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Reliability Centered Maintenance - Quantitative (RCM-Q) Applied to Hydropower Plants: Analysis from the Zero-Base Transition to the Quantitative Process

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This paper aims to present the process of transitioning from a maintenance policy based on zero-base reliability to a maintenance policy based on quantitative-reliability (RCM-Q). The RCM-Q is applied, as a case study, in a Francis-type hydro generator, pointing out the difficulties in carrying out this transition. Each hydro generator´s asset system is divided into subsystems, and each operational subsystem has its failure modes analyzed by the tool Failure Mode Effects and Criticality Analysis (FMECA), to select the significant functions and prioritize the risks related to failure modes. The failure modes classification considers the indicators of impacts on the safety, environment, operation, and economic aspects of the process. Through life data analysis, based on maintenance and failure historical data, it is possible to determine the cumulative probability density function of failure (CDF) and the cumulative probability density function of repair for each subsystem. These functions will be used as input parameters of the discrete event simulation model, which, in turn, uses the representation of reliability block diagrams. The RCM-Q approach proved effective for the composition of preventive maintenance plans for a power generation system, pointing the priority assets for preventive monitoring according to their failure risks probability.

Resulting in an effective maintenance policy able to guarantee high levels of productivity and optimize costs and resources.

Keywords: Reliability centered maintenance - quantitative (RCM-Q), Francis hydro turbine, Availability, Optimal time interval, Preventive maintenance tasks

1. Introduction

In general, engineers and industrial plant managers see an adequate maintenance policy as the key strategy to ensure the total reliability and availability of their equipment (Bellinello et al., 2020). It is because the reliability analysis is the main support required by ISO 55000 (Asset management - Overview, principles, and terminology) to consistently manage the life cycle of assets (Favarão et al., 2019).

The RCM process to develop preventive maintenance plans included a selection of operating systems for methodology application, failure data collection (maintenance history database), logical tree analysis, and failure criticality analysis for tasks prioritization and risk mitigation purposes. (Afefy, 2010).

However, there is difficult to structure and maintain records with reliable data in industrial organizations. The difficulties of the maintenance task selection process (to compose the preventive plans) increase when the company's database information is incomplete, this is due to the lack of data management (Ghosh & Roy,2010).

Generally, the industries execute the failure analysis process only qualitatively due to the lack of data. This deficiency in the database makes it difficult to establish an operation and reliability risk curve, which is unfeasible for the RCM consolidation. The RCM process implantation without the quantitative phase does not determine the failure real risk and the effective impact on the industrial performance indicators, this makes it infeasible to establish an effective maintenance policy.

Consequently, the companies' objectives in terms of reliability and availability indicators are achieved. Thus, this article aims to develop a process of transition from zero-base reliability-centered maintenance process (RCM) to quantitative- reliability centered maintenance (RCM-Q).

Hydropower plants (UHEs) are structurally immense systems, which makes maintenance and operation activities very complex. As a result, the maintenance task selection process becomes complicated due to the knowledge requirements about the power generation system and its critical failure modes.

The RCM-Q approach considers the impact of electrical and mechanical failures in electrical power on the hydro-generator unit operation performance, through life data analysis, based on maintenance and failure historical data, it is possible to determine the main reliability and maintainability functions. These functions provide an overall analysis of system reliability, maintainability, and availability, assisting engineers and maintenance managers to identify the optimal time interval for performing the maintenance tasks.

This paper presents part of the results from a research project (PD-06491-0341/2014 entitled “Methodology for asset management applied to hydro generators based on reliability and maintainability mathematical models”) developed by the Federal University of Technology – Paraná (UTFPR) and the University of São Paulo (USP) in partnership with COPEL - Energy Company of Paraná State S.A (generation and transmission sectors). This research project aims to reach the scope of the research and technological development program applied to the electric sector, which is regulated by the Brazilian Electricity Regulatory Agency (ANEEL).

2. Quantitative analysis methods applied to RCM

The Reliability Centered Maintenance (RCM) concept evolved as an alternative to the traditional approach to restore the inherent reliability of a system at the minimum cost by developing preventive maintenance tasks necessary to ensure that equipment meets its reliability requirement, its concept provides a means to address basic questions to the development of applicable and effective maintenance plans (Afef, 2010; Eriksen, Utne & Lützen, 2021).

RCM is well-established and used to analyze failure mode's impacts on the operational performance of the industrial systems, directing efficient decision-making to establish specific strategies that aim to manage failure risks and block their effects (Sevik & Aven, 2011).

