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Failure Mode and Effect Analysis (FMEA) for Periodic Maintenance Tasks of Medium Voltage Switchgear 20 kV

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***Abstract*— Medium voltage (MV) switchgear at 20 kV, known as Panel Hubung Bagi (PHB) 20 kV in Indonesia, is a critical component of the electrical power distribution system, containing fuses, switches, and power conductors. A failure in this switch gear could lead to system-wide malfunctions, with potential catastrophic consequences such as fires or explosions. To prevent such events, it is essential to perform regular and well-planned maintenance. This research aims to optimize the maintenance process for MV switchgear, focusing on reducing maintenance tasks and frequency without compromising system reliability. The study employs the Failure Mode and Effect Analysis (FMEA) methodology, refined to reduce unnecessary maintenance actions. A Systematic Literature Review (SLR) was also conducted to analyze previous research on FMEA applications in 20 kV MV switchgear maintenance. Traditionally, maintenance was guided by manufacturers' recommendations, experience, and technical judgment, resulting in 3554 man-hours (MH) of labor every two years. However, by applying the refined FMEA process, maintenance requirements were significantly reduced to just 212 MH over the same period. This reduction represents a cost saving of 1678%, while still ensuring that the reliability of the MV switchgear at 20 kV is maintained at a high level. These findings underscore the importance of adopting systematic maintenance approaches to improve operational efficiency and reduce costs in power distribution systems.**

Keywords— Failure Mode and Effect Analysis (FMEA), Maintenance Tasks, Medium Voltage, Switchgear 20 kV, Systematic Literature Review (SLR), Manhours.

I. INTRODUCTION

Medium-voltage (20 kV) switchgear is a critical component in electrical systems that controls, protects, and isolates equipment from damage due to faults or abnormal conditions. However, switchgear failure can cause extensive power outages, financial losses, as well as safety risks. Therefore, a more systematic and predictive maintenance approach, such as FMEA, is needed that is able to identify potential failure modes, analyze impacts, and prioritize effective preventive actions. The use of FMEA in this periodic maintenance task aims to improve switchgear reliability and reduce the risk of failures that could impact overall power system operations.

Data analysis requires attention to signs that indicate potential faults before actual failures occur [1]. Asset management techniques can enhance cost efficiency, balance cost, and risk, and extend the lifespan of aging switchgear [2]. Recently therefore implementing this proper maintenance method for 20 kV medium-voltage switchgear is essential to prevent malfunctions or catastrophic explosions while optimizing maintenance costs. Switchgear is a critical component in the power grid, and its condition directly influences the overall reliability of the grid [3].

Therefore, developing and implementing this method properly maintaining 20 kV medium voltage switchgear is essential to prevent malfunctions or catastrophic explosions while optimizing maintenance costs. Electricity is distributed from the power transformer to the feeder or consumer using medium voltage switchgear [4]. It acts as a link between the electrical generating and transmission system in the transmission system [5]. The primary electrical components of a system for electrical distribution and transmission are switchgear. Previous failures of this crucial equipment have resulted in safety events including flashovers, fires, and equipment malfunctions, which have caused significant production losses and equipment damage [6]. Controlling the reclose mechanism built into a smart switchboard is one method of controlling brief short circuits without damaging equipment [7]. Even with the prior high voltage experience, medium voltage took nearly two decades, and it is currently anticipated that this new transformation will be completed in three years [8]. A vital component of the electrical grid, switchgear's condition greatly affects the grid's overall dependability [3]. Development of diagnostic techniques for medium-voltage vacuum switching equipment, which can be applied to create a

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real-time pressure monitoring system for vacuum switching equipment used in electrical infrastructure [9]. The failure flow parameter value and recovery time for switchgear circuits, which are then transformed into a structural-analytical circuit reflecting the heavy-duty mode logic of the circuit [10].

Power grids are becoming more and more crucial for electric utilities. By extending the service life of aged switchgear, asset management procedures and techniques may increase efficiency, balance cost and risk, and reduce downtime [2].

It is especially cost-effective for big equipment like gas-insulated switchgear [11]. The aforementioned techniques are unable to reliably identify the internal isolation switch's dependability when the interior of the switch fails to make good contact or fails to achieve the intended position [12]. A double-action switchgear is proposed to fulfill the goal of online maintenance and increase the effectiveness of switchgear maintenance [13]. Using a set of standards and guidelines, this evaluation converts the measured parameters from Switchgear subsystems into condition status [14].

FMEA (Failure Mode and Effect Analysis) was performed yoe identify all potential failure modes (Kolehmainan, Markus, 2021). The FMEA introduces a data-driven approach to assessing failure mechanisms [15], and introduces a new methodology for Failure Causes Analysis of the grid [1].

Due to its installation or construction, the 20 kV medium voltage switchgear is of great importance in the electrical system, requiring proper maintenance to prevent malfunctions or catastrophic explosions. The 20 kV Medium Voltage Switchgear is responsible for distributing electricity from a 20 kV power source. This switchgear requires careful maintenance to avoid malfunctions or potentially catastrophic explosions when installed or constructed within the electrical system. Following the manufacturer's maintenance guidelines typically results in high initial maintenance costs for medium-voltage switchgear. Figure 1 shows the external appearance of the 20 kV medium voltage switchgear.

Figure 1 illustrates the external appearance of the 20 kV medium voltage switchgear.

