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Original Article

Integrated reliability-centered maintenance for power system reliability and resilience: A comprehensive review

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ABSTRACT

This study reviews the integrated reliability-centered maintenance (RCM) strategies designed to improve the reliability and resilience of power systems. It discusses the inherent challenges of maintaining modern electrical networks, which are characterized by an aging infrastructure, increasing energy demands, dynamic components, and inadequate maintenance practices. It also evaluates traditional maintenance strategies, including preventive, predictive, and reactive maintenance. By combining RCM with optimization techniques, such as fuzzy inference system, Genetic Algorithms, or Failure Mode Effects and Criticality Analysis, this review demonstrates how data-driven, artificial intelligence-enhanced maintenance strategies can optimize resource allocation, reduce downtime, and improve overall system performance. The study also identifies key research gaps, such as the need for more comprehensive criteria for critical equipment selection, improved reliability modeling under preventive maintenance actions, and integration of risk management. Addressing these gaps is essential for developing robust and adaptable maintenance frameworks to meet the evolving challenges of modern power networks.

Keywords: Fuzzy inference system, genetic algorithm, reactive maintenance, reliability-centered maintenance

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INTRODUCTION

An electric power network is inherently constrained, making the concept of a fully reliable system largely theoretical. The presence of numerous dynamic components, aging infrastructure, system instabilities, natural disturbances, and rising energy demands continuously challenges its operational reliability. These factors necessitate robust management and strategic maintenance approaches to mitigate risks and enhance system performance.[1] A fundamental strategy for mitigating these challenges and enhancing system reliability is the integration of a robust and appropriate maintenance scheme within the network's operational framework.[2] Reliability-centered maintenance (RCM) has proven to be a highly effective approach for achieving this essential integration.[3] Through its proactive approach to identifying and addressing potential failure modes, proper maintenance guided by RCM principles can significantly enhance the reliability and resilience of power system networks. The resilience of electrical grids is a growing concern and is of paramount importance in contemporary energy infrastructure management. Maintenance strategies also contribute significantly to system resilience by helping power networks withstand and recover from disruptions, such as extreme weather events, cyberattacks, or operational stresses. This heightened focus is driven by several converging factors, including the extensive expansion and increasing complexity of modern power systems, widespread use of distributed generation, mostly from renewable energy sources, and escalating challenges posed by adverse climatic conditions.[4]

Integrated RCM is an advanced approach that enhances traditional RCM by combining its core principles with modern optimization techniques, such as bee colony optimization, Genetic algorithms, fuzzy inference system, failure mode effect and criticality analysis (FMECA), and other advanced methodologies.[5] This integration helps improve maintenance decision-making, optimizes resource allocation, enhances system reliability, extends asset life, and reduces operational costs. Proactive strategies, such as condition-based maintenance and predictive maintenance (PdM), utilize real-time data

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to identify faults before they develop into major failures.[6] Figure 1 presents a comparison of reactive, preventive, and PdM in terms of maintenance costs and frequency. RCM further enhances maintenance efficiency by prioritizing tasks based on the criticality of components, ensuring that high-risk elements receive more attention while avoiding unnecessary servicing of low-risk assets. Instead of applying a uniform preventive maintenance (PM) schedule, utilities can focus their resources on high-failure-rate components and optimize their maintenance efforts.[7] This paper provides a comprehensive comparative review of various maintenance techniques used in the power sector, along with an in-depth analysis of optimization methods that can be effectively integrated with RCM to enhance the reliability of electric network and resilience the grid.

RCM

RCM is a proactive maintenance methodology aimed at preserving system functions by systematically identifying the necessary maintenance activities to ensure that physical assets continue to perform their intended roles within their present operating context.[8]

Although RCM is often seen as a modern concept, its origins date back to the 1960s.[9] Introduced by Nowlan and Heap in 1978, RCM was first applied in aviation. Initially, scheduled overhauls were believed to be necessary for optimal performance; however, this approach proved impractical for the Boeing 747. Studies have shown that regular overhauls do not significantly improve the reliability unless a dominant failure mode exists.[10] To better understand RCM, Figure 2 shows a brief taxonomy of maintenance philosophy. RCM falls under the category of proactive or planned maintenance because it emphasizes failure analysis and preventive strategies rather than waiting for breakdowns to occur.[11]

