Journal of Engineering and Technology

ISSN 2180-3811 eISSN 2289-814X https://jet.utem.edu.my/jet/index

DOI: https://doi.org/10.54554/jet.2026.17.1.012

PROBABILISTIC ENHANCEMENT OF AN ISLAND NETWORK USING RELIABILITY-CENTERED MAINTENANCE

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Article history:

Received Date: 31 October 2025

Revised Date: 24 February 2026

Accepted Date: 25 April 2026

Keywords: Reliability-Centered-Maintenance, Analytical Hierarchy

Abstract— The maintenance of electrical island networks presents major reliability and performance challenges. Traditional methods often overlook the probabilistic nature of failures, leading to avoidable outages. This study proposes an enhanced Reliability-Centered Maintenance (RCM) framework using FMEA-AHP methodology for island networks. An existing network was modelled in ETAP using equipment data and maintenance history from the IEEE Std-493 Gold Book and the Dangote Petroleum Refinery and Petrochemical (DPRP) Captive Power Plant. ETAP simulations quantified energy losses and annual failure

Process, Pareto, Failure Mode

rates. Critical equipment was identified using the Pareto Principle, and Failure Mode and Effect Analysis (FMEA) determined failure modes. The Analytical Hierarchy Process (AHP) prioritized high-impact failures, guiding task selection. Implementing ETAP-based reliability assessment combined with RCM, FMEA, and AHP resulted in a 56.36% reduction in interruption duration and a 64.87% reduction in failure rate. A structured preventive maintenance framework was developed to optimize strategies, reduce costs, and improve system reliability in island networks.

I. Introduction

The electrical power system is inherently imperfect, as achieving a completely failure-free design is technically impractical and economically unfeasible [1]. With increasing network complexity, ensuring reliability and quality is essential. Island networks, such as university or industrial facilities with their own generation, play a critical role in sectors like telecommunications, energy distribution, and transportation. These systems face challenges from unpredictable component failures and limited maintenance resources [2]. In parallel, deregulated and competitive power markets demand accurate performance assessment to ensure efficient allocation of maintenance funds and improved service reliability[3].

This study applies Reliability-Centered Maintenance (RCM) to enhance an existing island network by modelling the system in ETAP, assessing reliability performance, and developing an optimized maintenance decision framework.

Despite the critical role of island networks, maintenance practices are often reactive and not optimized for probabilistic failures, leading to high downtime and operational costs. This study addresses this gap by developing a structured RCM-based framework.

II. Literature Review

One key feature of RCM is to reduce the overall cost of maintenance. Minimizing maintenance costs is essential for the sustainability of off-grid systems[4]. Island networks are complex system that require regular maintenance in order to get ROI, in a report by Rajib Hasan[5]. The report states that by investing in routine maintenance, you can avoid potential issues and costly repairs in the future. Proper maintenance planning is critical in increasing availability, ensuring quality maintenance management, and controlling the safety and environmental risks associated with physical assets. This has been proven in many research for example, this research [6] proposed a Reliability and Risk Centered Maintenance (RRCM) method that allows organizations to determine maintenance plans that ensure the reliability of the physical assets while considering and prioritizing the risks associated with their potential functional failures. The result shows that by identifying and addressing minor issues promptly helps prevent larger problems and extends the lifespan of an equipment, which ultimately translates into substantial savings. Pareto Philosophy is a reliability tool that has been employed in maintenance planning and improvement. The Pareto Principle suggests that approximately 80% of maintenance issues arise from about 20% of assets. By identifying these critical assets, maintenance teams can focus their efforts on the components that most significantly impact overall system reliability and performance[7].

III. Methodology

This study employs ETAP to model an island network and assess reliability using key indices such as MTTR, annual failure rate, and MTBF. The Pareto Principle identifies critical components, while FMEA and AHP determine dominant failure modes for targeted maintenance planning.

The model is based on the DPRP Captive Power Plant. One year of reliability and maintenance data was analyzed using IEEE Std 493-2007 [8]. to develop an RCM-based maintenance decision framework.

