faulty	1	0.26	342	87.47
83	Building-Fire Fighting Fitting	1	0.26	343	87.72
84	Building-Lighting	1	0.26	344	87.98
85	Building-Roller Shutter	1	0.26	345	88.24
86	Building-Switch	1	0.26	346	88.49
87	Building-Toilet	1	0.26	347	88.75
88	Building-Water Pump	1	0.26	348	89.00
89	Building-Water Supply Fitting	1	0.26	349	89.26
90	Building-Water Tank	1	0.26	350	89.51
91	Building-Wiring	1	0.26	351	89.77
92	Capbank-Connector	1	0.26	352	90.03
93	Capbank-Post Insulator	1	0.26	353	90.28
94	Converter Tx-Aux Relay	1	0.26	354	90.54
95	Converter Tx-LED Indication	1	0.26	355	90.79
96	Converter Tx-Tripping Relay	1	0.26	356	91.05
97	Converter Tx-Tx Guard relay	1	0.26	357	91.30
98	DC Filter-Connector	1	0.26	358	91.56
99	DC Protection	1	0.26	359	91.82
100	Perimeter-Access Road	1	0.26	360	92.07
101	Perimeter-Drainage	1	0.26	361	92.33
102	Perimeter-Fencing	1	0.26	362	92.58
103	Perimeter-Guard House	1	0.26	363	92.84
104	Perimeter-Piping	1	0.26	364	93.09
105	Perimeter-Pump	1	0.26	365	93.35
106	Perimeter-Septic Tank	1	0.26	366	93.61
107	Perimeter-Water Supply Fittings	1	0.26	367	93.86
108	Perimeter-Water Tank	1	0.26	368	94.12
109	Pole control-Aux relay	1	0.26	369	94.37
110	Switchyard-Cable Slab	1	0.26	370	94.63
111	Switchyard-Chainlink Fencing	1	0.26	371	94.88
112	Switchyard-Detachable Fencing	1	0.26	372	95.14
113	Switchyard-Oil Pit Grating	1	0.26	373	95.40
114	Switchyard-Oil Pit Minimum water level	1	0.26	374	95.65
115	Switchyard-Signage	1	0.26	375	95.91

Continued

116	Switchyard-Spot Light	1	0.26	376	96.16
117	Switchyard-Stone Chipping	1	0.26	377	96.42
118	Swithyard-Street Lighting	1	0.26	378	96.68
119	Switchyard-Structure	1	0.26	379	96.93
120	Switchyard-Water Pump	1	0.26	380	97.19
121	Transformer-Bushing HV	1	0.26	381	97.44
122	Transformer-Conservator/Main Tank	1	0.26	382	97.70
123	Transformer-Conservator/Main tank/Cable box	1	0.26	383	97.95
124	Transformer-Coservator/Main tank/Cable box/Bushing	1	0.26	384	98.21
125	Transformer-Local Control Panel	1	0.26	385	98.47
126	Transformer-Main tank	1	0.26	386	98.72
127	Transformer-Multicore Cable	1	0.26	387	98.98
128	Transformer-OMS DGA	1	0.26	388	99.23
129	Transformer-Open bushing AIS insulation type	1	0.26	389	99.49
130	Transformer-Transformer Guard OLTC Oil Surge Relay	1	0.26	390	99.74
131	DC Filter-Post Insulator	1	0.26	391	100.00