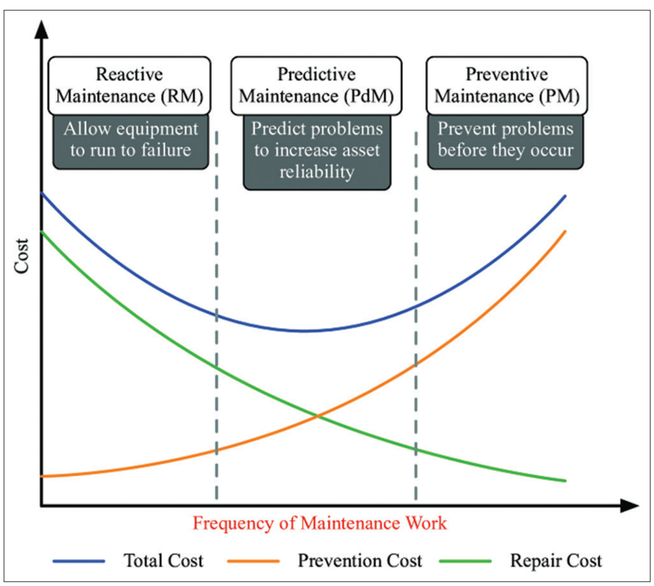

Figure 1: Cost against frequency of maintenance for centered maintenance, reactive maintenance, and predictive maintenance

Comparison of RCM with Traditional Maintenance: Benefits, Challenges and Applications

The selection of a good maintenance strategy frequently entails a trade-off between proactive and reactive actions, considering criteria such as equipment criticality, failure patterns, cost-effectiveness, and organizational objectives.

Figure 3 shows the maintenance framework for RM, PM, and PdM. Although traditional maintenance approaches such as reactive maintenance (RM), PdM, and PM remain in use, the integration of advanced techniques, such as RCM, enhances fault prediction and diagnosis accuracy, resulting in more efficient and cost-effective maintenance practices in the power industry.[12]

In summary, RM incurs the lowest prevention costs because it employs a run-to-failure approach, postponing scheduled interventions until failure occurs as seen in Table 1. By contrast, PM minimizes repair expenses by scheduling regular downtimes for services, thus reducing the likelihood of unexpected breakdowns. PdM leverages condition monitoring to optimize the timing of maintenance activities, achieve an optimal balance between repair and prevention costs, and minimize unplanned downtime without the expense of overly frequent servicing.

POWER SYSTEM RESILIENCE AND RELIABILITY

The potential of integrated RCM extends to improving both the reliability and resilience of electric power network. Power system reliability and resilience are essential components of modern electrical infrastructure, ensuring that the system can withstand disturbances and effectively recover from disruption. Reliability focuses on preventing failures, whereas resilience emphasizes the capacity of the system to adapt and recover from unexpected events.[13]

Power System Reliability

Reliability is the possibility that a system, component, or equipment will perform its planned function without failure for a given period, as instructed. This is a key factor in engineering, maintenance, and safety applications to ensure minimal downtime and operational efficiency. Reliability indices serve as versatile tools for assessing the reliability of a system, equipment, component, or network, helping to identify weak points effectively.[14] Mathematically, the reliability R(t) is expressed as

