

Preventive Maintenance Optimization Using a Reliability-Based Approach

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Abstract— Electrical substations are critical components in power transmission and distribution networks. They are responsible for transforming voltage, routing current safely, and protecting the entire grid against overloads. The traditional maintenance management model is reactive (emergency-driven), leading to reduced reliability, availability, and safety. In this paper, to reduce maintenance uncertainty, minimize the frequency and impact of system failures, and enhance operational safety, Reliability-Centered Maintenance (RCM) is applied to evaluate electrical substations. Following a Failure Mode and Effects Analysis (FMEA), a risk matrix is introduced to evaluate the criticality of failure modes, and a logic decision method is used to determine maintenance strategies for high-risk faults. This approach provides valuable technical support for the safety management of the SONELGAZ Company.

Keywords—Reliability Centered Maintenance(RCM), availability, industrial performance, preventive maintenance.

1. Introduction

Reliability-Centered Maintenance (RCM) originated in the civil aviation industry in the 1960s with the introduction of the Boeing 747 series, driven by the need to reduce preventive maintenance (PM) costs while achieving an optimal level of reliability. In 1975, The U.S. Department of Commerce formally defined the RCM concept and declared that it should be used in all major military systems [1]. In the 1980s, The Electric Power Research Institute (EPRI) introduced RCM into the nuclear power industry. In 1997, The "RCM II" methodology extended the scope of RCM analysis to all physical assets (tangible assets). This refined the theory of RCM and significantly broadened its field of application. Today, RCM is used or being considered by an increasing number of electrical utilities, railway companies, and petrochemical industries [2].

As experience proves, the application of RCM technology has yielded excellent results in several industrial sectors.

In France, the RCM concept was introduced in 1984 under the impetus of EDF, which sought to apply it to its nuclear power plants. This led to the OMF project (Reliability-Centered Maintenance Optimization), defined as a maintenance policy aimed at defining a preventive maintenance program to help maintain, or even improve, the reliability of system functions that are critical to the safety and availability of nuclear power units.

The main objectives of the OMF project are, Maintaining and improving nuclear safety, Cost control and the economic optimization of maintenance, Implementing a structured methodology based on functional failure analysis and Using operating experience (feedback) to readjust maintenance programs.

The idea of adapting RCM to general industry was developed in France around 1996. This approach relies on the technical analysis of equipment and a strong involvement of maintenance personnel. The core objective remains to improve equipment availability.

Based on the principle of guaranteeing safety and reliability, RCM reduces the workload associated with periodic maintenance by 40% to 60% [3, 4, 5].

To highlight the practical importance of our approach, we illustrate it using real data from an HT/MT electrical distribution substation located in western Algeria, provided by the National Electricity and Gas Company (SONELGAZ). These data include, in particular, the list of critical components, information derived from FMEA (Failure Modes and Effects Analysis), as well as the data required for RCM decision-making.

2. Reliability-Centered Maintenance Principles

RCM is a systematic process applied to electrical equipment to ensure power continuity and grid stability. It defines the required performance standards, such as dielectric strength or tripping speed, within their specific operating context (HV/MV). This process analyzes critical function losses (e.g., insulation failure), failure modes (e.g., arcing, overheating), as well as their frequency and impact on network security. It enables the establishment of preventive maintenance plans—such as oil analysis for transformers or infrared thermography—before a breakdown occurs. RCM thus optimizes the management of strategic spare parts and guides decisions regarding the renewal or design modification of electrical substations, while placing personnel safety and environmental protection (management of SF6 gas, dielectric oils) at the core of its priorities [6].

2.1. Implementation Phases of the RCM Approach

The RCM process is structured into four primary phases, as illustrated in Figure 1.

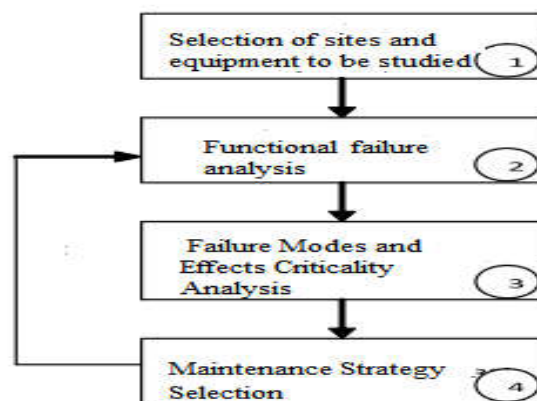


Fig.1. Framework for the maintenance program performance evaluation based on RCM.

