INTER-INDUSTRIAL COOPERATION FOR APPLICATION OF RELIABILITY-CENTERED MAINTENANCE

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Abstract

Among all contemporary technology of asset maintenance, RCM (Reliability-Centered Maintenance) has spread its application to practically all industrial sectors, achieving the status of preferential practice not only on the aviation industry, where it began, but also on world nuclear and electricity industries. RCM is distinguished for adopting a structured process for analysis and decision, aiming the selection of maintenance activities for any physical asset.

One key requisite from RCM is the availability of an interdisciplinary team of experts from design, maintenance, operation, testing, etc. for the selected installation. Experience on RCM has shown that this is one of the most difficult and onerous aspect to attain in an operating environment.

This paper describes the collaborating work, logistics, and difficulties experienced by a work group commissioned by Cigré-Brasil to produce an RCM Guide for Oil Immersed Power Transformers. It demonstrates the viability of collaboration among different actors from an industrial sector, on the proposal of maintenance policies for complex equipments.

Keywords: Reliability-Cantered Maintenance, Industrial Cooperation.

1 Introduction

This paper reports the result of application of RCM to oil immersed transformers, with the participation of experts from several companies, from utilities, manufacturers, consultancies, laboratories and universities. The importance and complexity of transformers to power systems, has motivated its choice as a pilot project from a Cigré-Brazil joint working group sponsored by Subcommittees B3 (Substation), B5 (Protection) and A2 (Transformers). It was the intent of the group to demonstrate and document the viability of applying RCM to equipments of this complexity. Many companies offered support and experts to the group, such as CHESF (Hydro Electric Company of San Francisco), TECNIX (Engineering and Systems Ltd), CEPEL (Electric Energy Research Center), ONS (National Operator for the Electric System), ELETROSUL (Eletrosul Electrical Power Plants), ABB (Group ABB), MR (Maschinenfabrik Reinhausen), SIEMENS (Group Siemens), CEMIG (Cemig Distribution), VONKEL (Doble Engineering), AES (Eletropaulo), CPFL (Paulista Power and Light Company), COPEL (Paranaense Energy Company), FURNAS (Furnas Electric Power Plants), TOSHIBA (Toshiba Brazil S.A.), KEMA (Kema Consulting), CPQD (Research and Development Center for Telecommunications), AES (Eletropaulo), TREETECH (Digital Systems Ltd.) and CTEEP (Paulista Transmission). To support the project, TECNIX Engineering and Systems Ltd., (http://www.tecnix.com.br) has supplied RCM and database software, and an internet site with FTP and HTTP services at http://www.tecnix.com.br/cigrercm, where all results are available. All reports, tables and graphics used in the Guide were done with Tecnix RCM software.

2 Methodology

The project development was divided in several steps, as is usual with RCM methodology, according to the order shown on the next picture, which serves also as the RCM software interface.

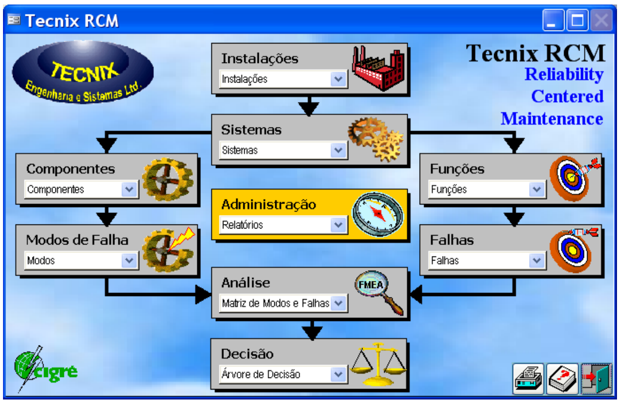


Figure 1 – RCM Software

Observe, in this picture, the independency of the steps related to Component and their Failure Modes Identification, from the steps of Function and Functional Failure Identification. This separation allowed the analysis of failure modes related to physical aspects of each component, while functional failure were related initially to system functions. This parallelism, shown on the picture, allows the steps to be conducted by independent subgroups, before the FMEA analysis.