$$R(t) = e^{(-\lambda t)} \quad (1)$$

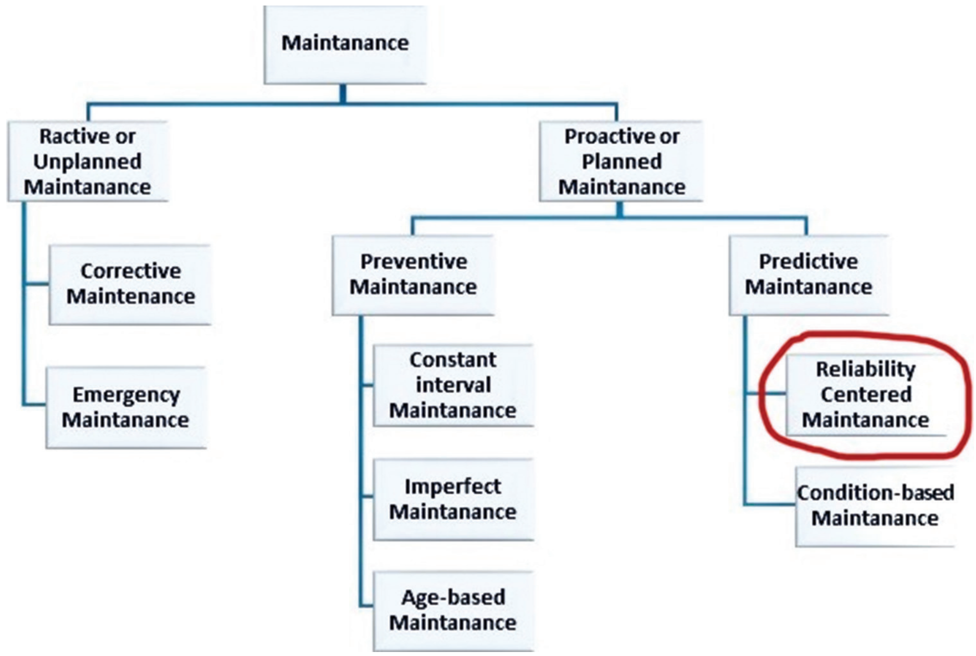

Figure 2: Taxonomy of maintenance philosophy

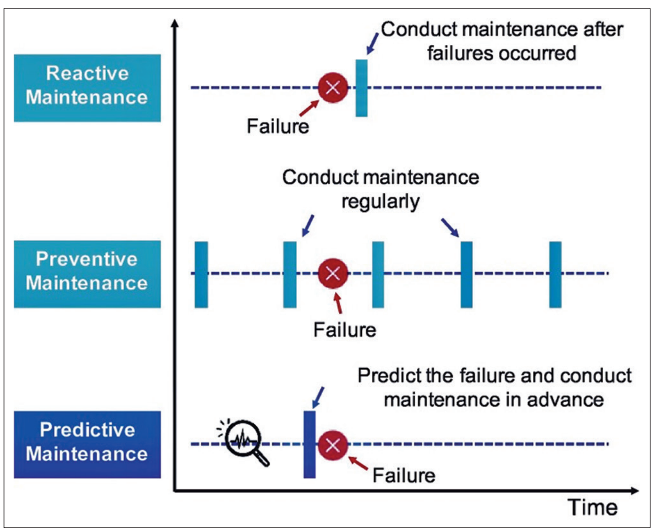

Figure 3: Maintenance framework for reactive maintenance, preventive maintenance, and predictive maintenance

Where: R(t) = system Reliability
λ = Failure rate (constant for exponential distribution)
t = Time of operation

Mean Time Between Failure (MTBF)

When a failure is observed and the system is repaired and operational again, the interval between these periods is the MTBF. It is given mathematically as

$$MTBF = m = \frac{Total\,Working\,Time \\ -Total\;Btreakdown\,Time}{Numbber\;of\;Breakdown} \quad (2)$$

Failure Rate (λ)

The failure rate represents the frequency at which a system or component fails within a given time frame. It is determined as the reciprocal of the MTBF. Mathematically, it is expressed as

$$\lambda = \frac{1}{MTBF} \quad (3)$$

Power System Resilience

As power systems face increasing challenges from climate change and the integration of various renewable energies, the concept of resilience has gained prominence.[25] Resilience assessment methods are designed to evaluate a system's capacity to endure and recover from disturbances effectively. For instance, a new resilience metric has been introduced to measure system resilience across different restoration capacities. These approaches help identify optimal strategies for improving system reliability and resilience while considering maintenance costs.[15] To effectively manage power system reliability and resilience, it is important to identify critical components and prioritize maintenance their maintenance activities.

CONCEPT OF INTEGRATED RCM IN POWER SYSTEM NETWORK

Standalone RCM approaches often face limitations in complex systems with multiple interacting components. The task selection process often relies heavily on expert judgment, which can introduce subjectivity and potential bias.[16] In

Table 1: Comparison of the advantages, challenges, and applications of RCM, RM, PM, and PdM