Figure 1. A physical example showing the external appearance of a 20 kV medium voltage switchgear (Source: PLN)

The 20 kV Medium Voltage Switchgear plays a vital role in distributing electricity from the 20 kV generator to transformers, electric motors, and other equipment. In the event of a catastrophic failure, such as an explosion within the switchgear, all connected equipment, including generators, cables, power transformers, and motors, would stop functioning. A single-line diagram, illustrated in Figure 2, provides an overview of the medium voltage switchgear's functionality. The diagram shows the real configuration of a geothermal facility in Indonesia, where the TR-1411 feeds an outside switchyard with electricity from a 20 kV–60 MW generator. An 80 MVA transformer steps up the voltage from 20 kV to 150 kV. The 150 kV electricity is then transmitted to PLN via several disconnecting switches (DS) and circuit breakers (CB) and connected to the 150 kV transmission line. Apart from the 150 kV of electricity sold to PLN, there is 20 kV of electricity reserved for internal use (PS), commonly referred to as houseload or self-consumption. The 20 kV power is routed to the 20 kV Medium Voltage Switchgear (indoor) through various CBs, which distribute power to the Motors Hot Well Pump, Motors Liquid Ring Vacuum, and the TR-1412 Power Transformer 6 MVA, which steps the voltage down to 6.3 kV for the plant's operations, as well as to the Steam Gathering System and other equipment. The Single Line Diagram emphasizes the crucial importance of the 20 kV (indoor) Medium Voltage Switchgear. Any damage to it, whether or not it involves an explosion, would cause the complete shutdown of all electricity production, including 150 kV and 6.3 kV outputs.

Thus, the purpose of this research is to optimize periodic maintenance on 20 kV medium voltage switchgear through the Failure Mode and Effect Analysis (FMEA) approach. This method is used to identify and prioritize potential failures in switchgear, so that more effective preventive measures can be implemented in order to reduce the risk of operational disruption. The novelty of this research lies in the application of FMEA combined with a data-based approach resulting from a systematic literature study (SLR), which results in more accurate risk mapping to formulate more efficient and sustainable maintenance measures for the 20 kV switchgear system.

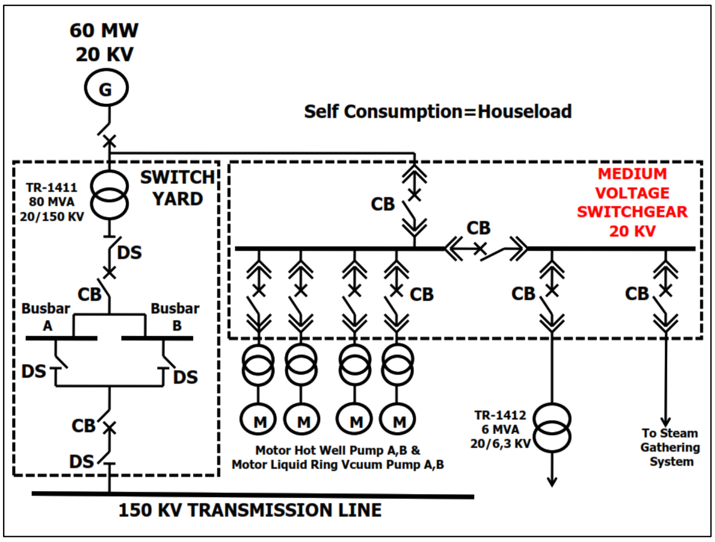

Figure 2. Simplified diagram illustrating the configuration of a 20 kV medium voltage switchgear (Source: A Geothermal Power Plant)

II. METHOD

The bathtub curve, depicted in Figure 3, is a fundamental concept in reliability engineering and is also relevant to human life stages. The curve illustrates a specific hazard function composed of three sections: i) The first section shows a declining failure rate, often referred to as early failure or infant mortality, which is analogous to childhood; ii) the second section depicts a steady failure rate, known as random failure, which is similar to adulthood; and iii) the third section shows an increasing failure rate, known as wear-out failure, which corresponds to old age. We created the bathtub curve by tracking the initial infant mortality rate when the asset was new, a consistently low random failure rate throughout its useful life, and finally, the wear-out failure rate as the asset neared its design life.

The layout and assets of the components dictate an appropriate maintenance strategy, and reliability-centered maintenance (RCM) is the best way to accomplish these goals. Additionally, the time since the last failure provides valuable insights, especially as many failures are recurrent (Kolehmainan, Markus, 2021). The design, installation process, and environmental conditions can lead to operational defects, such as the isolating switch not reaching its designated position, contributing to fault formation [12]. The bathtub curve is created by graphing the failure rate associated with infant mortality at the beginning of the asset's useful life, then a period of low, regular, random failures over that time, and finally the wear-out failure rate as the asset approaches its intended lifespan [16].

The following Figure 3 expresses the paradigm of Bathtub shape to illustrate the Failure rate and the related Time.

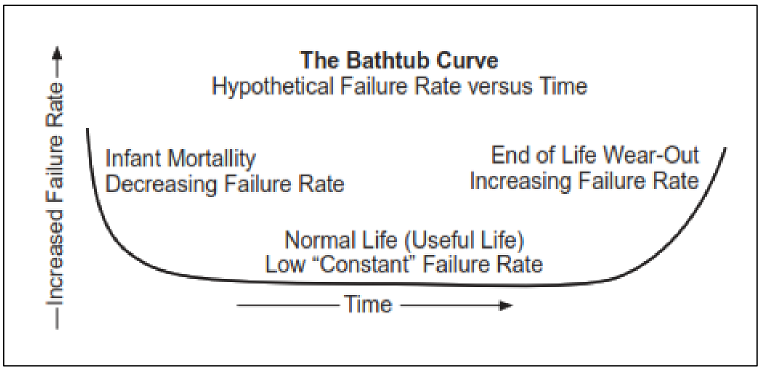

Figure 3. Bathtub Curve (Source: Book Maintenance and Reliability Best Practices Second Edition 2013 Ramesh Gulati, Page 161) [16]

A double-action switchgear is introduced to enhance the efficiency of switchgear maintenance, enabling the capability for online maintenance [13].