3 Power Transformers

According to Reliability-Centered Maintenance, installations are sets of systems, concrete or abstract, where it is possible to find or define some affinity relation. In industrial installations, this relation is established with the intent of attaining one or more objectives. In this work, a generic transformer is assumed as the installation. The following Picture shows the input screen for defining installations on the RCM software.

Figur2 2 – Installation Documentation

4 Systems

Systems are sets of physical or virtual components among which it is possible to find or define some functionality relation. In industrial systems, these relations are created to accomplish one or more functions. In the RCM Guide, this topic contains the result of the identification and description of every system that form each transformer. The following picture shows the systems identified by the work group as typical of power transformers.

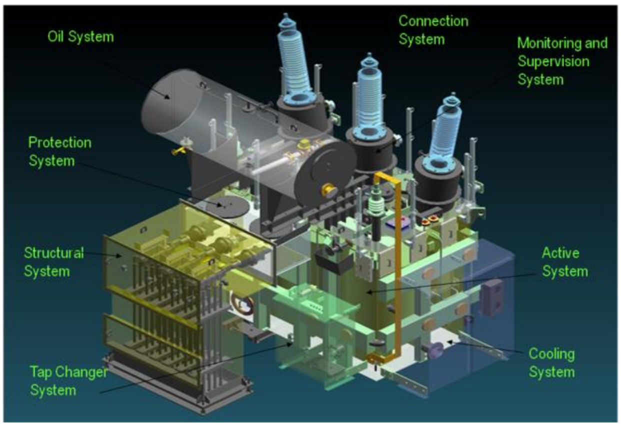


Figure 3 – Transformer Systems

As in all RCM study, the choice of systems is not unique, depending on the used criteria. In this guide, systems are related to group of functions performed in a transformer, resulting from several interactions by the work group. Each system is documented in the RCM database. The following picture shows the form used to input system details on the RCM software.

Figure 4 – System Documentation

5 Components

Components represent constitutive parts of systems. They can be physical (hardware), abstract (software), mix (firmware), solid, liquid or gaseous. All components of each system were identified and documented on the RCM database. The following picture shows the form used to input this data on the RCM software.

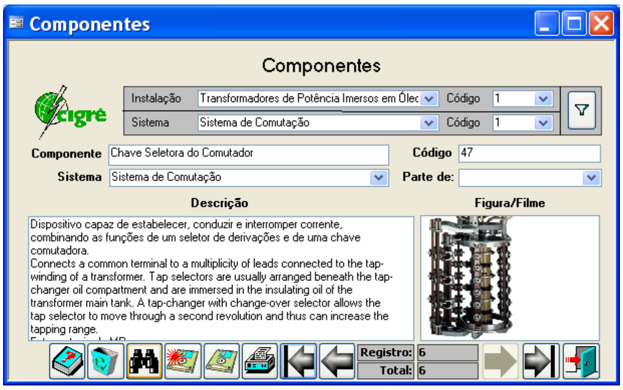


Figure 5 – Component Documentation

The following picture is a summary of the quantity and percent of components identified in each one of the eight typical systems of oil immersed power transformers. Observe the majority of components from the Tap Changer System (70), followed by the Monitoring System (45), showing the complexity and diversity usually associated to these systems.

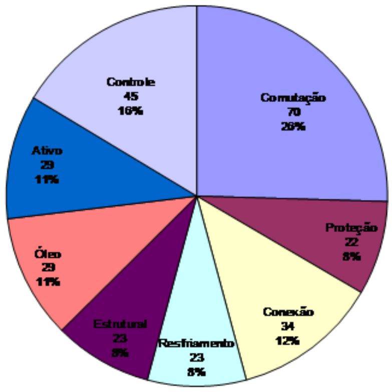


Figure 6 – Components per System

6 Functions

RCM considers a function as a relation among components to attain an objective. A function is also the smallest part of the installation that is required to maintain. That is, a functionality that is not part of the intended goal of the system will not take part in the RCM analysis. These criteria also guided the definition of the detail level of function identification, as adopted by the work group. In this project, as a convention, all functions were identified only to the first level below the systems. No sub functions were detailed. The documentation of each function was registered in the RCM database using the following form.