But most of the RCM application studies in industrial plants present a robust database returning reliable information to an efficient decision-making process about failure analysis (qualitative and quantitative RCM analysis).

Therefore, a quantitative approach to the failure-repair process from a robust database requires statistical and simulation methods.

Thus, this research proposes an RCM method that effectively applies this methodology (quantitative and qualitative analysis) from a zero-base to quantitative-reliability-centered maintenance (RCM-Q).

3. Enhanced RCM-Q Model: Case Study on Hydro Generator Francis Unity

Considering the need for assertive choices in asset maintenance management, this research presents a RCM-Q approach based on statistical inference techniques and discrete event simulation using the Reliability Block Diagrams (RBD) tool.

It was applied as a simulation structure to a Francis-type generating unit system: Grounding Neutral Cubicle of the Generator (GNC). The RCM-Q is structured in two phases: (i) the qualitative analysis using the FMECA quality tool and (ii) the quantitative analysis, which encompasses the survival analysis and discrete-event simulation (applying reliability block diagram RBD). The method's phases of development and application are shown in Figure 01.

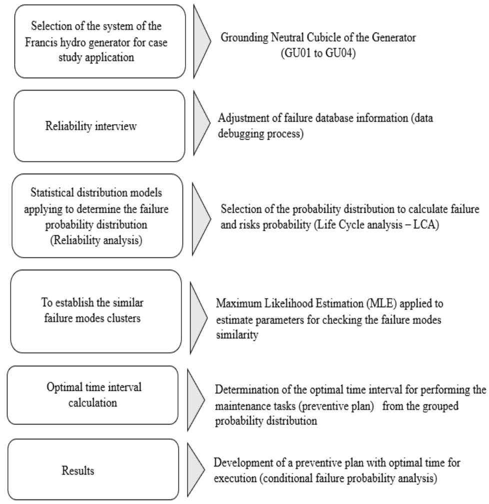

Figure 01. RCM-Q steps.

The case study was carried out in a Brazilian hydropower plant. This HPP has four Francis generator units, and it has a capacity of 1,240 MW of installed power approximately. Figure 02 presents the hydro-generator functional tree diagram highlighting the GNC main components analyzed in this study.

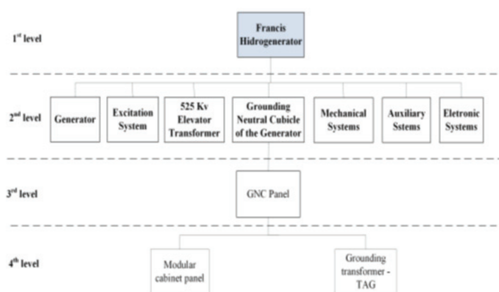

Figure 02. Francis hydro generator unit Functional Tree (FT).

3.1 Development of the Life Cycle Analysis (LCA)

In this case study, HPP already has a reliability analysis program implanted by the industrial maintenance sector, it is named Operation and Maintenance Based on Reliability (O&MBR).

However, the failure analysis executed is only qualitative. For the complete RCM methodology implantation (qualitative and quantitative analysis), is necessary to realize the database debugging of the current HPP maintenance failure records. This process was carried out by applying the reliability interview tool, which consists of developing interviews with HPP specialists (engineers, maintenance workers, and plant managers) to validate data and information about the maintenance history.

Thus, the maintenance records database is adjusted with more information conferring the necessary reliability to the database for an effective making decision. Once the database has been adjusted, it is possible to apply statistical methods for industrial systems reliability mathematical modeling.

Then, the life cycle analysis (or survival analysis) of the GNC components is applied. This one is a statistical technique to analyze various types of life cycle data (in this case study analyses maintenance failure records data) to predict the failure trend in the productive systems. This analysis is developed using theoretical probability distributions, being the two-parameter Weibull is one of the best-known distributions.

After probability distribution is determined, the reliability metrics can be calculated. Equation 01 shows the Availability calculation form (Lewis,1996; Lanthier,2012).

$$A_{(t)} = \frac{MTBF}{MTBF+MTTR} \tag{1}$$

Then the Functional Tree diagram (FT) was constructed, the FMECA analysis was applied, and this tool showed the CNG's most critical failure modes, which directly affect the synchronous generators belonging to the Francis units.

The GNC failure analysis was developed at the level of its main components: grounding resistor, relay REX 011, electrical power supply unit 220 Vca, contactors, fuses, and grounding transformer TAG). The other components (fastening elements, insulators, and panel sealing components) did not present a significant maintenance record (failure and maintenance tasks executed) that would allow an effective statistical analysis. Thus, CNG components that presented a low frequency of failures occurrence (or almost non-existent) in the HPP maintenance database, were disregarded to compose the failure analysis. This is due to the failure probability function (formed by this component class) presenting a low impact on the CNG operation. Or be, the failures that occur in this component class do not cause inoperative or do not impact this system's operational performance.