Figure 4 illustrates various failure patterns derived from the original study data. These patterns are classified into two main categories: age-related and random (Kolehmainan, Markus, 2021). Less than 20% of failures follow an age-related degradation pattern, while most exhibit a random pattern with a consistent failure rate [29]. Specifically, the failures are categorized into Age-Related (under 20%) including 4% for a bathtub curve, 2% for age-related failures, and 5% for fatigue-related issues and Non-Age-Related or Random (over 80%) further broken down into 7% rapid increase to random failures, 14%

random failures, and 68% infant mortality (early failures).

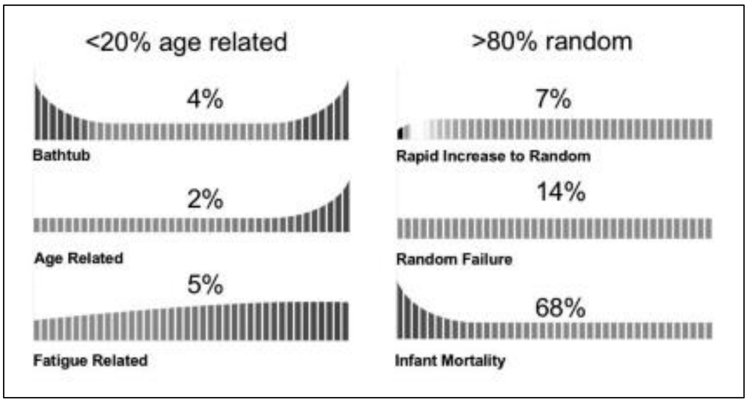

Figure 4. Patterns of Failure
(Referenced from: Maintenance and Reliability Best Practices, 2nd Edition, 2013 by Ramesh Gulati, Page 162) [16]

This article is a systematic literature review (SLR) that was carried out to find, assess, and explain all pertinent research findings pertaining to a certain research question, subject, or phenomena of interest [17]. A systematic literature review, or SLR, is the process of locating, evaluating, and interpreting all of the research that is currently available and relevant to the formulation of the problem or topic area under consideration. A systematic literature review, or SLR, is the process of identifying, assessing, and analyzing all study data that is currently accessible with the aim of answering specific research questions [17].

Using the Google Scholar search engine with the keywords Failure, Failure Mode, and Effect Analysis, and in 2020 and after, 26 Articles were obtained which were then used as the main reference

III. Results and Discussion

A. Frame of mind

The mindset and systematic approach of this research method are depicted in Figure 5 which illustrated on item no.2 using FMEA (Failure Mode and Effect Analysis) to get Maintenance Taks for Medium Voltage Switchgear 20 kV.

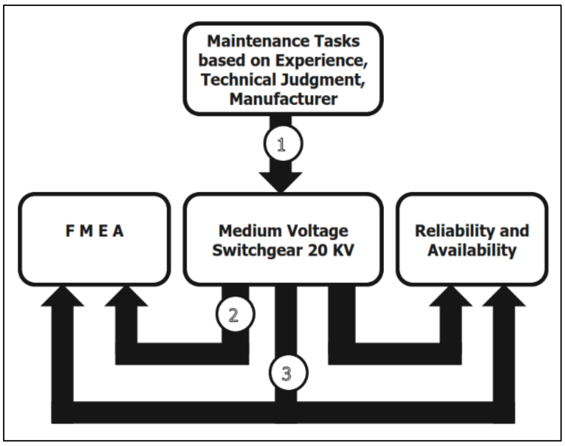

Figure 5: Mindset and Systematic approach

Electricity is sent from the power transformer to the feeder or end user using medium voltage switchgear [4]. **This approach** tends to neglect the crucial role of process design in preventing failures while also accounting for the impact of such failures on the economic performance of the process. **Managing the reclose function** is one method of dealing with short-duration short circuits without causing equipment failure [7].

B. Maintenace tasks and FMEA (Failure Mode and Effect Analysis)

Suitable maintenance strategies were recommended with the assistance of the Failure Mode and Effect Analysis (FMEA) technique, which identifies the main failure modes that impact the equipment's performance [18]. The technique is used to gather data from historical plant failure and breakdown records maintained by power utilities [19]. By using a variety of condition monitoring techniques to discover abnormalities early and taking early preventative action based on data analytics, these failures can be prevented [6].

Direct drive is the subassembly with the lowest failure rate, whereas the other has the highest due to its larger component count [20], Validate the electric power management system (PMS) redundancy plan for the development of digital twin technologies by conducting a failure modes and effects analysis (FMEA) (Yoon, Kyoungkuk et al, 2021). Generated a summary of the detection systems and a methodical outcome of the failure modes [21]. Diverse risks detailed on the FMECA clearly can be noticed with various types of failures [22].

