World Academics Journal of Engineering Sciences
Vol.10, Issue.1, pp.07-13, March 2023
E-ISSN: 2348-635X
Available online at: www.isroset.org

Research Paper

FTA Analysis of the Winding in Steam Power Plant: An Insight into the Stator

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Received: 08/Feb/2023; **Accepted**: 10/Mar/2023; **Published**: 31/Mar/2023

Abstract— The stator winding generator is a significant equipment in the steam power plant (SPP), which converts mechanical energy into electricity. The windings of the turbine generator were mainly used for power generation, and the failure of the winding caused much damage to the stator. In this paper, fault tree analysis (FTA) was used to determine the initial condition of deterioration of the winding fault. FTA results are preliminary indications of stator fault. The investigation results found the binding tape aging and seal oil generator issues. At some point, the binding tape coils in several slots on the exciter and turbine sides were found as loose binding tape (coil binder) that is not tight (loose) and can be interpreted as aging conditions. The earth stator alarm was also confirmed.

Keywords— Alarm Earth Stator Fault, Electric Steam Power Plant, Fault Tree Analysis, Generator Failure.

1. Introduction

The Static wind generator is an essential device in the steam power plant (SPP) that converts mechanical energy into electricity [1]. The generator's cooling system was in the stator using water, while the stator core and rotor winding used hydrogen coolant. SPP Rembang-Indonesia (SPP RI) was a two-synchronous generator with an output power of 300 megawatts. The turbine generator used at the SPP RI was a brand of Dongfang Electric model QFSN-300-2-20B type self-shunt static Excitation H_2O-H_2-H_2 (hydrogen-cooled generator unit) made by China Dongfang Electric Machine Co. Ltd. [2], one of the static excitation system of power plant synchronous generator [3].

SPP RI was operated since 2011 and continuously operated well; meanwhile, on May 14, 2021, unit #20 experienced a trip condition marked by a Differential Fault Generator Alarm (DFGA) appearance. After further checking, damage to the steering stator was found. Malfunctions of this generator lead to considerable cost losses [4].

Based on the results of the Root Cause Failure Analysis (RCFA), the damage occurred due to the lifetime of the tape seal [4]. The results of the RCFA allow for inspections related to solving problems in the power plant engine circuit [5]. Consequently, further analysis of the operating parameters that caused damage to the stator must be used as future learning and reference data for logical modification to avoid damage.

2. Related Work

Turbine generator set QFSN-300-2-20B was evaluated for an efficiency of about 98%. Unfortunately, this turbine generator reported a decrease in efficiency by about 5% [6]. Another type of turbine generator set called QFSN-350-2, a 350-megawatt generator, was also evaluated for the efficiency impacted by load capacity changes. There are increasing load capacity influences the efficiency of the isentropic. In addition, the efficiency of the turbine generator was influenced by the load capacity changes [7]. Permana and Kurniawan [8] and Dirmanto & Effendi [9] stated that the turbine efficiency would impact SPP performance. High-efficiency value means better system reliability [10].

The time-caused effects of performance quality sometimes affect the turbine generator's reliability. Some issues commonly appeared in the generator case, such as vibrations in the turbine rotor. Research by Romdhon et al. [11] used Root Cause Analysis (RCA) method to analyze that issue. The result showed that a short rotation and a closed slot-liner hole to activate a rotation generated electrical vibration and that it was necessary to fix it to reduce vibration disturbance.

Instead of the generator's rotor winding issue, the stator winding failure reported by Raymond et al. [12] occurred in 51 MVA, 11 kV generator stator, a type of hydro-generator. The investigation reported that the following procedures were obtained, including locating and assessing the fault's extent.

Subsequently, visual inspections and electrical tests were used to perform this task. Then discover the root cause of failure and collect valuable data to evaluate the wind insulation condition. According to the study, the condition of the stabilizer was assessed to determine the root cause of failure, obtain additional information about the vibration condition assessment, as well as the results of visual inspection and the details of the dissection and measurement campaign performed before the repaired generator is re-serviced.

Dehlinger and Stone [6] said partial discharge (PD) was a minor electrical discharge within voids within a hydro generator's stator winding insulation system. The ceaseless assault of electrons and particles on the void's surface continuously bursts the chemical bonds of the insulation's natural fixings, coming about in electrical treeing or following. PD debasement is ordinarily moderate in common stator separator frameworks that utilize mica tapes stuck by epoxy (numerous a long time or decades). PD indicates a maturing preparation more than a cause of corruption in hydro generator stator windings [13].