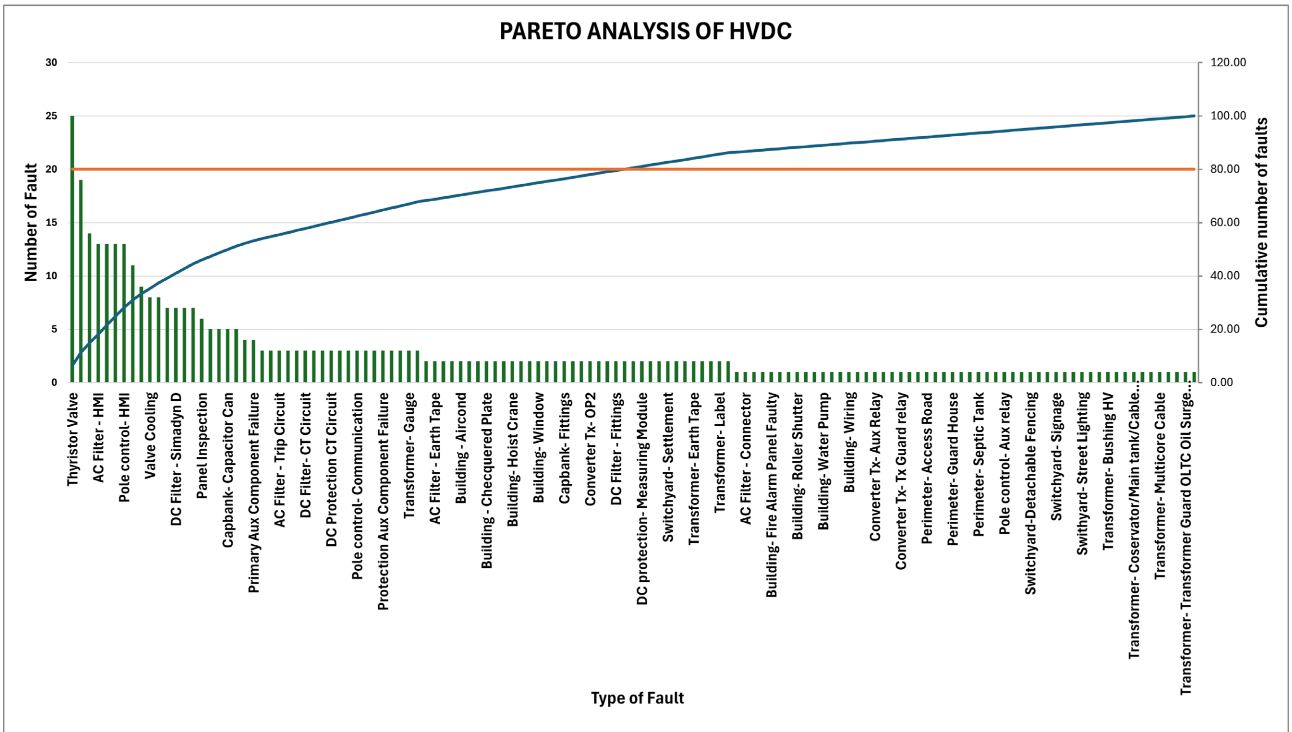

Figure 5. Pareto Analysis of HVDC.

4.3. Results FMEA of Protection and Automation

The FMEA in **Figure 6** presented six potential failure modes for a system, accompanied by their respective Risk Priority Numbers (RPNs), relative proportions, and cumulative effects. The foremost risk factor recognized is inadequate maintenance, characterized by an RPN of 200, representing 29.5% of the overall risk, and cumulatively amounting to 30%. Subsequently, errors in sensor calibration (RPN 144, 21.3%) constitute a considerable portion of the risk landscape, encompassing more than half of the total risk at 51% when combined with inadequate maintenance.

According to **Table 5** for the tabulated RPN for Remote Terminal Units, noteworthy is the substantial risk posed by incorrect installation procedures, evidenced by an RPN of 120, contributing 17.7% and elevating the cumulative risk to 69%. Failures in the Power Supply Unit (PSU), along with issues related to humidity, and component corrosion, follow suit with diminishing RPN values of 105, 63, and 45 respectively. These factors represent 15.5%, 9.3%, and 6.6% of the total risk, progressively heightening the cumulative risk to 100%. The examination indicates that prioritizing enhancements in maintenance protocols, sensor calibration, and installation practices would effectively alleviate a majority of the identified risks.

FMEA Form

Process/Product Name: REMOTE TERMINAL UNIT/ PROTECTION AND AUTOMATION

Prepared By: DR AHMAD FUAD AB GHANI

Responsible: MAINTENANCE DEPARTMENT

FMEA Date (Orig.): 23-Sep (Rev.):