All modern, high-tech electric cars are designed and manufactured using the failure mode and effects analysis methodology. The installation of modern, complex electric devices worked out several essential elements of failure mode and consequences analysis. Understanding the theory of failures is necessary to appreciate the role that failure mode and effects analysis plays in the design and production of modern, complex electric equipment. Failure mode and consequences analysis may therefore be applied effectively in modern electrical machine engineering [23].

Comparison of the failure mode, effects, and criticality analysis (FMECA) of photovoltaic (PV) power systems between string and central inverter concepts. The most frequent errors in the two plants were subjected to the FMECA, along with a comparative study of the effect of the system idea [24]. Using Failure Mode, Effects, and Criticality Analysis (FMECA) significantly enhances the reliability of power systems by systematically identifying potential failure modes, evaluating their effects on performance, determining their criticality, and prioritizing targeted interventions for maintenance and design modifications to reduce the likelihood of failures [24].

Finding the proper MAINTENANCE TASKS is the primary goal of FMEA (Failure Mode and Effect Analysis). Beginning with each component of the Medium Voltage Switchgear 20 KV, questions about its function, failure, mode of failure, effect, characteristic, and mode of failure—whether hidden or evident—are asked. Ultimately, an analysis is conducted to determine the appropriate maintenance tasks, as shown in the accompanying Figure 1.

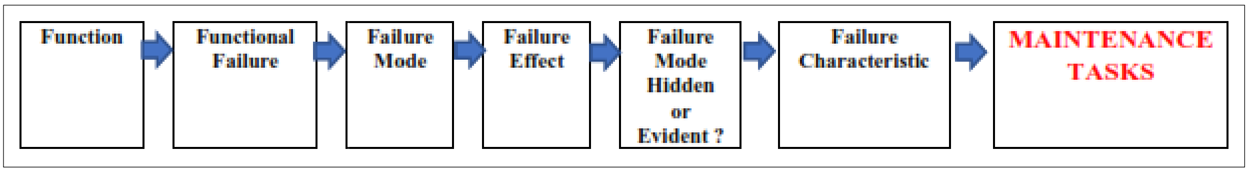

Figure 6. FMEA process sequence to obtain Maintenance Tasks
(Source: Sheets of BP - British Petroleum Berau Ltd, Tangguh Papua)

Function
Function: what the apparatus is capable of doing and the performance standards necessary for its present working environment (Sheets of BP-British Petroleum, Tangguh Papua).

Functional Failure
Functional Failure: any malfunction that stops the apparatus from performing its intended purpose). There are two levels
(1) First, by asking how can components fail to fulfill their functions. (2) Then by asking, what can each loss of function cause? (Sheets of BP-British Petroleum, Tangguh Papua).

Failure Mode
Failure Mode: how a malfunctioning component could lead to a malfunctioning system (Sheets of BP-British Petroleum, Tangguh Papua).

Failure Effect
Failure Effect: the effect on the apparatus of the failure mode.

Failure Characteristic (Sheets of BP-British Petroleum, Tangguh Papua)
Failure Characteristic: the characteristics (age-related, random, etc.) and behaviors of the failure mode (Sheets of BP-British Petroleum, Tangguh Papua).

Hidden and Evident
Hidden dan Evident: visibility of the failure mode to the operator during regular equipment operation; Evident refers to any failure that is able to be detected prior to the loss of equipment functioning; concealed refers to any failure that cannot be discovered (Sheets of BP-British Petroleum, Tangguh Papua).

Maintenance Tasks
Maintenance tasks: the procedure or examination that will identify the failure mode or take preventative measures against it (Sheets of BP-British Petroleum, Tangguh Papua).

FMEA Process
FMEA Process for Medium Voltage Switchgear 20 KV as stated in Table 1 below.

TABLE 1.
FMEA PROCESSING ON MEDIUMVOLTAGE SWITCHGEAR 20 KV

Function	Functional Failure	Failure Mode	Failure Effect	Description of MAINTENANCE TASKS merged and sorted well
1.ELECTRICAL CURRENT CARRYING:	Unable to properly conduct current between	Level 1: Overheating Flashover. Level 2:	Resulting in total loss of operations, possible	ONLY YEARLY: A. Visual and Mechanical Inspection

Function	Functional Failure	Failure Mode	Failure Effect	Description of MAINTENANCE TASKS merged and sorted well
1.1. Rail: Conducts flowing current, equipment connectors between Switchgear and other parts. 1.2. Main Terminal: Flowing current, Connecting the circuit from Rail to CB and Cable.	Switchgear (Cubicles) or other parts.	High contact resistance, Humid, Other objects in the main terminal, High clamp contact resistance, Level 3: Corrosion Poor terminals / poor contact, Heater not working / not plugged in, There is dust, dirt.	loss of production and equipment damage.	1. Check the physical, electrical, and mechanical conditions (1). 2. Check the anchorage, alignment, grounding, and clearance area required (2). 3.(Option) Before cleaning the unit, perform a test as found (3). 4. Clean the unit (4). 5. Verify that the size and type of fuse and / or circuit breaker conform to the drawings and coordination studies and circuit breaker addresses for the microprocessor communication package (5). 6. Verify that the current and voltage transformer ratio is in accordance with the drawing (6). 7. Ensure that the cable connection is secure and that the cable is properly fastened to avoid damage during the normal operation of moving components (7). 8. Examine the electrical connections of the bolts for high resistance by utilizing one or more of the following methods : 8.1. Use of low resistance ohmmeters (8). 8.2. Verify the tightness of the accessible bolt electrical connection with the calibrated torque of the wrench method in accordance with the manufacturer's published data, experience and technical considerations (9). 8.3. Conduct a thermographic survey (10). 9. Verify the proper functioning and sequence of the electrical and mechanical interlock system. 9.1. Try closing on a locked-open device. Try opening a locked-down device (11). 9.2. Execute key exchanges with all devices involved in the interlock scheme, as necessary (12). 10. Apply appropriate lubrication to the moving current-carrying components and to surfaces that are in motion or sliding (13). 11. Inspect the insulator for signs of physical damage or surface contamination (14). 12. Ensure that the barrier and shutter are installed correctly and functioning as intended (15). 13. Exercise all active components (16). 14. Check the mechanical indication device for correct operation (17). 15. (Options) Make sure the filter is installed, the filter is clean and free of dirt, and the ventilation is clean (18). 16. Conduct a visual and mechanical examination of the instrument transformer (19). 17. Conduct a visual and mechanical examination of the surge arrester (20). 18. Check the control power transformer. 18.1. Inspect for physical damage, cracked insulation, broken leads, tight connections, damaged wiring, and the overall condition (21).