Stone and Warren [14] looked into fractional release (PD) tests to check the electrical cover quality in engines and generators evaluated at 3.3 kV or higher. There are a few strategies for measuring PDs when the engine or generator is in day-to-day operation. Be that as it may, most measuring strategies combined stator PD with electrical-interference signals from awful electrical associations, control apparatus utilization, transmission line crown, and numerous more. As a result, ominous signs of stator winding challenges might happen, bringing down belief in PD estimations. Another challenge with online PD testing is elucidation, or deciding which machines are in fantastic working arrange and which require support.

PD analysis was used in the manufacturing stages up to lifetime commissioning related to the insulation integrity of high-voltage equipment to be confirmed as feasible or avoid failure. Besides, PD testing could identify whether the motor and generator stator windings have poor insulation [15]. In addition, another research by Campbell and Stone [16] used temperature detectors as stator winding PD detectors. Based on the lab-scale demonstration, the characteristics of PD beats were recognized by resistance temperature locators (RTDs), which fundamentally identify the PD signals. The found signals were regularly uncorrelated with the PD estimation if utilized with conventional sensors and consequently with the stator winding's known state. Whereas RTD leads might distinguish PD, the information cannot be deciphered based on sufficiency, extremity, or stage position. As a result, even an experienced engineer's perception is very subjective.

3. Theory

The stator and rotor windings had different components, each with a particular reason. The stator winding separator framework comprised various components and highlighted that work together to ensure that no electrical shorts happened, and that warm from conductor I2R misfortune was exchanged to a warm sink, which the conductors did not shake despite their attractive weight. The electrical cover was displayed on synchronous engines and generators with central shafts, circular rotors, wound rotors, acceptance engines, and generators. In differentiation to the tall AC voltage on the stator, the rotor windings of synchronous engines and generators were subjected to comparatively moo DC voltage [17].

Sometimes, stator windings would become issues with reliability as well as performance. Meanwhile, the inspection of the issue used various ways [18]. Visual measurements [19], lifetime estimation with cycles modeling [20], electromagnetic force analysis [21], and partial discharge (PD) measurement [22] were used for stator winding inspection. Besides, with thousands of machines monitored using online PD measurement [15], a recognized, for 25 years, proven tool to assist maintenance engineers in determining which stator windings require offline testing, inspections, and repairs [23]. PD testing would run online or offline methods based on the IEEE and IEC standards. Stone et al. [24] reported the recent development of these standardizations for the role of motor and stator winding generator tests.

The system safety and reliability analytic tool used since the 1960s was fault tree analysis (FTA) [25], [26]. FTA was developed in a computer-based program [26] and Boolean logic program [27]. FTA converts a visual system into a logical diagram, making it one of the industry's most popular methods for reliability and safety calculations. It began in the aerospace sector and was later adopted by the nuclear power plant industry to assess and quantify the dangers and risks associated with nuclear power generation [28]. The strategy of FTA examination comprises eight stages: 1) characterize the framework of intrigued, 2) characterize the beat occasion of the framework, 3) characterize the beat tree structure, 4) investigate each department in progressive levels of subtle elements, 5) unravel the blame tree for the combination of occasions contributing to the beat occasion, 6) distinguish critical subordinate disappointment possibilities and alter the demonstrate suitably, 7) perform quantitative investigation, and 8) utilize the comes about in choice making [29]. This paper would inspect the stator winding's issue using FTA for reliability and good analytic tools.

4. Experimental Method

The data was collected from the operating parameters based on the Distributed Control System (DCS) (Figure 1) parameters and the routine generator testing that has been carried out. The generator operation standard manual [30], [31], [32] was compared based on the results of the historical data of DCS. Based on historical data from 2019 and 2021, the binding tape aging and seal oil generator issues were found. Offline measurements confirmed it, including visual measurements. Investigation results showed that unit #20 was conducting an overhaul. Complete inspections were conducted to determine the factors influencing the stator winding fault.

Meanwhile, the generator status is still in the standard range SPLN K5.007 [33] after being conducted by the level assessment generator. PD data was obtained on January 1 – May 14, 2022, before the short occurrence of the generator stator winding. Then an analysis was carried out using the Fault Tree Analysis (FTA) method to prevent repeated events.