A. Island Network Model using ETAP

The island network as shown in Figure 1 was modelled in ETAP and comprises two 34.5 MW GE MS6001B gas turbine generators connected through circuit breakers to an 11/66 kV step-up transformer. Power flows to a 69 kV SF_6 GIS busbar arranged in a mesh via a bus-tie transformer for synchronization. The system then connects to a circuit breaker, potential transformer, and 66/11 kV step-down transformer using underground XLPE armoured cables for reliability assessment in ETAP IDE.

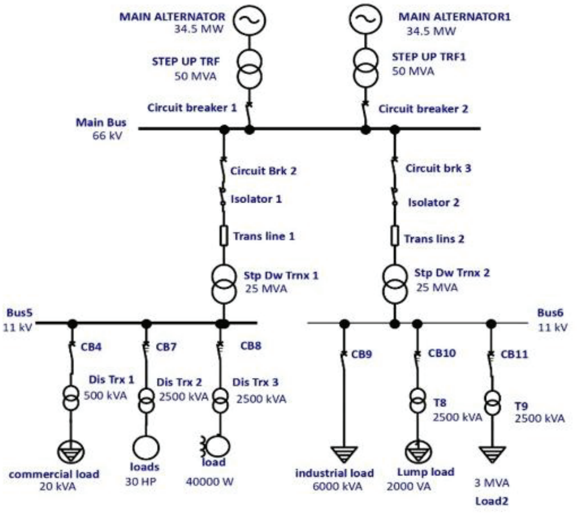

Figure 1: Model of an Island Network

B. Model Reliability Analysis

The analysis for system model was done using ETAP IDE reliability assessment tool and ETAP database which has been derived from IEEE Gold book, Std 493-2007.

Failure rate per year and Mean Time to Repair (MTTR) was calculated for each equipment on ETAP using the mathematical Equation (1) and (2), respectively.

$$\lambda_A = \frac{number\ of\ failure}{sum\ of\ operating\ poriods/8760}(hr/yr) \quad (1)$$

$$MTTR = \frac{sum\ of\ total\ repair\ time\ per\ year}{number\ of\ brekdown} \quad (2)$$

Table 1 was used to compile data for the equipment in the system model over a period of one year. The data compiled are sourced from the DPRP CPP and IEEE 493 Gold Book [9], and the reliability block diagram is applied according to IEEE 493[8].

Table 1: Island Network Equipment Summary

Equipment	Rating	Quantity	Failure rate/year	MTTR (hours)	Repair/ year
Generator	34.5 MW	2 GTG	0.033	50	1.65
Electrical line	< 60 km	< 60 km	0.003	5	0.15
GIS	69 kV, 2500 A	2	0.004	12	0.01938
Main Busbar	69 kV	1	0.001	2	0.001
Battery bank	1500 mAh	1	0.008	4	0.008
Current transformer	2500 A	2	0.002	3	0.004
Potential transformer	69 kV/120 V	2	0.0015	2.5	0.003
Power transformer	60 MVA	2	0.012	72	0.02
Arresters	60 kV	2	0.001	6	0.002
Feeder bus	11 kV, 630A	2	0.018	5.5	0.03172
Isolators	11 kV, 630A	2	0.005	2	0.01
Generator Circuit breaker	66 kV	2	0.007	35	0.0104
Distribution transformer	2500 kVA	6	0.01	36	0.2
Protection Relay	5 A	2	0.003	2	0.006
Backup Diesel Generator	16 MW	1	0.035	45	1.575

The reliability of a system can be calculated by determining the cumulative failure rate as shown in Equation (3) [10]. The cumulative failure rate equals the negative natural logarithm of the threshold reliability (Rthj) as expressed in Equations (4) and (5). The failure rate function $\lambda_i^j(t)$ describes how the likelihood of failure changes over time.

