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Development of diagnostic rules for hydrogenerators

Roberto LIMÃO – Roger da SILVA – Anderson SENA – *Jacques SANZ
Universidade Federal do Pará – UFPA **Eletronorte**
Brazil

SUMMARY

1. We have determinate what components present the most frequent and expansive defects, and focused the action at them. We have classified the five main components, following our experience and previous Cigre report: Stator, specially the insulation losses; Bearings; Slip ring; Rotor; Turbine.
2. For each component we selected the most representative variables to observe its wearing.
   - For the stator wearing, temperature of winding, cooling water and core are available, as well as tension, current, active and reactive power furnished by the supervision system; we measure also partial discharges (01 point for each winding per phase), air gap, and vibrations of the core.
   - Bearings are controlled by the measure of oil temperature, metal temperature, shaft oscillations, and vibrations of the bearings covers. We consider also air gap measurement.
   - We control the slip ring measuring its temperature by IR sensor; the excitation current and voltage are available from the supervision system.
   - For the rotor, we only dispose in the moment the temperature, measured by indirect method; in a next future, we will be able to measure data on the rotor, as temperatures and strains with a new optical system, actually in experimental test.
   - The turbine is represented by the pressure of spiral box, cover and suction.
3. The next step is to describe the probable defect in formation, using the knowledge and the experience of our project and maintenance technical staff; in this first work, we have considered only stator, bearings and slip ring; some example are described below:
   - For the stator: heating of winding and core, losses of insulation, slackening of the core foils…
   - For the bearings: heating of oil and metal, unbalance rotor, shaft inclination or deformation…
   - For the slip ring: bad commutation by the brushes on the ring, carbon film formation incorrect…
4. We treat the variables by the fuzzy method, determining for each one limit for normal and alarm values, diagram of her evolution. After that we determine the logic rules attaching the observed variables with the probable defects; the state of each variable out off the normal condition is showed as a weight, more important when the variable is going to critical situation; the combination of each variable point considered that the rule permit to estimate the probability for the formation of each defect. For example:

- Stator: losses of insulation is associated with PD´s measurement, core vibrations, and sometimes with core heating;
- An unbalance rotor is associated with shaft oscillations, but also with bearings temperature increase;
- Slip ring: the consequence of a bad commutation is directly an increase of the surface temperature; but this one must be measured at the same excitation condition;

We verify the exactness running the rules with a fictitious data bank, where we simulate abnormal conditions of the representative variables.

KEYWORDS: Diagnosis – Model – Rules – Stator – Bearings - Slip ring - Fuzzy logic

DEVELOPMENT OF DIAGNOSTIC RULES FOR HYDROGENERATOR

1. INTRODUCTION

Currently, there are many investments in research on energy resources that have less social and environmental impact. However, hydroelectric plants are still the main source of energy in some countries, like Brazil, and infact, this should not change in a short and medium time.
The hydro generators, therefore, are important machines, and they should respect the generation program, without interruption.
Supply interruptions caused by power failures in hydro generators affect industrial and domestic consumers, services ...., which could have a considerable damage. These situation increases the importance of predictive maintenance with a maximum efficiency.
The system for the diagnosis works in conjunction with monitoring systems, to complement them in order to increase the availability of the equipment and the reduction of maintenance costs; in addition both turn quicker the process of diagnosing defects.
Many researches are conducted to determine diagnosis of hydro generators, looking for symptoms that the machine can show. These studies are mainly based on three elements that cause the most problems in hydro, insulation of the stator, bearings and slip ring [1]. The diagnostic of these components request tool of artificial intelligence. Emmendoerfer et al [2] developed a system to offer a support for maintenance, the *fuzzy* logic, used mainly bearings temperatures and oscillations. Yang & Shen [3] also developed a system using *fuzzy* logic, but the input signals considered by the system were only the vibrations. Rodriguez and Arkkio [1] used *fuzzy* logic to study the stator winding.
The developed system consists of software to diagnose defects in hydro generators. The modules were developed using algorithms based on *fuzzy* logic and knowledge base formed by the company's technical team in order to diagnose faults related to the loss of insulating capacity of the stator, bearing wear and the risk of burning the slip ring.

2. PREDICTIVE MAINTENANCE

The difference of predictive maintenance consist in measuring and analyzing often the physical variables considered representative of the operational state of the equipment [4].The adoption of predictive maintenance provides details of specific items, such as controlling and maintaining the quality of the final product with is generated at the equipment or installation. It also provides greater reliability of the electrical system, increased equipment life and improving process safety, installation, equipment and people. So, as benefits have been: reduction of maintenance costs decreasing the number of failures in machines and equipment downtime for repair, reducing parts inventory and increased production [4, 5].A predictive maintenance program can minimize the number of breaks and ensure that repaired equipment is in conformity to normal condition. Associated with a diagnostic system, it can identify machine problems before they become serious, principally if considered that mechanical problems can be minimized if they are detected and repaired in advance. Therefore, when a problem is detected early, usually larger problems can be avoided [6].A diagnosis system plays an important role in cost reduction and agility in the diagnosis of defects, because with this tool is possible to avoid the displacement of specialists to the location where the equipment is installed. In addition, the time of the detection of possible defects is reduced and the correction is made quickly. Thus, the equipment life is extended, maintenance costs are reduced and the work of specialist is more profitable.