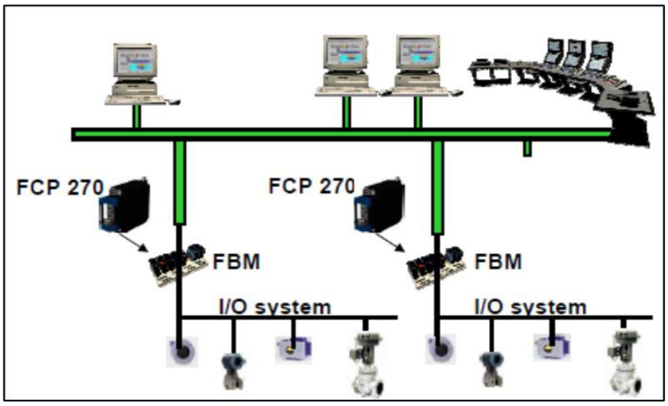

Figure 1. DCS system overview of SPP RI's generator.

5. Results and Discussion

Figure 2 shows the sketch anatomy of the unit #20 generator in SPP RI. From the investigation results, the binding tape is aging, and the stator contains oil contamination (seal oil generator). It was obtained from the rotor maintenance history from DCS and visual findings in Figure 3. In addition, damage to the binding tape issue was found during an inspection of the stator side in the form of loose binding tape coils in several slots on the exciter and turbine sides (Figure 4); the earth stator fault alarm was also confirmed. In these conditions, it is fundamental to re-bind tape and conduct a bump test to degree the characteristic recurrence of the coiled stator. A stator coil component with a substandard frequency value would be strengthened on the coil side. Then, the bumping test was conducted. The results obtained from the bump test on both sides of both the exciter side coil and the turbine side coil are still in good condition, or the category meets the acceptable matrix standards of IEEE 1665-2009 [34].

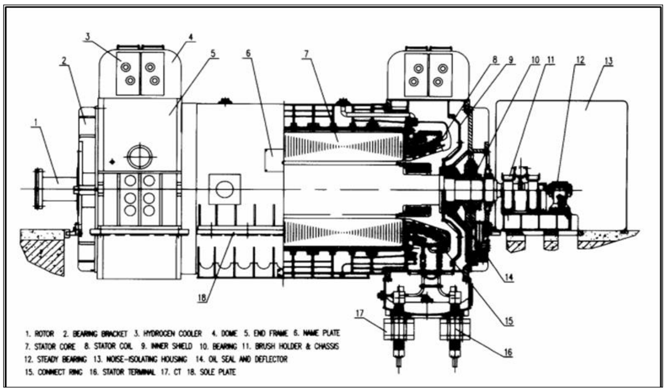

Figure 2. Generator anatomy of unit #20.

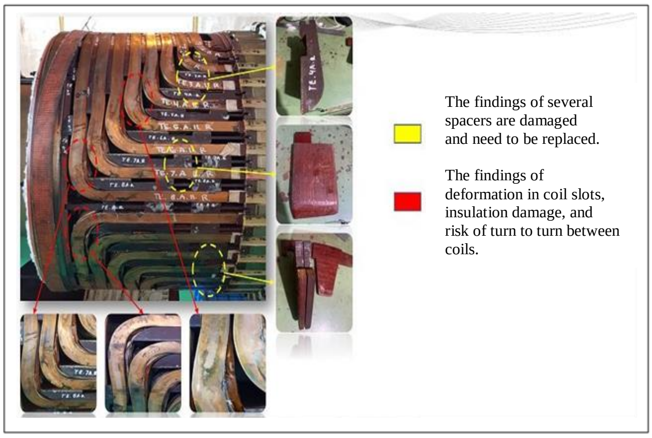

Figure 3. Winding coil rotor generator findings based on visual measurements.

Figure 4. Slack on binding tape on the contents of the exciter as many as 75 points or 35% of the 216 points as well as the turbine side as many as 135 points or 62% of the 216 points.

Before a malfunction occurs, the 2nd level generator assessment results show normal conditions, there were two findings, namely, a decrease in insulation quality marked by an earth stator fault alarm and stator failure events due to the presence of coil stator components (binding tape) that were aged so as to affect grip on the stator coil & there was oil contamination on the stator which resulted in soot due to arching, no water contamination either from the oil side or from condensation due to operating parameters that do not match the manual book. In this case, the possible causes include short circuits due to the stator components' aging (binding tape) and the stator coil's oil contamination.

Based on historical data of the operation in 2021 and visual measurements (Figure 4), where there are findings on the coiled stator in the form of binding tape (coil binder) at some point that is not tight (loose), it can be interpreted that the binding tape is experiencing aging conditions.