$$R(t) = e^{-\lambda t} \quad (3)$$

$$Failure_{Rate} = \int_0^{T_i^j} \lambda_i^j(t)dt \quad (4)$$

$$\int_0^{T_i^j} \lambda_i^j(t)dt = -\ln({R_{th}}^j) \quad (5)$$

C. Reliability Centered Maintenance Steps

- **Phase 1: Study Preparation and Critical Item Selection**

Phase 1 to 3 were performed using the Pareto Principle, which states that 80% of maintenance issues arise from about 20% of equipment. This focuses analysis on high-impact components which represent in Equation (6).

$$Impact\ Factor = \lambda_i \times MTTR_i (6)$$

where λ_i is failure rate per year and $MTTR_i$ is Mean Time to Repair.

$$I_1 \geq I_2 \geq I_n \quad (7)$$

Cumulative impact factor and percentage were computed using Equations (8) and (9) [7].

$$CI = \sum_{j=1}^{i} Ij \quad (8)$$

$$P_i = \left[\frac{C_i}{\sum_{k=1}^{n} Ik}\right] \times 100 \quad (9)$$

where $\sum_{k=1}^{n} Ik$ is the total impact factor or all components. Applying Pareto Principle helped prioritize critical equipment for maintenance.

Table 2: High Priority Equipment Table

Equipment	Failure rate/year	MTTR	Cost of maintenance ($)/yr
Generators	0.03	50	200000
Power Transformer	0.01	72	150000
Circuit Breaker	0.0052	35	100000
Feeder Bus	0.01586	5.5	50000
GIS	0.0025	12	100000

According to the Pareto Principle, 80% of the impact comes from a few components. The top six contribute 97% of total impact and are prioritized in the RCM process. Selected equipment includes generators, power transformer, circuit breaker, feeder bus, and GIS. The backup diesel generator was excluded since it's non-critical. Cost data in Table 2 are from the IEEE Gold Book, partly hypothetical.

- **RCM Phase 2: Failure Mode and Effect Analysis (FMEA)**

In RCM Phase 2 (FMEA), failure modes were identified per IEC 60812:2018 [11], using the Risk Priority Number (RPN) as in Equation (10).

$$RPN_i = S_i \times D_i \times O_i \quad (10)$$

Optimization employed the Analytical Hierarchy. AHP, based on Saaty's scale [11], assigned importance levels through pairwise comparison:

Severity (S) is 2 times more important than Occurrence (O).

Severity (S) is 3 times more important than Detectability (D).

Occurrence (O) is 2 times more important than Detectability (D).

The Pairwise comparison matrix is given as A,

$$A_{pw} = \begin{pmatrix} 1 & 2 & 3 \\ \frac{1}{2} & 1 & 2 \\ \frac{1}{3} & \frac{1}{2} & 1 \end{pmatrix}$$

Normalized as:

$$A_{NM} = \begin{pmatrix} \frac{1}{1+\frac{1}{2}+\frac{1}{3}} & \frac{3}{2+1+\frac{1}{2}} & \frac{5}{3+2+1} \\ \frac{\frac{1}{2}}{1.833} & \frac{1}{3.5} & \frac{2}{6} \\ \frac{\frac{1}{3}}{1.833} & \frac{\frac{1}{2}}{3.5} & \frac{1}{6} \end{pmatrix} = \begin{pmatrix} 0.545 & 0.571 & 0.5 \\ 0.273 & 0.286 & 0.333 \\ 0.181 & 0.143 & 0.167 \end{pmatrix}$$

$$Eigen\ Vector = average\ of\ each\ row = \begin{pmatrix} (0.545 + 0.571 + 0.5) \div 3 \\ (0.273 + 0.286 + 0.333) \div 3 \\ (0.182 + 0.143 + 0.167) \div 3 \end{pmatrix} = \begin{pmatrix} 0.539 \\ 0.297 \\ 0.164 \end{pmatrix}$$

Weight matrix is given as:

$$\begin{pmatrix} 0.539 \\ 0.297 \\ 0.164 \end{pmatrix} = \begin{pmatrix} Ws \\ Wo \\ Wd \end{pmatrix}$$

The AHP uses this equation to calculate weighted RPN number as in Equation (11).

$$RPN = RPN_w = (S \times W_S) + (O \times W_O) + (D \times W_D) \quad (11)$$

where W_S is weight of Severity, W_O is weight of Occurrence and W_D is weight of Detection.