Maintenance strategy	Advantages	Challenges	Good applications	Not good applications
RM	• Maximizes equipment usage and output efficiency. • Reduces PM costs.	• Leads to unplanned downtime. • Risk of more damage to machine. - Results in higher repair costs.	• Suitable for redundant or non-critical equipment. • Effective for repairing low-cost equipment after failure.	• Not ideal when equipment failure poses a safety hazard. • Unsuitable for systems requiring 24/7 availability.
PM	• Lowers repair costs. • Reduces equipment malfunctions and unexpected failures.	• Requires maintaining spare parts inventory. • Increases planned downtime	• Best for equipment prone to failure. • Suitable for assets with random failures unrelated to maintenance.	• Not suitable for critical systems where failure leads to major disruptions or safety risks.
PdM	• Offers a holistic assessment of equipment condition • Avoids premature replacement of components with remaining useful life.	• High initial investment in infrastructure and setup.	• Highly effective for equipment with predictable failure patterns that can be monitored in a cost-efficient manner.	• Unsuitable for equipment with failure modes that are difficult to predict accurately.
RCM	• Optimizes maintenance strategies based on risk and cost. • Balances.	• Requires detailed analysis and expertise. • Can be complex and time-consuming to implement.	• Ideal for critical systems where reliability and safety are paramount. • Used in industries like power generation.	• May not be necessary for low-risk, non-critical equipment where simpler strategies are sufficient.

RM: Reactive maintenance, PM: Preventive maintenance, PdM: Predictive maintenance, RCM: Reliability-centered maintenance

addition, without integration with optimization techniques, RCM may not effectively schedule maintenance or allocate resources under operational constraints, limiting its overall effectiveness in dynamic environments.[17] This has led to the concept of integrated RCM, which involves combining the principles and methodologies of RCM with various optimization techniques.

Review of Related Literature

Reliability-enhancement strategies in power systems have evolved from traditional approaches to advanced techniques. Among PM, CM, and PdM, the PdM has shown significant superiority over CM and PM due to its proactive nature and ability to optimize maintenance activities.[26]

The selection of an optimal maintenance policy can significantly impact the efficiency, quality, cost, reliability, and profitability of a system.[18] A study conducted at Kaghaz Kar Kasra Co. applied Technique for Order of Preference by Similarity to Ideal Solution techniques to prioritize maintenance strategies, considering the cost, added value, safety, and feasibility of the maintenance technique.[19] This approach demonstrates the importance of considering multiple criteria when selecting maintenance strategies for power systems. Standalone RCM models have limitations in addressing the complexities of modern industrial systems and optimizing maintenance strategies. To address these limitations, researchers have proposed integrating RCM with various optimization techniques and complementary methodologies.[25]

Failure mode and effect analysis (FMEA) is one of the seven steps in the RCM process.[20] FMEA was officially structured in 1949 when military protocols were introduced for conducting FMECA.[16] The primary objective was to classify failures according to their impact on mission success and the safety of personnel and equipment. FMEA is used to identify potential failure modes, their causes, and their impact on a system.[21] It assesses three key factors: Severity, Occurrence, and Detection, which are combined to calculate the risk priority number which is a measure of failure mode significance. An alternative approach within FMEA is the analytic network process (ANP), which is an advanced version of the analytic hierarchy process (AHP).[22] ANP enhances risk prioritization by considering the connections between different risks. Unlike basic ranking methods, ANP recognizes that some risks influence others, making the analysis more realistic and leading to a more precise evaluation of critical factors.

The application of FMEA and AHP-FMEA has been shown to improve the maintenance prioritization process by effectively weighing the system risks. Previous studies have demonstrated that AHP offers greater efficiency than traditional FMEA methods. A key advantage of AHP is its ability to perform consistency checks, ensuring that judgments made during pairwise comparisons are logically sound. Airoboman *et al*.[27] study focuses on assessing risks in injection substations in Nigeria within Kaduna Metropolis by employing FMECA to identify critical components affecting feeder reliability. The findings of this study indicate that inadequate maintenance strategies can severely affect network reliability, emphasizing the urgent need for improved maintenance policies.

The integration of RCM with optimization techniques provides more quantitative and data-driven decision-making, addressing the limitations of traditional RCM.[28] For example, this Alizadeh *et al*.[29] study developed a two-stage robust RCM model that accounts for failure rate uncertainties and solved it using benders decomposition and outer approximation algorithms. The results demonstrate that the proposed approach outperforms deterministic models by achieving higher reliability and financial efficiency in both RBTS2 and Finnish distribution systems.[29]

Summary of Literature Review

This section presents a brief summary of key findings from the literature on integrated RCM strategies. Table 2 synthesizes these insights and offers a clear summary of how each strategy contributes to operational efficiency and system reliability.