This database made it possible to develop the life cycle analysis of the CNG´s selected components. The LCA process used CNG maintenance records of the four Francis generator units (GU01 to GU04). The evaluation period was from 1999 (from the 3rd week of this year) to 2021 (until the 51st week of this year).

In the analyzed period (1999 to 2021), the data events were classified into two distinct categories, being category 01 referring to information about the duration time of the failures, and category 02 which refers to the duration times data of inspections and/or maintenance repairs whose execution did not cause the CNG component interruption. The data grouped into category 2 were considered as data censored. This means that data were kept in the LCA analysis computation (co-variables) but not considered as breakdown (failures events) that affect the system operation.

With the probability distribution determined, the application searched for the similarity among failure modes that occurred in the four GNCs. Once satisfied with the similarity condition, the failure mode information is grouped to perform a broad analysis of your behaviour.

In the Life Cycle Analysis (LCA) the maintenance costs also must be considered. This cost analysis is realized through cost optimization. Considering that the corrective and preventive maintenance costs follow a 5 :1 ratio. Equations 02 and 03 are applied to calculate this aforementioned cost optimization (Galar, Sanborn &Kumar,2017).

$$TMC_{(t)} = \frac{Pmc*R_{(t)}+Cmc*F_{(t)}}{\int_0^t R_{(s)}\, ds} \tag{2}$$

$$TMC_{(t)} = \frac{Pmc*R_{(t)}+Cmc*[1-R_{(t)}]}{\int_0^t R_{(s)}\, ds} \tag{3}$$

Where: $R_{(t)}$ and $F_{(t)}$ were previously defined. Pmc Preventive maintenance cost; Cmc Corrective maintenance cost; $TMC_{(t)}$ Total maintenance cost over time *t and* $\int_0^t R(s)\, ds$ Instantaneous system reliability value.

3.2 Systemic analysis for discrete event simulation based on reliability block diagram (RBD)

The systemic analysis consists of the discrete event simulation process application using the reliability block diagram tool (RBD).

The statistical model found with greater grip was the 2-parameter Weibull CDF distribution. The Weibull failure density function is given by equation 04 (Lewis,1996; Lanthier,2012).

$$F(T) = 1 - e^{-\left(\frac{T}{\eta}\right)^{\beta}} \tag{4}$$

Where: η scale parameter (characteristic life) represents the time in which 63.2% of failures are expected to occur; β shape parameter (non-dimensional number) and T refers to the time.

The β shape parameter indicates the failure rate trend over time (component lifecycle). (Lewis,1996; Sifonte & Reyes-Picknell,2017; Basson,2019). The survival (reliability) function is calculated using Equation 05:

$$R(T) = 1 - F(T) = e^{-\left(\frac{T}{\eta}\right)^{\beta}} \tag{5}$$

Subsequently, the block diagram was structured aiming to analyze the system reliability. It is important to highlight that the GNC´s components are configured in a system as a series into RBD. Figure 03 shows the Grounding Neutral Cubicle of the generator RBD.

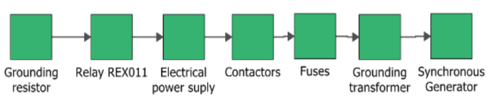

Figure 03. GNC of the Generator RBD (Reliasoft® Synthesis Platform - BlockSim)

With the RBD structure was executed a simulation with 1000 repetitions, using as main information the final time value equal to 10^6 hours. It should be noted that components such as fasteners, insulators, terminals, and cables were not regarded in the RBD diagram, because they present low quantity maintenance failure records in the HPP database.

For this block diagram simulation was used the failure distribution and the component repairs distribution as input data. Technical open databases also were consulted to obtain the distributions (failures and components repairs) distributions of the components considered in the GNC reliability block diagram that have few maintenance records. The searched technical open databases were IAEA-TECDOC-478, Gold Book (IEEE), and MIL-HDBK-217 – Reliability Prediction of Electronic Equipment.

3.3 Results and Discussions

The Life Cycle Analysis (LCA) developed was based on a simulated database that connected the technical open and the HPP´s maintenance records databases. Though this mixed database does not reflect the HPP´s real operational condition, it presents a set of maintenance actions that could be executed with RCM-Q process implementation.