The consistency of pairwise matrix was validated using the Equation (12) and (13) to confirm if the decision is logically acceptable in practice [12].

$$CI = \frac{\Lambda max - n}{n-1} \quad (12)$$

$$CR = \frac{CI}{RI} \quad (13)$$

where CI is Consistency index, Λmax is largest Eigenvalue of matrix A. RI is Random Index (RI for a 3×3 matrix is 0.58) and CR is Consistency Ratio.

If $CR < 0.1$, the judgments are consistent.

$$\Lambda max = A \times \begin{pmatrix} 0.539 \\ 0.297 \\ 0.164 \end{pmatrix} = \begin{pmatrix} 1.625 \\ 0.899 \\ 0.496 \end{pmatrix}$$

$$\Lambda max = \frac{1.625}{0.539} = 3.015, \frac{0.899}{0.297} = 3.025, \frac{0.496}{0.164} = 3.024$$

$$\Lambda max = \frac{3.105 + 3.025 + 3.024}{3} = 3.021$$

$$CI = \frac{3.0241 \ - \ 3}{3 \ - \ 1} = 0.0105$$

$$CR = \frac{CI}{RI} = \frac{0.0105}{0.58} = 0.018$$

Since the CR is 0.018, which is much less than 0.1, the matrix is consistent.

After weighted RPN Number was calculated the result was normalized to determine the failure mode with the most impact on the island network equipment using Equation (14).

$$Normalized - RPN_j = \frac{w\_RPN_i - w\_RPN_{min}}{w\_RPN_{max} - w\_RPN_{min}} \quad (14)$$

where w_RPN_i is weighted RPN number, w_RPN_{max} is maximum weighted RPN , w_RPN_{min} is minimum weighted RPN.

The results obtained in the FMEA process will be sampled in the result section.

- **RCM Phase 3: Logic Decision Tree Analysis (LTA)**

The failure modes considered for this research are the High Impact Failure mode; those whose normalized weighted RPN value is above 0.7. The standard scaling threshold according to IEC60812:2018 standard is as follows,

High Impact Failure Modes: $Normalized\ RPN > 0.7$

Medium Impact Failure Modes: $0.4 < Normalized\ RPN < 0.7$

Low Impact Failure Modes: $Normalized\ RPN < 0.4$

IV. Results and Discussion

The system model was analysed using ETAP IDE reliability tools. Based on

FMEA recommendations, a new model was developed. In the new model, the GIS was upgraded to a double bus, a bus-tie transformer was added, and the power transformer was replaced with a 37.5 MVA unit to enhance reliability. These upgrades improved system performance by reducing failure rates and outage durations. The feeder bus and GIS redundancy improved overall network reliability, while the upgraded transformer supported higher load capacity. Interruption costs for the main bus, feeder bus, and step-up transformer were not calculated individually because their impacts are already reflected through the connected loads. Overall, the improved model achieved better reliability performance The modified model is presented in Figure 2.

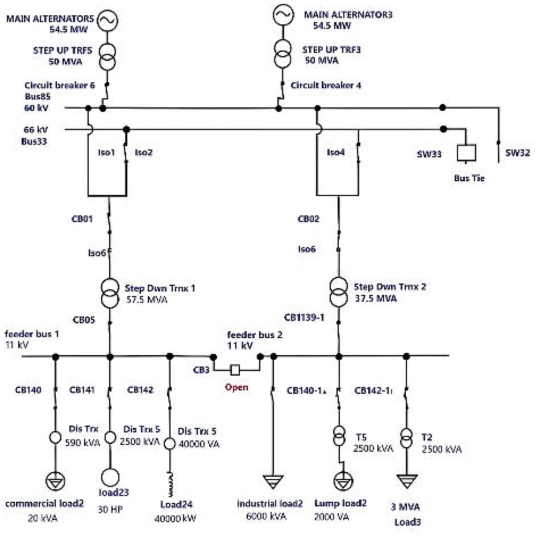

Figure 2: Modified Island Network based on Recommendation

The analysis shows that applying the AHP-FMEA framework significantly improved system performance. The high impact failure modes were prioritized for maintenance intervention. Implementing recommended actions for these high and medium impact modes led to a 56.36% reduction in interruption duration and a 64.87% decrease in failure rate, indicating better system availability and reliability.