Figure 7 – Function Documentation

The following picture is a summary of the quantity and percent of functions indentified in each one of the eight typical systems of oil immersed transformers. Note that the majority of functions are from Monitoring system (43), followed by Tap Changer system (36), due again to their complexity and diversity. The percent distribution of all 184 functions on the several transformer systems is shown on the next picture.

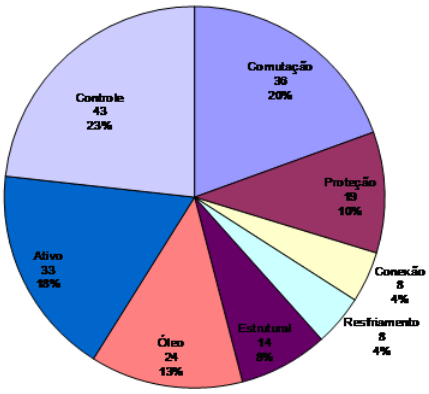


Figure 8 –Percent of Functions per System

7 Failures

According to RCM, failures represent abnormal states of system functions. They can vary from the complete absence of the function, to a partial degradation of the expected performance level. Failures usually are independent from the components that implement them. In this project, failures are directly associated to the functions of each system. That is, systems fail only as far as their functions fail.

The documentation of failures of each function must be registered in the RCM database. The following picture shows the input form used in these registers.

Figure 9 – Functional Failure Documentation

The following picture is a summary of the functional failures related to each transformer system. Note the large quantity of failures of the Monitoring system (106), followed by the Tap Changer system (80) and Active system (74), reflecting their high complexity and diversity.

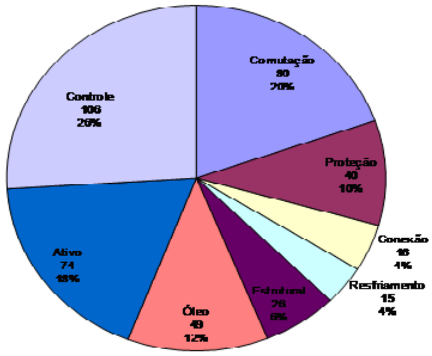


Figure 10 –Percent Failure per System

8 Failure Modes

Failure modes represent abnormal events occurring in system components. They can vary from the complete loss of the component, to a partial degradation of a specific characteristic that is important for a system function. According to RCM, failure modes of interest are those that interfere on the performance of a function. They represent the main aim of the maintenance activities. In this guide, failure modes are related directly to system components. That is, systems do not have other failure modes beyond those related to their components.

Failure modes of each component must be registered on the database that supports the RCM software. The following picture shows the form used to input failure mode data.

Figure 11 – Failure Mode Documentation

The relationship among failure modes and functional failure is registered in a correlation matrix, as shown on the next picture, for each system, function and component.

Figure 12 – Failure and Modes Matrix

Each line in this matrix identifies a failure mode that is associated to functional failures on the columns, for each system, function and component. Each sign in this matrix means that the failure mode of the line results in a functional failure listed on the column.

The following picture is a summary of the failure modes that were identified in each of the eight systems of oil immersed power transformers. Observe the majority of failure modes of Tap Changer system (342), followed by Monitoring system (231) and Oil system (200), due again to their complexity and diversity. These numbers, a total of 1436 failure modes, are shown in graphical form on the next picture.