IDENTIFIED GAP

Despite advancements in integrated RCM, several critical research gaps remain. Addressing these gaps will enhance the effectiveness, applicability, and robustness of RCM methodologies across various industries.

Advancing Criteria for Critical Equipment and Failure Selection

Many RCM models lack clear criteria for identifying critical equipment and failure modes. For instance, Shin *et al*.,[30] fail to explain component selection for maintenance scheduling. Future research should develop selection frameworks that combine reliability, operational significance, and cost impact.

Improving Integration of RCM with Optimization Techniques

Hybrid RCM approaches using hybrid linguistic (HL)-FMEA, co-evolutionary multi-objective particle swarm optimization (CMPSO), ANP, and Developed Maintenance Decision Tree (DMDT) have improved generator maintenance. However future research should validate models across industries and assets, design adaptive algorithms for real-time adjustments use

Table 2: Summary of literature review

Author (year)	Method	Case study	Nature of work	Remark
Jafarpisheh *et al*. (2021)	PROMETHEE, MCDM -FMECA, TOPSIS, AHP	A mining transportation machine for the limestone complex at Esfahan	Critical machines were identified using PROMETHEE and FMECA for selecting and prioritizing high-risk failures. TOPSIS was applied to prioritize failures' risk.	Used for high-risk failures
Alrifaey *et al*. (2020)	HL-FMEA, CMPSO, ANP, DMDT	An electrical generator in a oil and gas plant in Yemeni	The proposed model provided optimal maintenance policies and scheduling for the electrical generator in a well-structured, economical, and effective plan, outperforming previous studies	Risk and cost optimization
Torun and Çetinkaya (2019)	FIS	conventional milling machine	The result helped in deciding machine criticality levels for maintenance activities based on some reliability metrics, such as MTBF, machine occupancy, and breakdown cost.	Optimum maintenance strategy
Ankush and Prasad (2024)	GA, FTA	marine diesel engine	Underperforming and degraded components were evaluated using FMEA and FTA, a reliability model was designed to improve maintenance	Maintenance optimization
Ravaghi (2020)	Markov model	Electrical Distribution Network	The method was implemented on bus number four of the Roy Billinton test system to evaluate its efficacy.	Economic and reliability
Goutam *et al*. (2025)	GA, SA, BSO	coal-fired power plants in India	Each algorithm's effectiveness is evaluated based on its ability to achieve the desired balance between maximizing plant availability and reducing maintenance expenditures	Improves availability and reduces maintenance costs.

GA: Genetic algorithm, FIS: Fuzzy inference system, FMECA: Failure mode effect and criticality analysis, FEMA: Failure mode and effect analysis, MTBF: Mean time between failure, AHP: Analytic hierarchy process, ANP: Analytic network process, PROMETHEE: Preference ranking organization method for enrichment of evaluations, MCDM: Multi-criteria decision making, FMECA: Failure mode, effects critical analysis, TOPSIS: Technique for order of preference by similarity to ideal solution, HL-FMEA: Hybrid linguistic failure mode and effect analysis, CMPSO: Co-evolutionary multi-objective particle swarm optimization, FTA: Fault tree analysis, SA: Simulated annealing, BSO: Bee colony optimization machine learning (ML)-driven predictive models to improve RCM decisions.

Prioritizing Maintenance with Economic Considerations

RCM must guide maintenance based on cost-effectiveness and account for PM budgets and outage costs.

Although integrated RCM models have made significant progress in optimizing maintenance and reliability, key gaps remain. Addressing these gaps will ensure the continued evolution of RCM, making it more robust, adaptive, and effective for modern asset management.

CONCLUSION

The future of power system maintenance is shifting toward data-driven, Artificial Intelligence-enhanced, and condition-based strategies that promote continuous improvement and adaptability to evolving operational challenges. An optimized maintenance policy ensures that the right personnel, equipped with appropriate tools, execute maintenance tasks at the right time and location, ultimately improving operational efficiency and resource utilization. By emphasizing proactive maintenance and leveraging emerging technologies, power utilities can enhance system reliability, minimize downtime, and establish more resilient and sustainable electrical networks.

This study emphasizes the promising role of integrated RCM approaches in enhancing maintenance decision-making; however, further research is required to validate the effectiveness of these hybrid models across diverse industries and asset types. Addressing these research gaps will strengthen the applicability of integrated RCM in modern asset management, fostering a more data-driven and efficient approach to power system maintenance.

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