Function	Functional Failure	Failure Mode	Failure Effect	Description of MAINTENANCE TASKS merged and sorted well
				18.2. Ensure that the ratings of the primary and secondary fuses or circuit breakers correspond with the specifications in the drawings (22). 18.3. Verify the correct function of the withdrawal disconnection contact, grounding contact, and interlock (23). 19. Take an as-left test (24). B. Electrical Test 1. Conduct resistance measurements on bolt electrical connections using a low-resistance ohmmeter (25). 2. Conduct a one-minute insulation resistance test on each component of the bus, measuring both phase-to-phase and phase-to-ground resistance. Apply the voltage according to the manufacturer's published data, experience and technical considerations. In the absence of published data of the manufacturer, experience and technical considerations (26). 3. (Option) Conduct a dielectric withstand voltage test on each section of the bus, testing each phase to ground while ensuring that the phase not under test is grounded, in accordance with the manufacturer's published data, expertise, and technical considerations. In the absence of published data of the manufacturer, experience and technical considerations. The test voltage should be applied for one minute. before conducting the test (27). 4. (Option) Test the control cable's insulation resistance in relation to ground. For a cable rated 300 volts, the applied potential should be 500 volts dc, and for a cable rated 600 volts, it should be 1000 volts de. The test ought to last for one minute. Pay attention to the manufacturer's recommendations, expertise, and technical considerations when it comes to units that include solid-state components or control devices that are unable to withstand the applied voltage (28). 5. Perform an electrical test on the instrument transformers (29). 6. Conduct a grounding resistance test (30). 7. Test measurement device (31). 8. Power transformer control. 8.1. Conduct an insulation resistance test by measuring the resistance between each winding and from each winding to the ground. The test voltage must be in accordance with the data published by the manufacturer. In the absence of publish data of the manufacturer, experience and technical considerations (32). 8.2. Verify the tightness of the accessible bolt elctrical connection with the calibrated torque of the wrench method in accordance with the manufacturer's published data, experience and technical considerations (33).

Function	Functional Failure	Failure Mode	Failure Effect	Description of MAINTENANCE TASKS merged and sorted well
				9. Verify the operation of the switchgear/switchboard heater and its controller (34). 10. Perform a surge arrester electrical test (35). 11. (Option) Conduct an online partial release survey (36). 12. Perform a system function test (37). C. Test Values - Visual and Mechanical 1. Compare the resistance value of the bolt joint to that of a similar connection, ensuring to check for any deviations exceeding 50 percent of the lowest value among the comparable bolt connections (38). 2. The torque level of the bolt must align with the manufacturer's published data, as well as relevant experience and technical factors. In the absence of published data of the manufacturer, experience and technical considerations (39). 3. Results of thermography surveys (40). D. Test Value - Electricity 1. Compare the resistance value of the bolt joint with the value of a similar connection. Checking for deviations from similar bolt connections of more than 50 percent of the lowest value (41). 2. The manufacturer's expertise and the technical factors of the given data should be taken into account when determining the insulation resistance value of the bus insulation. In the absence of published data of the manufacturer, experience and technical considerations. Insulation resistance values that fall below those specified in this table or do not meet the manufacturer's recommendations, experience, and technical considerations must be examined. The dielectric withstand voltage test should not proceed until the insulation resistance level is improved above the minimum threshold (42). 3. If no signs of distress or insulation failure are detected at the conclusion of the total voltage application time during the dielectric resistance test, the test specimen is deemed to have passed (43). 4. The minimum insulation resistance value for the control cable should correspond to the previous results obtained, but it must not be less than two megohms (44). 5. (Option) Electrical test results on the instrument transformer (45). 6. Results of grouding resistance test (46). 7. Accuracy of measuring device (47). 8. Power transformer control 8.1. The control power transformer's insulation resistance value must match published data, practical experience, and technical concerns from the manufacturer. Insulation resistance values less than this table or the manufacturer's recommendations,

Function	Functional Failure	Failure Mode	Failure Effect	Description of MAINTENANCE TASKS merged and sorted well
				experience and technical considerations should be investigated (48). 8.2. The control transfer relay must function as designed (49). 9. The heater must be operational (50). 10. Electrical test results on surge arresters (51). 11. The data released by the factory must match the findings of the online partial discharge survey (52). 12. System function test results (53).