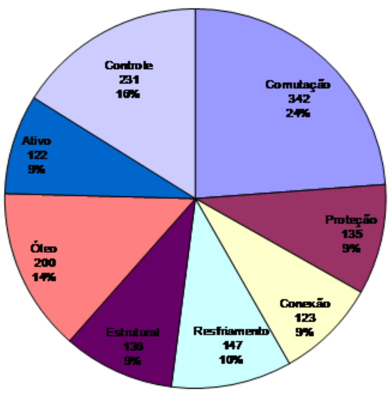


Figure 13 – Percent of System Failure Modes

9 Failure Effects

Failure effects are events resulting from a failure mode on the other components, systems or functions of an installation. They generate the consequences of each event. This chapter contains the result of performing a Failure Mode and Effects Analysis (FMEA), by relating each functional failure to the relevant failure modes, and the description of resultant effects. The analysis is documented in the database of the RCM software, as shown before.

Each failure mode is also classified according to their criticality, defined by their effects. The following classes were adopted by the work group to classify them:

- **Catastrophic** – deaths, loss of the installation or environment disaster;
- **Critic** – severe wound, a death, significant damage or environment impact;
- **Marginal** – small injury or damages to people, installation or environment;
- **Minimum** – reduced impact on operation, security or environment;
- **Insignificant** – minute effects on operation, security or environment.

In this guide, these classes were grouped in three levels, according to the attitude of maintenance when confronted to their effects.

- **Critic** – effects are Catastrophic or Critic;
- **Significant** – effects are Marginal or Minimum;
- **Minimum** – effects are Insignificant.

These levels also define the criteria used to choose the significant failure modes as those that will be analyzed in the remaining part of the RCM process. Modes considered not significant (with minimum effects) will be registered but not subject to further analysis. In this case, only modes considered critical or significant were analyzed, and registered on the RCM database.

The following Picture is a summary of the classification levels according to criticality of all failure modes of the eight typical systems of oil immersed Power transformers. The majority of critical failure modes are from Tap Changer system (137), followed by Oil system (134) and Active system (111). Failure on these systems may result on significant damage or total loss of the transformer.

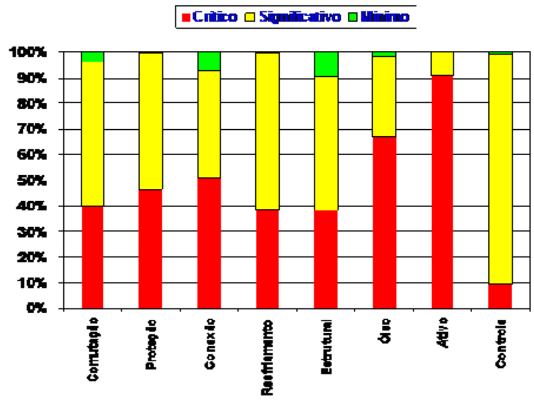


Figure 14 –Percent of System Criticalities

10 Activity Selection

The selection of maintenance activities and their time interval form the decision phase of RCM, according to their consequences in terms of economic, operational and environmental impacts. A structured process was used to define the most applicable and effective maintenance activity to combat each failure mode. The first phase of this process evaluated the visibility of the effects, to classify as visible or hidden to the installation operator or user. The next phase analyzed the consequences with respect to economic, operational, security or environmental impacts, classifying in one of the following classes:

- **ESA** – Evident, Security or Environment
- **EEO** – Evident, Economic or Operational
- **OEO** – Hidden, Economic or Operational
- **OSA** – Hidden, Security or Environment.

These steps are recorded on the RCM database using the form shown on the next Picture, for each failure mode.