Based on the history of unit #20, in 2019, there was a flashover (short) on the Generator Circuit Breaker (GCB) component which resulted in damage to the Low Voltage (LV) transformer connection. Most likely, this problem also affects the condition of the generator, which is affected or the effect when the current surge is high due to short on the GCB so that vibrations occur and resonance arises in the core stator core, which has an impact on binding tape.

Based on these conditions, the binding tape undergoes slagging that cannot hold intact on the surface of the stator coil, resulting in continuous friction, which causes the insulation of the stator coil to erode. The erosion of the stator coil isolation would impact arching or flashover, so there is a short between cores.

The most noteworthy plausibility of oil defilement within the stator is sourced from the Seal Oil Generator (SOG) framework, where the seal oil framework is closer to the internal zone of the stator. This anomaly within the seal oil framework can influence the cooling framework, in this case, hydrogen (H_2). Conditional pressure and flow settings on the oil seal would cause H_2 consumption to increase and would cause excess seal oil in the generator. Trending data of different seal oil and hydrogen pressure can be seen in Figure 5, showing the difference in seal oil and H_2 pressure and an average difference of 0.2 MPa.

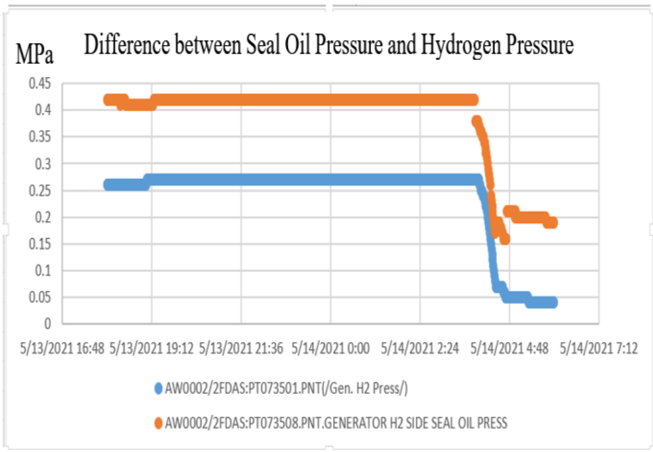

Figure 5. Trending data of seal oil & hydrogen pressure.

Operational conditions of the SOG system when start-up post-overhaul can be seen in Figure 6; the oil level of the H_2 side of the seal oil tank experiences a high level for ± 4 hours, which is likely that the seal oil does not circulate appropriately, so that the generator rotation is already high, it would cause oil splashes to enter the stator coil.

The oil supply that leads to the Air Side Seal Oil Generator (ASSOG) system has two manual valves connected. When starting the lube oil turbine (circulation) using the AOP (AC Oil Pump) pump after overhauling and not closing (close the valve/valve open), then most likely, the lube oil would fill into the side of the Air Side Generator (ASG) inlet pipe and can enter the generator. The weight depletes SOG moreover influences the passage of the seal oil, where in case the weight of the debilitate seal oil increments, the alteration of the oil seal on the depleted side is decreased so that the oil cannot circulate appropriately.

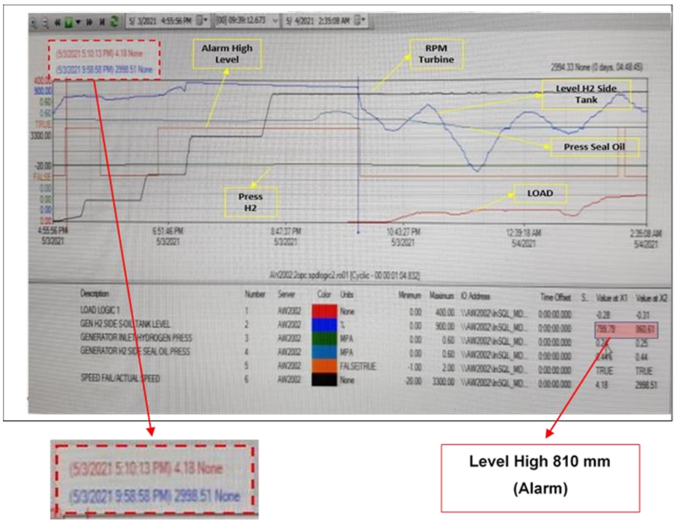

Figure 6. SOG system result indicates the oil contamination.