Based on the Life Cycle (LC), the 2-parameters Weibull distribution was selected. This statistical distribution was the one that best adhered to the dataset of the GNCs (units UG01 to UG04). Table 01 presents the results of this distribution applied to the GNCs data.

Table 01 -The 2-parameters Weibull distribution results

GNC system	β	η	R(t)	F(t)	Median
UG01	2.954	50,4	0.72	0.29	44,515
UG02	4.671	33,5	0.39	0.61	32,857
UG03	1.863	49,6	0.59	0.40	40,700
UG04	6.846	36,8	0.49	0.51	34,922

R(t) for *t* equal to 35,040 hours (4 years) - F(t) t equal to 35,040 hours (4 years) / Median = hours

Based on this statistical distribution (Weibull) and the cost proportion between corrective and preventive maintenance (5 to 1 ratio), the optimal time to execute a preventive maintenance plan was determined. Table 02 shows the results regarding the optimal times.

Table 02 – Optimal time to execute preventive maintenance plans

GNC system	β Shape	[1] η scale	[2] Time (h)	[3] Time (years)
UG01	2.9535	50,397	25,262	2.9

UG02	4.6710	33,539	20,020	2.3
UG03	1.863	49,547	18,652	2.1
UG04	6.8462	36,843	23,258	2.7

(1) η scale parameter (characteristic life) in hours / (2) The optimal time to execute preventive maintenance (hours) / (3) The optimal time to execute preventive maintenance in years

Figure 04 shows the curves generated from the probability density function.

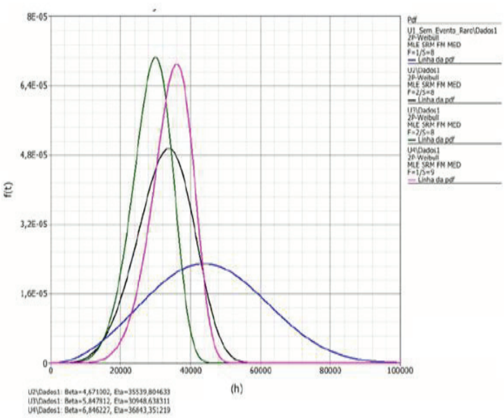

Figure 04 – PDF of the CNGs Failures dataset - UG01 to UG04 (Reliasoft® Synthesis Platform – Weibull^{++}).

The similarity analysis process among the GNCs (GU01 to GU04) enabled the grouping of similar maintenance records data. With similar data analysis, the 2-parameters Weibull result was obtained: β equal to 5.99 and η equal to 42,531.47 hours.

The distribution calculation, using the cumulative failure data of all CNGs, returned, as a result, an optimal time of 25,821.72 hours (2 years and 346 days) for the preventive maintenance activities execution.

For the GNC´s block diagram simulation development was considered two databases: (i) The debugged data from the current HPP maintenance failure records and (ii) the failures data searched in the technical open databases. Table 03 contains the results of the simulations performed for 4 and 4.5 years of the CNG system operation.

Table 03 - RBD simulation results in time operation of the CNGs equal to 4 years and equal to 4.5 years.

indicator	[1] Historical maintenance	[2] Historical maintenance
R(t)	0.73	0.53
F(t)	0.27	0.47
LC $B_{50\%}$ (median	40,008.45 h	40,008.45 h

(1) Historical maintenance data analyzed from the HPP database over 4 years/ (R (*t*) and F(t)= 35,040 h) (2) Historical maintenance records analyzed from open technical databases over 4.5 years. R (*t*) and F(t)= 39,420 h

The mean time to repair (MTTR) was calculated from the sum of the hours spent on maintenance tasks executed by the maintenance workers of the hydroelectric plant, and the sum of the maintenance repairs executed by hand-outsourced labour.

With the determination of the repair times (using the failure database of all CNGs) it was possible to obtain a tri-parametric Weibull repair density distribution. The development of the calculation of this statistical distribution resulted in the following parameters: β equal to 1.41, η equal to 8.55 hours, and γ equal to 2.45 hours.

The gamma parameter (γ) can be interpreted as a delay time between failure occurrence and mobilization of the maintenance workforce to repair the failure event. Applying Weibull´s tri-parametric distribution was calculated the probabilities of repair execution for 4, 6, 8, and 10 hours. Table 04 presents the probability calculation results.

Table 04 – Time-to-repair probability calculation

Time *t* (hours)	*Probability - repair (*t*)
4	0.086
6	0.252
8	0.419
10	0.568

*The probability that the repair will be executed in time *t*

Executing 1,000 simulation events considering 10^6 hours of simulation time and MTTR equal to 10 hours in its execution, it is possible to obtain the following results presented in Table 05.