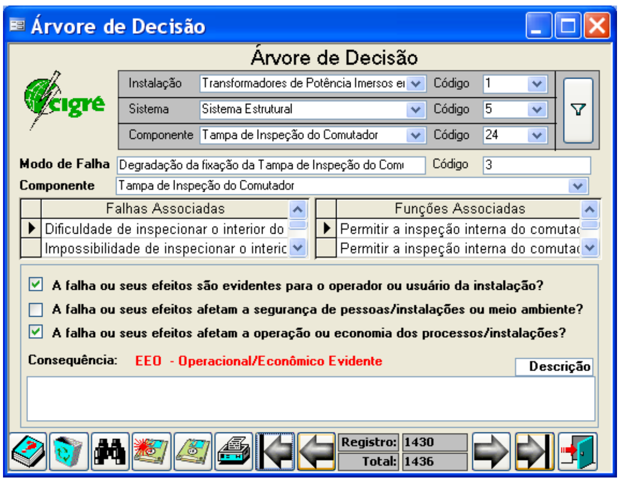


Figure 15 – Decision Tree Documentation

Once the visibility is defined, it is possible to select the most applicable and effective maintenance activity, from one of the following types:

1. **Operational Service** (SO): tasks done by the operator;
2. **Predictive Inspection** (IP): tasks to detect the evolution of failures;
3. **Preventive Restoration** (RP): periodic restoration of components;
4. **Preventive Substitution** (SP): periodic reposition of components;
5. **Functional Inspection** (IF): simulation of the function of components;
6. **Combined Maintenance** (MC): joining of two or more activities;
7. **Project Modification** (MP): change in functionality;
8. **Functional Repair** (RF): restoration of function after a functional failure.

The choice of the activity follows a sequential process of question answering, guided by the RCM logic, and registered on the software database using the following form.

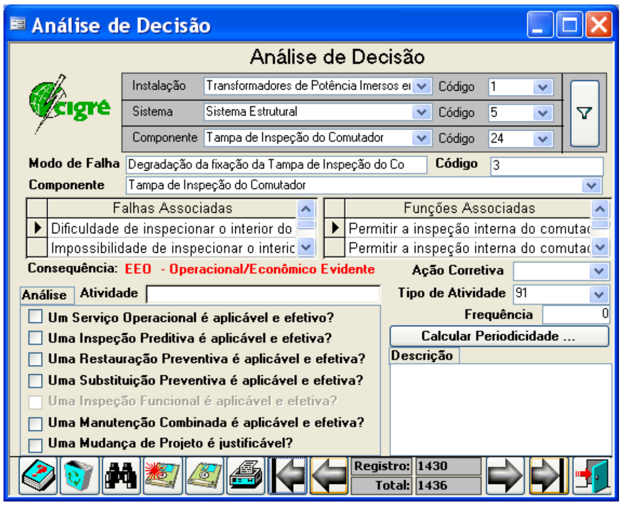


Figure 16 – Documentation of Activity Selection

The following picture shows a summary of visibility classification and consequences of every failure mode of oil immersed transformers. Most failure modes are hidden, with most of them resulting in environmental or security impacts. These confirm the importance of the maintenance of transformers in power systems.

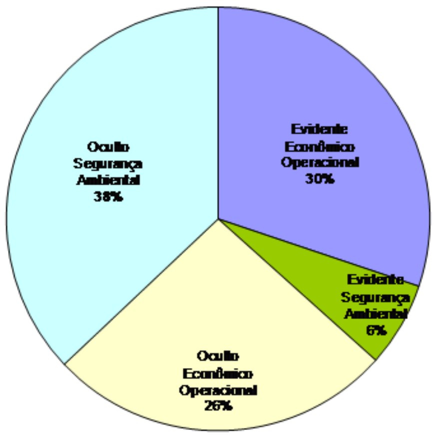
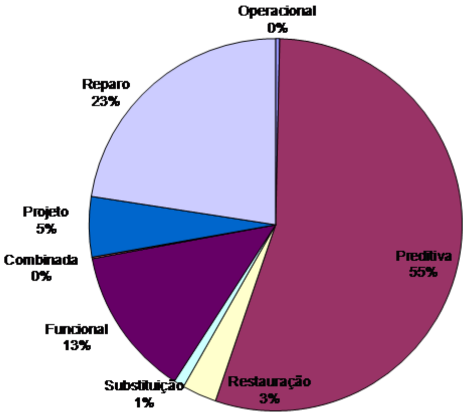


Figure 17 – Percents of Visibility and Consequences

Following the RCM approach, applicable and effective activities are chosen to combat each failure mode. The next picture shows the distribution of activities by type. Predictive Inspection is the recommended maintenance activity (788 cases) for almost half of the failure modes, followed by Functional Repair (324 cases) where a Run-To-Failure attitude is suggested for the transformer.