Table 1 shows the Failure Mode and Effect Analysis (FMEA) process applied to 20 kV medium voltage switchgear maintenance. FMEA is a systematic method for identifying and analyzing potential failure modes in switchgear components, as well as the effects of such failures on the overall function of the system. In the table, the main function of switchgear, which is to carry electrical current, is outlined along with the potential failures that can occur, such as overheating and high contact resistance. The impact of these failures can lead to a complete loss of operation, potentially causing production losses and equipment damage.

In periodic maintenance, FMEA (Failure Mode and Effect Analysis) provides invaluable guidance on the maintenance tasks that need to be performed to ensure the reliability and performance of equipment in substations. These tasks include activities such as visual and mechanical inspections, electrical testing, and checks on critical components such as terminals, transformers, and surge arrestors [25]. By analyzing failure modes and their impacts, technicians can identify weak points in the system that require special attention, making it easier to plan more effective preventive measures [26].

Using the FMEA approach, technicians can design more efficient maintenance programs. For example, by identifying potential failures in a particular component, they can schedule more frequent checks and tests on that component compared to others. This not only ensures that all components function according to specifications, but also helps in better allocation of maintenance resources and time. Thus, maintenance can be performed in a more organized and targeted manner [27].

Successful implementation of FMEA in periodic maintenance contributes significantly to reducing the risk of operational failure. By prioritizing tasks based on risk analysis, technicians can be more proactive in addressing issues before they develop into larger failures [28]. As a result, the electrical system at the substation can function optimally, supporting the primary objective of maintaining the stability and reliability of electricity supply. This approach not only improves operational efficiency, but also provides a sense of security for electricity users and service providers.

Duration of Implementation of Maintenance Tasks as a Result of FMEA Process

Table 2 below expresses the implementation time of maintenance tasks as a result of the FMEA (Failure Mode and Effect Analysis) Process for Visual and Mechanical Inspection on Medium Voltage Switchgear 20 kV, beginning from Check the physical electrical and mechanical conditions to Verify the correct function of the withdrawal disconnection contact, grounding contact, and interlock.

TABLE 2.
DURATION OF IMPLEMENTATION OF MAINTENANCETASKS AS A RESULT OF FMEA PROCESS FOR VISUAL AND MECHANICAL INSPECTION (A).

No.	Maintenance task (Description of maintenance work) Processing results with FMEA	Average Execution Duration [MH (Man Hours)]
1.	ONLY YEARLY: A. Visual and Mechanical Inspection 1. Check the physical, electrical, and mechanical conditions.	2 MH
2.	2. Check the anchorage, alignment, grounding, and clearance area required.	2 MH
3.	3.(Option) Before cleaning the unit, perform a test as found.	2 MH
4.	4. Clean the unit.	2 MH
5.	5. Verify that the size and type of fuse and / or circuit breaker conform to the drawings and coordination studies and circuit breaker addresses for the microprocessor communication package.	2 MH
6.	6. Verify that the current and voltage transformer ratio is in accordance with the drawing.	2 MH
7.	7. When moving parts are regularly used, make sure the cable is secure and the connection is tight to avoid damage.	2 MH
8.	8. Check the bolt electrical connections for high resistance using one or more of the following: 8.1. Use of low resistance ohmmeters.	2 MH

No.	Maintenance task (Description of maintenance work) Processing results with FMEA	Average Execution Duration [MH (Man Hours)]
9.	8.2. Verify the tightness of the accessible bolt electrical connection with the calibrated torque of the wrench method in accordance with the manufacturer's published data, experience and technical considerations.	2 MH
10.	8.3. Conduct a thermographic survey.	2 MH
11.	9. Verify that the electrical and mechanical interlock systems are operating correctly and in the right order. 9.1. Try closing on a locked-open device. Try opening a locked-down device.	2 MH
12.	9.2. Perform key exchanges with all devices included in the interlock scheme as applicable.	2 MH
13	10. When moving and sliding the surface, as well as on the moving current-carrying components, use the appropriate lubricant.	2 MH
14.	11. Examine the insulator for signs of surface contamination or physical damage.	2 MH
15.	12. Verify the correct installation and operation of the barrier and shutter.	2 MH
16.	13. Exercise all active components.	2 MH
17.	14. Check the mechanical indication device for correct operation.	2 MH
18.	15. (Options) Make sure the filter is installed, the filter is clean and free of dirt, and the ventilation is clean.	2 MH
19.	16. Conduct an examination of the instrument transformer both visually and mechanically.	2 MH
20.	17. Perform a visual and mechanical inspection of the surge arrester.	2 MH
21.	18. Check the control power transformer. 18.1. Examine the area for any physical harm, broken lead, cracked insulation, tight connections, faulty wiring, and general wear and tear.	2 MH
22.	18.2. Check to make sure the primary and secondary fuses' or circuit breakers' ratings line up with the drawings.	2 MH
23.	18.3. Verify the correct function of the withdrawal disconnection contact, grounding contact, and interlock.	2 MH
24.	19. Take an as-left test.	2 MH

Table 2 presents the duration of execution of maintenance tasks resulting from the Failure Mode and Effect Analysis (FMEA) process for visual and mechanical inspections of 20 kV medium voltage switchgear. Each maintenance task described in this table has a consistent average execution time of 2 working hours (MH) for each task. This shows that the specific maintenance tasks, ranging from physical, electrical, and mechanical condition checks to verification of interlock system functions, are designed for high efficiency and effectiveness in maintaining switchgear performance.