The integrated decision framework combined RPN based prioritization with maintenance strategy selection, ensuring that critical failures received predictive or condition-based maintenance, while medium impact failures were further evaluated for the most suitable strategy. This proactive approach enhanced resource allocation, minimized risks, and strengthened overall system reliability and operational efficiency.

Based on system analysis and operator feedback, targeted maintenance actions were recommended for each equipment category to address high and medium impact failure modes. Using these actions, a modified RCM task selection framework was developed to enhance reliability and optimize resources as shown in Figure 3.

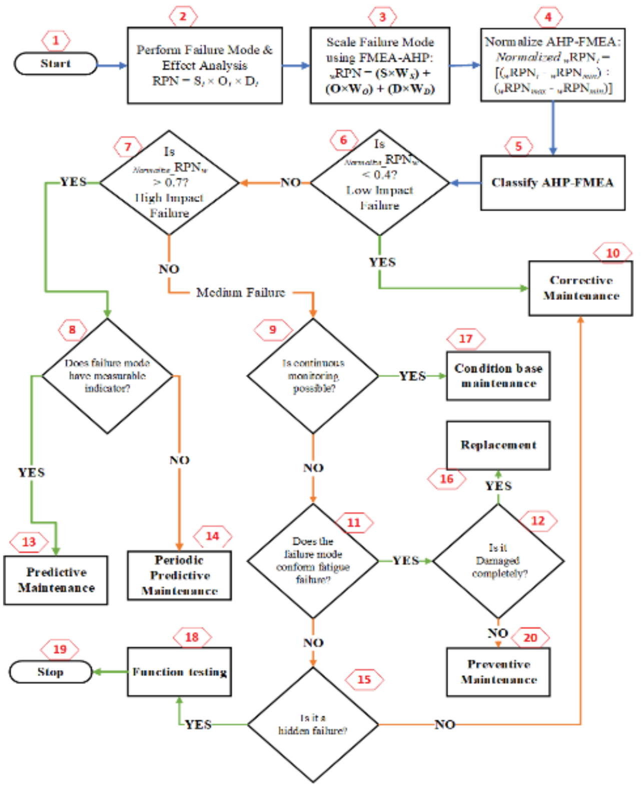

Figure 3: Structured RCM Decisions Framework for Failure

The integrated AHP-FMEA framework combines risk prioritization (RPN) with maintenance strategy selection. The high impact failures were managed using predictive or condition-based maintenance for early fault detection. Medium impact failures followed the same logic with further evaluation. This proactive approach improves reliability, reduces risks, and supports efficient maintenance planning.

V. Conclusion

This study demonstrated the effectiveness of a structured Reliability Centered Maintenance (RCM) framework in enhancing the reliability of island network systems. Through ETAP modeling, Pareto analysis, FMEA, and AHP, critical components and high impact failure modes were systematically identified and addressed with targeted maintenance strategies. The improved network exhibited lower failure rates and reduced outage costs, validating the proposed methodology. This research provides a robust, data-driven approach for optimizing maintenance decisions, improving system performance, and supporting long-term operational reliability in critical power infrastructure.

VI. Acknowledgement

We express our profound gratitude to Almighty God for His grace, mercy, and blessings throughout this research. Our sincere appreciation goes to the Department of Electrical and Electronics Engineering, Nigeria Defence Academy, for providing an enabling environment and resources that supported this work. We are especially grateful to the Head of Department for his leadership, encouragement, and valuable contributions. We also acknowledge the support and guidance of all faculty members whose input contributed to the successful completion of this research.

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