Figur3 18 –Percent of Maintenance Types

11 Activity Frequencies

Several criteria are adopted in the electric industry to choose maintenance intervals, according to the knowledge level available about the failure mode mechanisms. For oil immersed transformers, the work group selected one of the following alternatives:

- **None** Unknown criteria;
- **Experience** Based on expert opinion;
- **Experimental** Subject to test to avail results;
- **Manufacturer** Defined by supplier;
- **Similarity** Copied from other equipment;
- **Opportunity** Executed by chance;
- **Statistic** Based on a stochastic process;
- **Other** Chosen base on other criteria.

The following picture shows the distribution of classification for choosing maintenance activities of power transformers according to the above criteria, as used by the work group. The most common criteria corresponds to Experience (585), followed by Opportunity (401). A small number of failure modes (82) have their maintenance defined by a Statistical criteria. This unveils the incipient application of these techniques in this type of equipment.

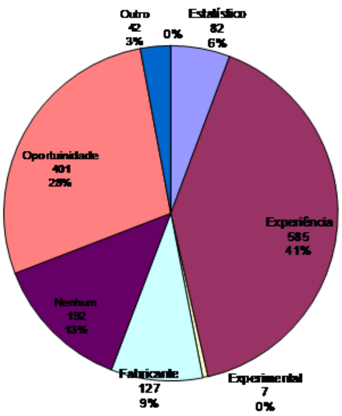


Figure 19 –Percent Criteria for Periodicity.

The following picture shows the time distribution of maintenance interval for all failure modes of oil immersed transformers. Note that roughly a third of failure modes (492) are not subject to any kind of maintenance. The other third part follows a one and half year interval. The remaining third is only maintained at the end of the useful life of the transformer. A significant number (69) of maintenance activities is suggested for operators, typically at one hour interval.

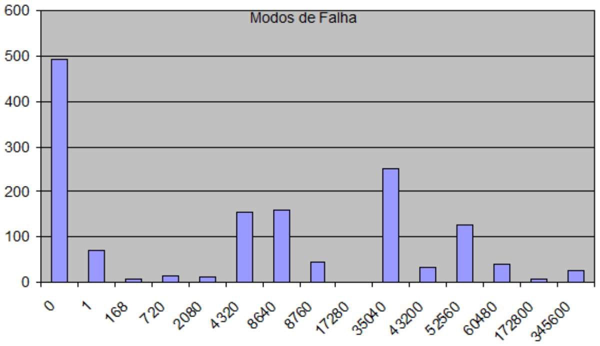
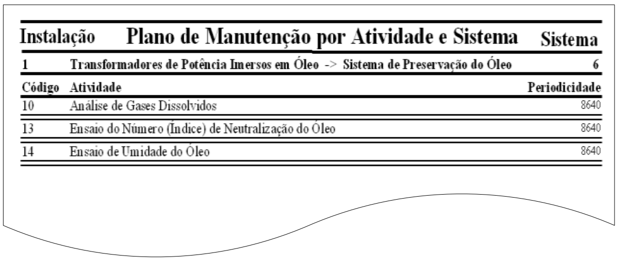


Figure 20 – Time Distribution of Maintenance Intervals

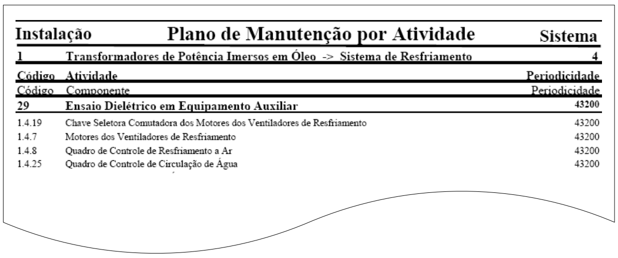
12 Maintenance Plan

As the last part of the RCM methodology, the RCM software can group the suggested activities by system, activity, failure mode, etc. as shown on the following reports.