By implementing FMEA (Failure Mode and Effect Analysis), the maintenance process becomes more structured and focused on failure prevention. Scheduling these maintenance tasks becomes easier, helping technicians to ensure that all critical aspects of the switchgear system are thoroughly checked [29]. This approach allows maintenance to be carried out proactively, identifying potential problems before they develop into more serious failures. This is expected to extend equipment life, reduce the risk of breakdowns, and minimize operational downtime.

Therefore, the table compiled from the results of the FMEA analysis serves not only as a guide for the timing of maintenance implementation, but also as a tool to improve the reliability and operational safety of the 20 kV switchgear. By having a clear and systematic schedule, maintenance management can be performed more effectively, thereby improving the overall efficiency of the electrical system. The implementation of FMEA is instrumental in creating a safer and more reliable operational environment for all stakeholders [30].

Table 3 below presents the duration required to implement maintenance tasks following the FMEA (Failure Mode and Effect Analysis) process for Electrical Testing on Medium Voltage 20 kV Switchgear, starting from Perform resistance measurements through bolt electrical connections with low ohmmeter resistance to Perform a surge arrester electrical test.

TABLE 3
DURATION OF IMPLEMENTATION OF MAINTENANCETASKS AS A RESULT OF FMEA PROCESS FOR ELECTRICAL TEST (B)

No.	Maintenance task (Description of maintenance work) Processing results with FMEA	Average Execution Duration [MH (Man Hours)]
25.	B. Electrical Test 1. Utilizing bolt electrical connections with low ohmmeter resistance, measure resistance.	2 MH
26.	2. Phase-to-phase and phase-to-ground insulation resistance tests should be conducted on every component of the bus in a minute. Utilize the voltage in accordance with experience, published data from the manufacturer, and technical concerns. In the absence of published data of the manufacturer, experience and technical considerations.	2 MH
27.	3. (Option) According to the manufacturer's published data, experience, and technical considerations, do a dielectric withstand voltage test on every component of the bus, testing each phase to ground with a phase that is not tested grounded. In the absence of published data of the manufacturer, experience and technical considerations. The test voltage should be applied for one minute. before conducting the test.	2 MH
28.	4. (Option) Test the control cable's insulation resistance in relation to ground. For a cable rated 300 volts, the applied potential should be 500 volts dc, and for a cable rated 600 volts,	2 MH

No.	Maintenance task (Description of maintenance work) Processing results with FMEA	Average Execution Duration [MH (Man Hours)]
	it should be 1000 volts de. The test ought to last for one minute. Pay attention to the manufacturer's recommendations, expertise, and technical concerns when it comes to units that include solid-state components or control devices that are unable to withstand the applied voltage.	
29.	5. Perform an electrical test on the instrument transformers.	2 MH
30.	6. Conduct a grounding resistance test.	2 MH
31.	7. Test measurement device.	2 MH
32.	8. Power transformer control. 8.1. Test the insulation's resilience. Measure each winding's distance from the ground as well as from winding to winding. The test voltage needs to match the information provided by the manufacturer. When the manufacturer's data isn't publicly available, take experience and technical factors into account.	2 MH
33.	8.2. Verify the tightness of the accessible bolt elctrical connection with the calibrated torque of the wrench method in accordance with the manufacturer's published data, experience and technical considerations.	2 MH
34.	9. Verify the operation of the switchgear/switchboard heater and its controller.	2 MH
35.	10. Perform a surge arrester electrical test.	2 MH
36.	11. (Option) Conduct an online partial discharge release survey.	2 MH
37.	12. Perform a system function test.	2 MH

Table 3 presents the duration of implementation of maintenance tasks generated from the Failure Mode and Effect Analysis (FMEA) process for electrical testing of 20 kV medium voltage switchgear. Each maintenance task in this table, ranging from resistance measurement through bolt connections using a low ohmmeter to electrical testing of surge arresters, has an average execution duration of 2 man-hours (MH) per task. This shows that the electrical testing process has been efficiently and thoroughly planned, focusing on the steps required to ensure optimal performance and system safety.

By applying FMEA (Failure Mode and Effect Analysis), electrical testing becomes more systematic, which can reduce the likelihood of failures in the system that can cause operational disruptions. Each step in the test table is designed to evaluate the reliability and safety of switchgear components, including insulation testing and amperage testing [31]. This FMEA approach not only improves the efficiency of the maintenance process but also provides a clear framework for assessing and improving the condition of equipment on an ongoing basis.

Consistent implementation of these tasks is expected to support the longevity and reliability of switchgear, thus ensuring stable and safe operation. By conducting regular and systematic testing, potential problems can be identified and addressed before they develop into more serious failures [32]. This will contribute to reduced downtime and maintenance costs, creating a more efficient and safer operational environment for all users of the electrical system.

Table 4 below expresses the implementation time of maintenance tasks as a result of the FMEA (Failure Mode and Effect Analysis) Process for Test Values - Visual and Mechanical on Medium Voltage Switchgear 20 kV, beginning from Compare the resistance value of the bolt joint with the value of a similar connection to Checking for deviations from similar bolt connections of more than 50 percent of the lowest value, and Thermography surveys.