Figure 7 shows the partial discharge (PD) measurements (online). Results show no significant increase in each phase related to partial discharge, which was still below 5 Pico Coloumb. The online PD data in the picture shows a difference in values between offline PD performed during overhauling. Therefore, it is necessary to inspect the online PD to ensure the results follow the rules for measuring instrument equipment. The data in Figure 7 is taken by removing some data when the unit is not voltage, and the data is processed first to ensure measurements at the same hour in the three phases.

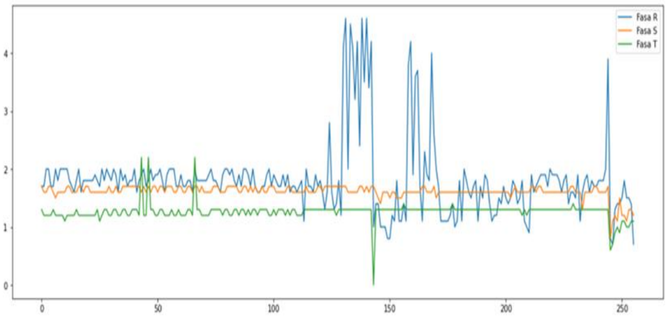

Figure 7. Trending data of partial discharge online.

The condition of the leak drain sensor (Figure 8) is damaged, making it unable to drain automation when there is a complete oil or water level. Damage occurs to magnets inside the switch-level equipment.

Based on the complete inspections, the Fault Tree Analysis (FTA) results on the stator winding fault can be seen in Figure 9. In addition, FTA results related to early indications of stator winding interference can be seen in Figure 10.

The following findings regarding the analysis of Fault Tree Analysis (FTA):

1) The initial parameter that detects the initial condition of deterioration of stator winding fault is the "Earth Stator Fault Alarm."

2) Factors causing failure of the winding stator:
   a. Leading cause: the condition of the insulation tape has begun not to bind,
   b. Side cause: high hydrogen side tank level (over a long period), valve supply seal oil is abnormal, vacuum extractor pressure is abnormal, and the differential pressure between seal oil and hydrogen exceeds the standard.

Recommendations related to the results of the Fault Tree Analysis (FTA) include: (1) if there is an alarm earth stator fault, it is necessary to carry out inspections related to binding tape coil & insulation of generators at the 3rd assessment level; (2) take precautions by ensuring that there is no oil entering the winding stator.

Figure 8. Leak drain sensor that broken.

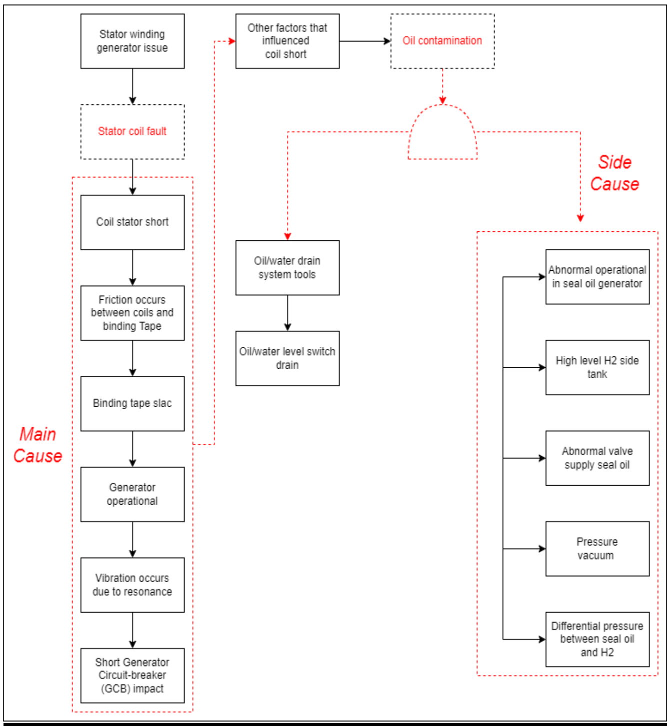

Figure 9. Results of Fault Tree Analysis (FTA) of stator winding issue.