2.2. Analysis of Failure Modes and Effects (FMECA)

It is a methodology intended to identify and analyze potential failures and to quantify the effect that these failures have in normal operation of the production system in question and to minimize the effects on production, facilitating planning of work activities, Basten et al (2012) and strategies to carry out to optimize the reliability of the installation, setting the functions of each component and its functional failures with its corresponding failure modes. With FMECA technology three parameters are used: severity, occurrence and detection probability, which together form the basis of equitable assessment of risk RPN (Risk Priority Number). To quantify this parameter it is needed an early qualification of failures and prioritizing corrective, preventive predictive and proactive tasks to be done in order to eradicate or control these failures [7,8].

For the calculation of RPN use following equation:

$$RPN = \text{Severity} \times \text{Occurrence} \times \text{Detection Probability} = S \times O \times D \tag{1}$$

Once the necessary activities for improvement derived from the procedure FMCA have been affected, the RPN evaluation is implemented again and the process is begun again until the control of the failures is met [9].

Table 1
Parameters FMECA (Occurrence)

Occurrence (O)		
Possible rate of occurrence	Criterion of occurrence	Value
Once every 12 years	Failure near zero or no	1
Once every 10 years	Very low, failure isolation, rarely	2
Once every 8 years	Low, often fail	3
Once every 6 years		4
Once every 4 years	Average, occasional failure	5
Once every 2 years		6
Once every year		7
Once every 6months	High, frequent failure	8
Once every month		9
Once every week	Very high, very high failure	10

Table 2
Parameters FMECA (Severity)

Severity (S)		
Duration of service interruption	Criterion of severity	Value
> 8h	Very catastrophic	8
7h	catastrophic	7
6h	Very serious	6
5h	Serious	5
4h	Medium	4
3h	Significant	3
2h	Minor	2
1h	Very minor	1
30 min	Small	0.6
< 30 min	Very small	0.2

Table 3
Parameters FMECA (Detectability)

Detectability (D)		
Level of detectability	Criterion of detectability	Value
Not detectable	Impossible	10
Difficult to detect	Very difficult	9
	Very late	8
Detecting random (Unlikely)	Not sure	7
	Occasional	6
Possible detection	Low	5
	Late	4
Reliable detection	Easy	3
	Immediate	2
Detection at all times	Immediate corrective action	1

Table 4

Parameters FMECA (Criticality)

Criticality (C)		Risk or Hazard
Degree of criticality	Value	
Minor	0 – 30	Acceptable
Medium	31 – 60	tolerable
High	61 - 180	
Very high	181 – 252	Unacceptable
Critical	253 - 324	
Very critical	> 324	

Tables 1–4 present the evaluation criteria for each parameter: occurrence frequency (O), severity (S), detectability (D), and criticality (C).

3. Case study

This section presents a case study to illustrate and demonstrate the practical effectiveness of the proposed methodology.

The electrical substation illustrated in Figure 2 is HT/MT substation. The architecture features a double busbar system (SB1 and SB2) linked via a bus coupler bay (Coupling), ensuring high operational flexibility and preventing power supply interruptions during maintenance. The substation is energized by two 60 kV overhead lines (L1 and L2). On the distribution side, three identical outgoing bays are connected to the busbars. Each bay integrates bus-selection disconnectors, a circuit breaker (CB), instrument transformers (CT and VT), and feeds a dedicated power transformer (PTR). Surge arresters (PL) and earthing switches (G) are implemented throughout the system to ensure comprehensive overvoltage and personnel protection[10].

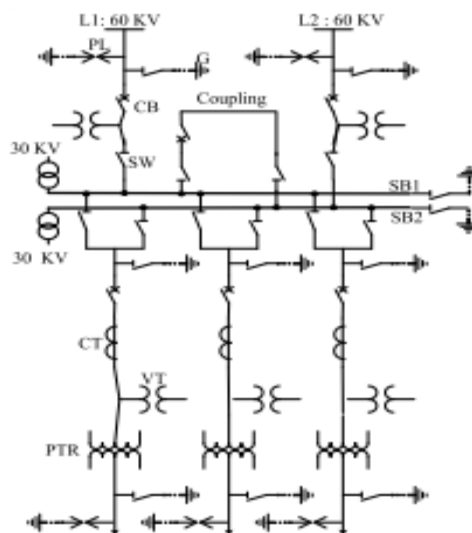


Fig.1. H/MT substation

The second phase of the RCM framework involves a two-level functional analysis of the substation. First, an external analysis is conducted based on the context diagram in Figure.2, to map the global interactions between the substation and its environment (including dispatching control centers, input/output power flows, environmental risks, and human operators).

Second, an internal analysis performs a technical functional decomposition to define the specific operational duties of each individual asset, such as the circuit breakers, disconnectors, and transformers shown in Figure 3. This integrated approach establishes the essential baseline required to systematically identify and categorize functional failures within the system."