TABLE 4
DURATION OF IMPLEMENTATION OF MAINTENANCE TASKS AS A RESULT OF FMEA PROCESS FOR TEST VALUES – VISUAL AND MECHANICAL (C)

No.	Maintenance task (Description of maintenance work) Processing results with FMEA	Average Execution Duration [MH (Man Hours)]
38.	C. Test Values - Visual and Mechanical 1. Compare the resistance value of the bolt joint with the value of a similar connection. Checking for deviations from similar bolt connections of more than 50 percent of the lowest value.	2 MH
39.	2. The torque level of the bolt should be in accordance with the manufacturer's published data, experience, and technical considerations. In the absence of published data of the manufacturer, experience and technical considerations.	2 MH
40.	3. Results of thermography surveys.	2 MH

Table 4 presents the duration of execution of maintenance tasks resulting from the Failure Mode and Effect Analysis (FMEA) process for visual and mechanical value testing of 20 kV medium voltage switchgear. Each maintenance task in this table, ranging from comparing bolt joint resistance values with similar joint values to thermographic survey results, has an average execution duration of 2 man-hours (MH) per task. This approach shows that maintenance steps are carefully planned to ensure the reliability and safety of switchgear connections and components.

The implementation of FMEA in visual and mechanical value testing not only ensures that all connections and components function according to specification, but also supports the identification of potential problems before they develop into more serious failures. By conducting periodic inspections and tests, technicians can detect non-conformities or damage at an early stage, allowing corrective action to be taken before operational disruption occurs. Therefore, Table 4 serves as a practical guide that supports efficient maintenance management, strengthens system integrity, and extends the service life of 20 kV switchgear equipment.

Table 5 below presents the duration required to implement maintenance tasks following the FMEA (Failure Mode and Effect Analysis) process for Test Values - Electricity on Medium Voltage 20 kV Switchgear, starting from Comparing the resistance value of the bolt joint with the value of a similar connection, to Partial discharge survey

TABLE 5
DURATION OF IMPLEMENTATION OF MAINTENANCETASKS AS A RESULT OF FMEA PROCESS FOR TEST VALUES - ELECTRICITY (D).

No.	Maintenance task (Description of maintenance work) Processing results with FMEA	Average Execution Duration [MH (Man Hours)]
41.	D. Test Values - Electricity 1. Comparing the resistance value of the bolt joint with the value of a similar connection. Checking for deviations from similar bolt connections of more than 50 percent of the lowest value.	2 MH
42.	2. The manufacturer's expertise and the technical factors of the given data should be taken into account when determining the insulation resistance value of the bus insulation. In the absence of published data of the manufacturer, experience and technical considerations. It is advisable to look at insulation resistance values that are lower than those in this table, as well as the manufacturer's recommendations, experience, and technical factors. Until the insulation resistance level is raised over the minimal value, the dielectric withstand voltage test should not be continued.	2 MH
43.	3. The test specimen is said to have passed the dielectric resistance test if, at the conclusion of the whole voltage application duration, no signs of distress or insulation failure are seen.	2 MH
44.	4. The control cable's minimum insulation resistance value should be at least two megohms and proportionate to the prior outcome.	2 MH
45.	5. (Option) Electrical test results on the instrument transformer.	2 MH
46.	6. Results of grouding resistance test.	2 MH
47.	7. Accuracy of measuring device.	2 MH
48.	8. Power transformer control 8.1. The control power transformer's insulation resistance value must match published data, practical experience, and technical concerns from the manufacturer. It is advisable to look into insulation resistance levels that are lower than those in this table, the manufacturer's recommendations, and technical factors.	2 MH
49.	8.2. The control transfer relay must function as designed.	2 MH
50.	9. The heater must be operational.	2 MH
51.	10. Electrical test results on surge arresters.	2 MH
52.	11. The data released by the factory must match the findings of the online partial discharge survey.	2 MH
53.	12. System function test results.	2 MH
	Total Man Hours (MH) per year for A+B+C+D =	106 MH

Total Man Hours (MH) for two (2) years = 2 x 106 MH = 212 MH

Table 5 presents the duration required to carry out maintenance tasks based on the Failure Mode and Effect Analysis (FMEA) process for electrical value testing at 20 kV medium voltage switchgear. In this table, there are various maintenance tasks that include testing bolt connection resistance values, evaluating insulation resistance values, and testing grounding results. Each maintenance task is estimated to require 2 man-hours (MH) of execution time, creating a total annual duration of 106 MH for all tasks listed.

This approach not only underscores the importance of electrical value testing in ensuring system reliability and safety, but also demonstrates how FMEA can assist in planning and prioritizing maintenance activities. By focusing on testing resistance values and component performance, technicians can be more proactive in detecting issues before they lead to larger system failures. In this context, Table 5 serves as a comprehensive maintenance management tool, assisting in task scheduling and resource allocation to minimize the risk of equipment damage and improve the operational effectiveness of 20 kV switchgear.

IV. Conclusion

The results showed that the application of Failure Mode and Effect Analysis (FMEA) in the maintenance of 20 kV medium voltage switchgear can have a significant positive impact on reducing maintenance time and costs. By using the FMEA approach, maintenance time that previously reached 3558 man-hours every two years can be cut to only 212 man-hours. This time reduction reflects the increased efficiency gained through systematic identification and handling of potential risks, making the maintenance process more planned and targeted.

In addition to time savings, the analysis also shows that FMEA has the potential to reduce the risk of malfunctions and failures that can disrupt system operations. By understanding and mitigating possible failure modes, the reliability and performance of 20 kV switchgear systems can be significantly improved. This research confirms that FMEA is not only an efficient method in maintenance, but also contributes to better operational sustainability by reducing the likelihood of faults. Overall, this research provides evidence that FMEA is an effective approach to improve performance and reduce costs in switchgear systems.

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