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	RPN	Action Recommended	Responsibility	Actions Taken	SEVERITY (1 - 10)	OCCURRENCE (1 - 10)	DETECTION (1 - 10)	RPN
Environment	Humidity & Moisture	Corrosion of components, short cicuits, mold growth	9	High Humidity, Condensation, Water Ingress	5	Regular Inspection, Preventive Maintenance	4	180	Use of moisuture - resistance enclosure	Maintenance Team	*Environmental Monitoring*	7	3	3	63
Materials	Components corrosion	Degradation of components, leading to signal loss/short circuit	8	Degradation and loss of materials due to corrosion/pitting	4	Operator Inspections	5	160	Use of corrosion - resistance materials	Quality control team	Monitor Maintenance Performance	5	3	5	75
People	Improper Maintenance	RTU may degrade over time or fail unexpectedly	5	Skipping maintenance procedure, using incorrect tools/parts	3	Provide details maintenance manual	6	90	Audit to ensure maintenance compliance	HR and Training Department	Establish maintenance schedule	3	3	6	54
Measurement	Sensor Calibration Error	Incorrect readings, leading to erroneous monitoring	6	Drift over time, improper initial calibration	4	Regular calibration schedule	6	144	Periodic validation against reference standard	Quality control team	Evaluate detectability	8	4	3	96
Equipment	Power Supply Unit (PSU) failure	RTU losses power leading to complete halt	7	Power surges, component aging	5	Regular maintenance	3	105	Use high quality PSUs	Maintenance Team	Asses failure effects	9	3	3	81
Method	Improper Installation Procedure	Incorrect set up, leading to operational	8	Inadequate training, poor documentation	5	Provide training	4	160	Develop comprehensive installation method	Logistic Team	Risk Prioritization	6	4	5	120

Figure 6. Failure Mode and Effect Analysis of Remote Terminal Units (RTU).

Table 5. RPN for remote terminal units.

No.	Potential Failure Mode	RPN	Relative Number (%)	Cumulative number of failure modes	Cumulative relative number (%)
1	Improper maintenance	200	29.5	200	30%
2	Sensor calibration error	144	21.3	344	51%
3	Improper Installation Procedures	120	17.7	464	69%
4	Power Supply Unit (PSU) failure	105	15.5	569	84%
5	Humidity and moisture	63	9.3	632	93%
6	Component corrosion	45	6.6	677	100%
	Total	677			

5. Discussion

Findings revealed that transformers, particularly tap changers and bushings, account for a significant share of lifecycle costs due to frequent failures and high maintenance demands. Additionally, capacitor banks and circuit breakers were identified as key contributors to operational and corrective maintenance costs, highlighting areas requiring improvement. Pareto analysis demonstrated that a small number of components are responsible for the majority of issues, emphasizing the importance of allocating resources to these critical areas. While initial investment in predictive maintenance strategies is required, the study found them effective in reducing unexpected failures and extending the service life of essential equipment, resulting in long-term economic benefits. It also integrated energy loss assessments into the LCC framework, demonstrating how proper capacitor placement minimizes reactive power losses, enhancing cost efficiency and reducing environmental impact. The research concludes that a structured LCC approach effectively leverages data to improve reliability, sustainability, and economic efficiency in power distribution systems. The power distribution field employs the use of the HVDC systems in the transportation of electricity over a long distance with minimum loss. It is, however, certain that strong maintenance will have to be ensured for such systems to achieve dependability and effectiveness. In developing such a plan, the application of FMEA in combination with Pareto analysis has been quite useful. All these issues have an impact on the overall dependability and effectiveness of the system by causing hardware failures, communication mistakes, and operational inefficiencies.

Some other common problems in the HVDC systems are the deterioration of power factors, electrical short circuits, and protocol timeout mistakes among others like dust accumulation, moisture intrusion, and thermal expansion. The first one is the reason why most of these issues are quite fundamental inconsideration of the resulting high voltage levels that can greatly dent system stability and power transmission. Although some failure scenarios may be common between the two systems, the implications on operations take another dimension. The HVDC system focuses on steady and efficient long distance power transmission, while Protection and Automation systems focus on network dependability and safety.

6. Conclusion

FMEA constitutes a methodical approach employed to recognize potential failure modes inherent in a system, evaluate the associated risks of each failure mode, and undertake measures to alleviate such risks. The RPN computed serves as a numerical value computed through the multiplication of severity, occurrence, and detection ratings assigned to each failure mode. A higher RPN value signifies an escalated level of risk. The outcomes of the FMEA can be leveraged to pinpoint and prioritize areas necessitating enhancement within the system. The power distribution plant case study has deployed pareto analysis and followed by failure mode and effect analysis in assessing the critical maintenance issues faced by the operator which encompassed the area of Protection and Automation System, High-Voltage Direct Current (HVDC) systems and Remote Terminal Units (RTU).

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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