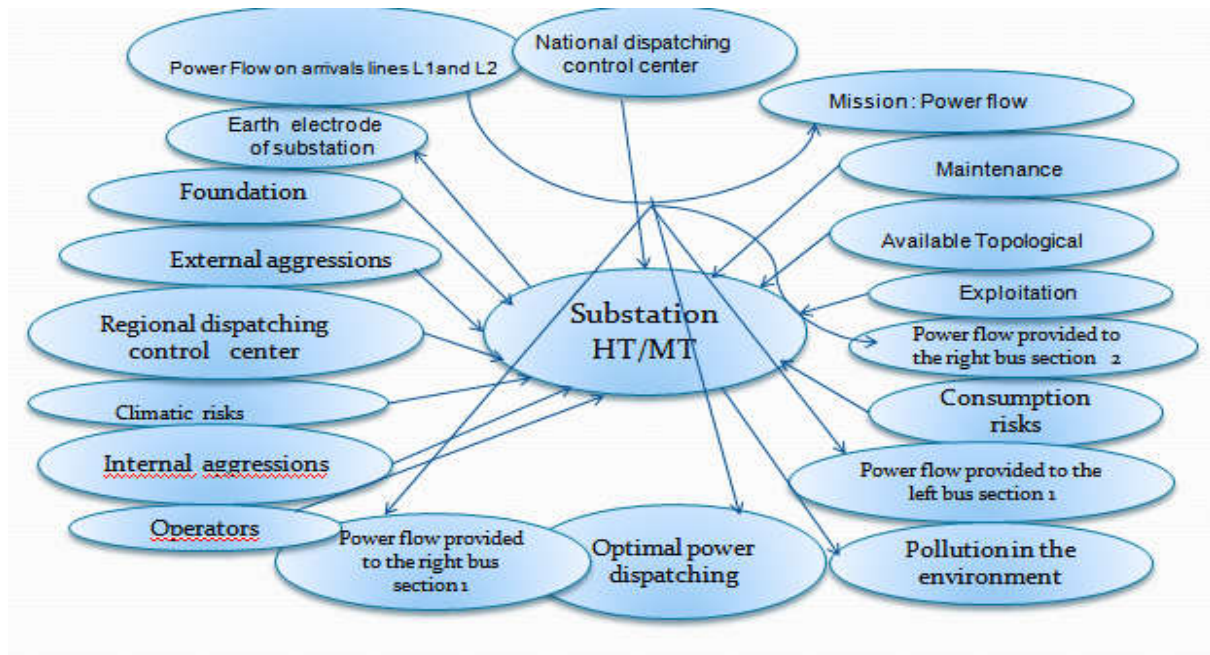


Fig.2. Context diagram of the substation and its external environment

Transformation Substation	60 kV Incoming Line Bays	[PL], [G], [CB], [SW]
	30 kV Double Busbar System	[SB1], [SB2], [Coupling]
	Transformation Outgoing Bays (HTA Side)	Bays 1, 2, 3: [DS] -> [CB] -> [CT] -> [VT] -> PTR]

Fig.4. Internal functional decomposition of the substation.

The results illustrated in the FMEA application table 6 show that:

- each component may present several failure modes;
- each failure mode may result from one or more causes;
- failure causes may originate from inside or outside the system.

After determining the criticality of each component from the FMEA table, a maintenance strategy was defined in the form of decision rules establishing the sequence of maintenance actions to be carried out. However, the selection of maintenance tasks is based on three main criteria: economic criterion, effectiveness, and applicability. For each task, the intervention frequency, allocated time, responsible personnel, and associated spare parts are specified.

Table 7
Classification of components according to their criticality

Element	Criticality	Maintenance action
EL	360	Systematic preventive maintenance (Regular corridor inspections, thermal imaging, and immediate line clearing)
PT	294	Condition-based & predictive maintenance (Dissolved gas analysis, oil testing, and continuous thermal monitoring)
CB	144	Systematic preventive maintenance (Contact resistance tests,

		mechanical timing tests, and periodic lubrication)
IS	108	Systematic preventive maintenance (Regular cleaning/washing to prevent pollution flashovers, silicone coating application)
DS	60	Corrective & minor preventive maintenance (Visual checks, annual cleaning of contacts, and mechanical alignment checks)
F	45	Corrective maintenance (Run-to-failure strategy: immediate replacement upon melting or clearing)
B	24	Routine preventive inspection (Annual bolting torque verification and thermographic scan during low load)
PL	8	Corrective maintenance (Visual inspection after major lightning storms, replacement only upon structural failure or leakage current trip)