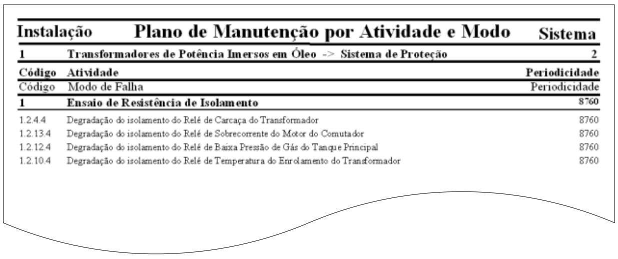
Instalação	Plano de Manutenção por Atividade e Sistema	Sistema
1	Transformadores de Potência Imersos em Óleo -> Sistema de Preservação do Óleo	6
Código	Atividade	Periodicidade
10	Análise de Gases Dissolvidos	8640
13	Ensaio do Número (Índice) de Neutralização do Óleo	8640
14	Ensaio de Umidade do Óleo	8640

Figure 21 – Maintenance Plan per System



Instalação	Plano de Manutenção por Atividade	Sistema
1	Transformadores de Potência Imersos em Óleo -> Sistema de Resfriamento	4
Código	Atividade	Periodicidade
Código	Componente	Periodicidade
29	Ensaio Dielétrico em Equipamento Auxiliar	43200
1.4.19	Chave Seletora Comutadora dos Motores dos Ventiladores de Resfriamento	43200
1.4.7	Motores dos Ventiladores de Resfriamento	43200
1.4.8	Quadro de Controle de Resfriamento a Ar	43200
1.4.25	Quadro de Controle de Circulação de Água	43200

Figure 22 – Maintenance Plan per Activity



Instalação	Plano de Manutenção por Atividade e Modo	Sistema
1	Transformadores de Potência Imersos em Óleo -> Sistema de Proteção	2
Código	Atividade	Periodicidade
Código	Modo de Falha	Periodicidade
1	Ensaio de Resistência de Isolamento	8760
1.2.4.4	Degradação do isolamento do Relé de Carcaça do Transformador	8760
1.2.13.4	Degradação do isolamento do Relé de Sobrecorrente do Motor do Comutador	8760
1.2.12.4	Degradação do isolamento do Relé de Baixa Pressão de Gás do Tanque Principal	8760
1.2.10.4	Degradação do isolamento do Relé de Temperatura do Enrolamento do Transformador	8760

Figure 23 – Maintenance Plan per Failure Mode

13 Conclusions

The application of RCM to transformers can serve as a pilot for other kind of equipments and systems common to the electric industry. The guide produced by the Cigré work group gives answers to the 4W basic questions (What, When, Where, Why) of maintenance:

- **What** kind of maintenance must be done?
- **When** should it be done?
- **Where** should it be applied? and
- **Why** must it be done?

The Guide does not answer how to do the maintenance, as it depends on specific factors that are particular to each company. It can be used as a guide to the application of RCM to these equipments, with the necessary changes to the peculiarities of each installation and company. It can also be used as a reference to possible failures and failure modes for CMMS – Computerized Maintenance Management Systems, or as a consultant about maintenance frequencies and policies recommended by suppliers for new equipments. Further, it can be a help in the buying specification for new transformers or for maintenance contracting, and as a model of the application of RCM.

In general, the Guide reflects the level of knowledge of the group about the failure processes and maintenance of transformers, as well as the available technical resources to prevent failures. It is expected that this case proofs the viability of interdisciplinary work groups for the application of RCM to complex equipments.

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