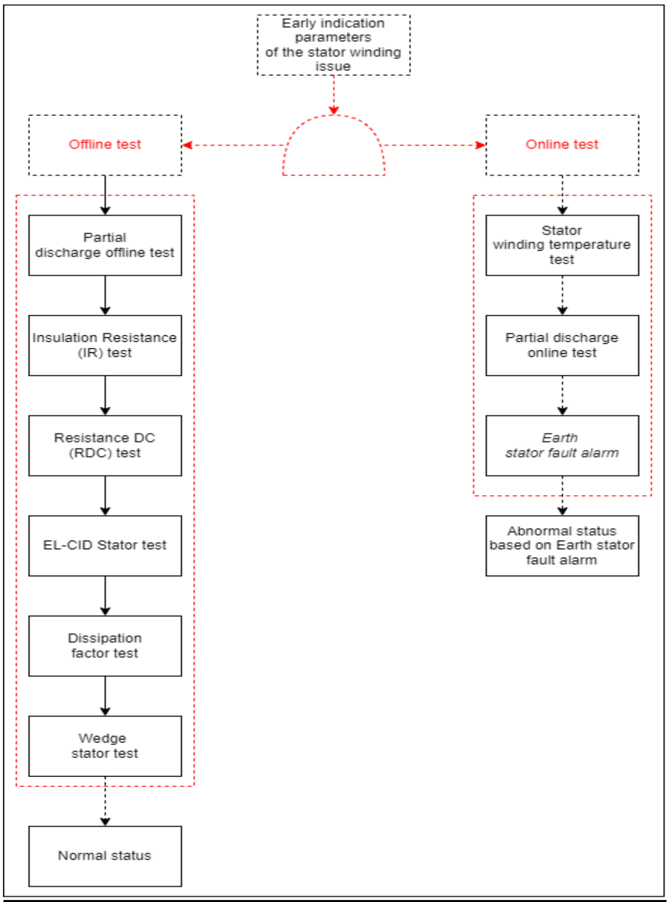

Figure 10. Fault Tree Analysis (FTA) results are preliminary indications of stator winding issues.

Recommendations for oil not to enter the winding stator include (1) H2 level side tanks that need to make modifications related to logic at the h2 side tank level by providing an alarm to the HMI so that it becomes an awareness to the operator when a high level occurs and the operation would maneuver; (2) valve supply seal oil that needs to be made sops related to the maneuvering of the valve supply seal oil at the time of firing so that the operator does not miss-maneuver; (3) pressure vacuum extractor that needs to be added to the alarm on the DCS logic and displayed on the HMI to become awareness in the operator when inappropriate pressure occurs; (4) the differential weight between the oil seal and hydrogen surpasses the standard, so it is vital to include parameters to the DCS related to the differential weight between the oil seal and hydrogen so that when it is exterior the standard, there’s an caution and gets to be mindfulness for the administrator; (5) drain switch level that needs to be checked periodically regarding the level of drain oil/water switch to ensure the condition of the equipment.

Furthermore, instead of fault tree analysis (FTA) for generator fault detection, the machine learning method can also propose fault forecasting. Machine learning is commonly used for any engineering-based intelligent computing method, including detection, diagnosis, forecasting, and classification [35]. Besides, any electrical power plant should be maintained well, and it is essential to keep it working within good reliability performance [36]. The generator is an essential part of the electrical power plant. It should ensure that it always makes running well, as well as in good performance conditions.

6. Conclusion and Future Scope

After collecting data and conducting an analysis, conclusions were obtained that the damage that occurs to the generator stator is the insulation that has experienced deterioration and also factors from oil that add to the impact of the failure of the stator winding generator. In addition, to avoid repeating events, it is necessary to make modifications.

We recommend several things for future scope based on this study, including:

1) Further analysis related to the breakdown voltage in the oil entering the generator stator;
2) Earth stator fault alarm because it can detect earlier than partial discharge parameters related to stator winding generator damage.
3) Other analysis tools would probably be used as fault detection and fault forecasting, including the machine learning method, an intelligent computing method commonly used to detect, diagnose, forecast, and classify, instead of fault tree analysis (FTA). It is possible to understand the performance of the analysis between each other.

Data Availability

Data to support the study's findings can be obtained at the author's request. The authors proposed available repository data with the Joint Declaration of Data Citation Principles

Conflict of Interest

The authors declare that they have no conflicts of interest.

Funding Source

None.

Authors' Contributions

Ade Suhendar inquired about the writing and conceived the ponder. Besides, Yanuar Z. Arief was included in method advancement, issue examination, and information investigation. Sinka Wilyanti composed the primary composition draft. Besides, Rosyid R. Al-Hakim finalizes the draft of the original copy. In addition, Roma San Rego approved the result investigation. All creators looked into and altered the manuscript and affirmed the ultimate form of the composition.

Acknowledgments

The creator would thank PT. Pembangkitan Jawa Bali Services due to back and assertion for doing this investigation.

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