4. Conclusion and Future Perspectives

This paper successfully presented a structured framework for optimizing maintenance policies within strategic electrical infrastructures by applying the Reliability-Centered Maintenance (RCM) methodology combined with Failure Mode, Effects, and Criticality Analysis (FMECA). Applied practically to an HT/MT transformation substation of the SONELGAZ Company in Western Algeria, this approach replaces the traditional reactive maintenance model (emergency-driven) with a proactive and mapped vision of industrial risk. The primary insights and contributions of this study are summarized as follows: Rigorous Risk Prioritization: The evaluation of the criticality index C , highlighted that the transmission line (EL, $C=360$) and the power transformer (PT, $C=294$) represent the most critical assets of the substation. This demands an immediate shift toward systematic and condition-based preventive maintenance strategies (e.g., dissolved gas analysis, infrared thermography). Resource Optimization: Unlike a uniform and costly maintenance plan, the criticality matrix allows for the rational allocation of economic and human resources where the risk of power supply interruption is highest. Low-criticality components, such as the surge arrester (PL, $C=8$) or fuses (F, $C=45$), were efficiently assigned to corrective maintenance policies (run-to-failure strategy), thereby optimizing spare parts inventory management. Global Reliability Modeling: The system-level analysis demonstrates that the accumulation of failures, even minor or environmental (weather conditions, insulator pollution), exponentially degrades the global reliability of the electrical substation. Consequently, maintenance must no longer be managed asset by asset, but rather globally to guarantee power grid stability and service continuity. As a perspective, this RCM model establishes a solid operational baseline that can be seamlessly integrated into a Computerized Maintenance Management System (CMMS). Furthermore, the natural evolution of this research lies in the development of predictive maintenance algorithms based on artificial intelligence (Machine Learning), leveraging IoT sensor data installed on SONELGAZ transformers to anticipate insulation faults well before they reach the critical thresholds computed in this study.

Table 6
FMECA

FMECA : Analysis of failure modes effects and criticality						FMECA machine				
System : Substation HT /MT				Operational Phase:		Date : 23/04/2026				
Element	Function	Failure Mode	Cause	Effect	Detection	O	S	D	C	Maintenance plan adopted
Transmission line (EL)	Electrical transport	contact of two lines	Overheating, short-circuit, lightning and electric arcs, extreme weather conditions	Power supply interruption, impact on safety, and operational disruptions	Multimeter	9	8	5	360	<input type="checkbox"/> Corrective action for minor failures. <input type="checkbox"/> Systematic preventive maintenance. <input type="checkbox"/> Further engineering study: use cables of identical material (replacement).
Insulator (IS)	Isolate electrical conductors	Aging, flashover	Exposure to UV rays, humidity, and environmental pollution	Loss of power supply continuity	Visual inspection	6	6	3	108	<input type="checkbox"/> Corrective action: can be covered with silicone grease or washed regularly. <input type="checkbox"/> Ameliorative/improvement study. <input type="checkbox"/> Systematic preventive maintenance action.
Busbar (SB)	Electrical distribution	Short-circuit	Insulation defect	Sudden current surge, heat generation, and overheating	Visual inspection	4	3	2	24	Systematic preventive maintenance action.
Lightning Arrester (PL)	Overvoltage protection	Overvoltage	Atmospheric discharges (Lightning strikes)	Equipment damage and safety risks	Visual inspection	2	2	2	8	Corrective maintenance.

Circuit Breaker (CB)	Electrical protection	Short and long outages	Transient overvoltage, overload, and short-circuit	Repetitive tripping and consumer discomfort	Visual inspection and operational testing	6	4	6	144	<input type="checkbox"/> Systematic preventive maintenance action. <input type="checkbox"/> Ameliorative/improvement study. <input type="checkbox"/> Modification of system architecture.
Fuse (F)	Electrical circuit protection	Overloads	Excessive electrical loads, equipment operating malfunctions	Electrical safety issues, fire hazards, fuse melting	Multimeter	3	3	5	45	Replacement
Power Transformer (PT)	Voltage conversion	Low insulation, noise, trip at start	Overcurrent, material aging, fatigue, mechanical shock, vibration, and high ambient temperature	Increased losses, audible noise discomfort, and impact on power generation	Buchholz relay	6	7	7	294	<input type="checkbox"/> Special monitoring. <input type="checkbox"/> Conditional preventive maintenance.
Disconnecter (DS)	Electrical isolation	Hard opening / closing	Corrosion, improper operation, insulation defects, and mechanical wear	Equipment damage and safety risks	Insulation testing	5	4	3	60	Vacuum and clean all accessible parts by blowing out the transformer with nitrogen or dry air.

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