Table 05- Simulation Results considering MTTR equal to 10 hours

Reliability indicator analyzed	Result
Mean Availability (all events)	99.98 %
Available time	999,750.91 h
Total unavailable time	249.09 h
Meantime to the first failure	39,079 h
Total MTBF considering TTR	40,146 h
MTBF no consider the MTTR	40,136 h

The actual GNC maintenance preventive plan has an execution cyclical frequency of 4 years. The cumulative density (Weibull) distribution of failures calculated the estimated risk for the execution of the CNG´s preventive plan in 4 years and execution in 4.5 years. According to Table 04, the estimated risk result (failure probability) for 4 years is 0.27 and for 4.5 years it is 0.47, evincing an increase of 20% in the estimated risk when adopting a cyclical period of 4.5 years for the execution of the CNG's preventive plans.

In its essence, this failure probability estimate does not consider the system operation time without interruptions until the CNG´s preventive plan execution period arrives. As the system operated (survived) for a period of 4 years (35,040 h) without a break, it is important to determine the system survival probability for a further 6 months (4,480 h), which means changing the frequency of the preventive maintenance plan execution from 4 to 4.5 years.

To obtain the system failure conditional probability is applied to the function presented in equation 06.

$$R(T,t) = \frac{R(T+t)}{R(T)} \qquad (6)$$

Where: R(T) operation probability without failure occurrence during time T and R (T+t) survival probability during a new operational campaign over time t.

For this case, the variable T is equal to 35,040 hours (4 years) and the variable t is equal to 4,380 hours (six months), which refers to the additional time of the GNC operational campaign. The failure conditional probability resulted in survival reliability of 0.7253 (72.53%) to the preventive plan execution in 4.5 years (6-month extension). This result presents a system survival favorable, concluding that in this condition it is possible to extend for longer 6 months the maintenance preventive plan frequency execution, on a certain safety margin.

It is noteworthy that despite the calculated survival probability showing a favorable condition, this extension period to maintenance plan execution is only possible if fault events in the differential protection circuit do not occur before 4.5 years. This event can occur in two modes:

(i) The event of non-activation of the differential protection, which promotes the direct flow of unspecified curve currents (harmonic currents) through the CNG. Differential protection compares measured values concerning magnitude and phase by direct comparison of instantaneous values or by a vector (phasor). Generators are protected by a differential protection circuit, as high sensitivity and fast action are ideal for minimizing damage. The direct flow of high magnitude currents through the GNC can damage both systems: GNC and synchronous generator.

(ii) The event of improper activation of the differential protection, which means the occurrence of activation of this device even if there is no current magnitude variation (short circuit).

The differential protection circuit must have high reliability during its operation. The failures occurrence in this protection device can cause total loss and replacement of high-cost assets. Then, the period for carrying out the CNG´s preventive maintenance plan can be extended if these failure events (non-activation or event of improper activation) do not occur. In case they occur, regardless of the date of the last preventive plan execution, it is mandatory to realize the preventive tasks in the CNG system again.

3. Conclusion

Considering the need for assertive choices in asset maintenance management, this research developed a RCM-Q approach model based on statistical inference techniques and discrete events. A real case study in a Brazilian HPP was developed to verify the applicability of the proposed model.

The HPP database debugged by the reliability interview tool was sufficient to develop an accurate and coherent failure analysis. Additionally, information was searched from Technical open databases to obtain the failure and repair distributions to components that have few maintenance records, conferring reliability to the database.

The quantitative RCM approach demonstrated the efficacy of the reliability metrics application (MTTF, MTBF, R(t), F(t), $\lambda(t)$, among others) in support of the RCM quantitative phase, aiming to establish an adequate maintenance policy that guarantees high levels of productivity and reliability industrial system. The subsystem clusters, which have similar failure modes and optimal times, helped in the decision on the planning and scheduling of preventive maintenance activities that include several components of the GNC.

Considering the mixed maintenance records database, the RCM-Q simulation result returned a smaller interval between preventive maintenance plans execution than the current interval of 4 years carried out by the HPP. In the future, this optimal interval (simulation) to execute maintenance plans must be recalculated with greater acuity, whereas the database will be composed only of HPP´s maintenance records.

Therefore, the RCM-Q approach proved to be effective for the preventive maintenance plans composition in a power generation system, pointing the priority assets for preventive monitoring according to their failure risks, structuring an effective maintenance policy that guarantees high levels of productivity and is capable of optimizing costs and resources.

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