3. FUZZY SYSTEMS.

The *fuzzy* systems were created by Lotfi A. Zadeh in the sixties [7] and are primarily based on the representation and manipulation of uncertain and imprecise information, so common in the human quotidian. Expressions such as "near", "very" and "little" represent this imprecision, which usually cannot be considered by the systems of classical logic. Allowing, for example, the system responds to evidence a gradual scale, with values between 0 and 100% (uncertainty), and also provides rules or standards to represent an evidence not informed, or when the answer is "not sure" (indeterminate) [8, 9].
The combination of expert system and fuzzy logic allows the rule to be represented in a textual form, easily understood as: "If < Variable A> AND < Variable B> THEN < Output Variable A >." In this article, the system for the diagnosis uses *fuzzy* logic-based algorithms and also the expert knowledge, and transforms it in the form of rules applied to the diagnosis, in order to reproduce the human form of thinking and making decisions. The *fuzzy* systems can support reasoning modes which are approximate. It can be translated into verbal, inaccurate, quantitative expressions and inherent with the human communication. Introducing linguistic variables that represent a set of ideas, intuitive judgments and the interpretation of every human being on the words. Examples can be seen as low, medium, high, etc., see Figure 1 [10].

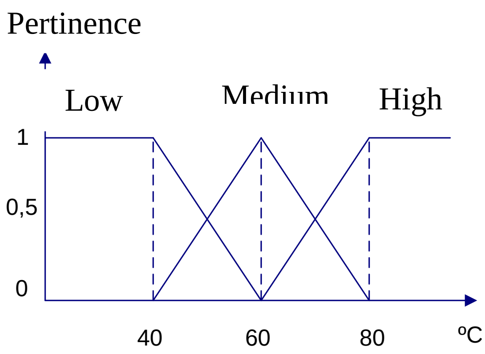

FIGURE 1 - *fuzzy* sets, linguistic variables and functions each

All information non-*fuzzy* or deterministic (temperature, vibration, etc.), are translated into the language of *fuzzy* sets in the module called fuzzyfier. This work used as the input linguistic variables of monitored quantities, namely: temperature of the metal and oil bearings (generator and turbine guide, thrust); oscillations in the radial guide bearings of the generator and turbine; maximum values of winding temperature, air temperature and core temperature, growth rate of partial discharges and temperature of the slip ring current referenced. Each of these quantities generates sets with trapezoidal and triangular pertinent functions based on the format shown in Figure 1, called *Normal*, *Alarm 1* and *Alarm 2*.The inference machine combines, through logical principles, the information from the rule basis and fuzzyfier, to provide a decision. The inference machine used was the Mamdani type.

As this decision is *fuzzy* in nature, it is usually necessary to make an interpretation in order to translate it into a deterministic value. This procedure is done by defuzzyfier. This system uses the method of defuzzyfication *Center Area*.
As output linguistic variables, we used the most frequent defects related to the bearings, they are: danger of rubbing, eccentricity of the guide bearings (generator and turbine), defects in the oil cooling systems of bearings. And likewise, the most common defects related to the insulation of the stator, such as: high level of partial discharge, overheating of the stator winding and localized overheating. For the slip ring is verified the risk of burning it. Each defect has functions of pertinence Low, Medium and High, all in a triangular shape.

4. SYSTEM DIAGNOSTIC SUPPORT

The system of support to diagnosis in hydro generator was developed in order to serve primarily as a tool to assist the decision-making team responsible for the maintenance of such equipment. Moreover, it can be used as a training tool for beginners and also serve to test validation rules; it allows to the user enter variables in simulations (fictitious data from monitored variables).
The diagnostic system consists of two modules, the diagnostic with real data and a simulation module. The diagnostic module communicates with the monitoring systems, and data access systems are done through SQL Server database. By having access to the system, the user can choose a particular record. After choosing the system returns with the diagnosis for a given time when there was made the acquisition of information. The simulation module is similar to the diagnosis thus having the same input variables, output and rules. The difference is in data entry, in simulation module the data are not from the database, but are entered manually by users. This system was developed using the LabVIEW graphical programming language from National Instruments [11, 12, 13].

4.1. Diagnosis of Defects in Hydro generator.

The system displays the input variables (variáveis de entrada) and output variables (variáveis de saída), see Figure 2. The input variables result from measurements stored in the database monitoring systems. And the output variables correspond to defects that can be diagnosed for hydro generator.

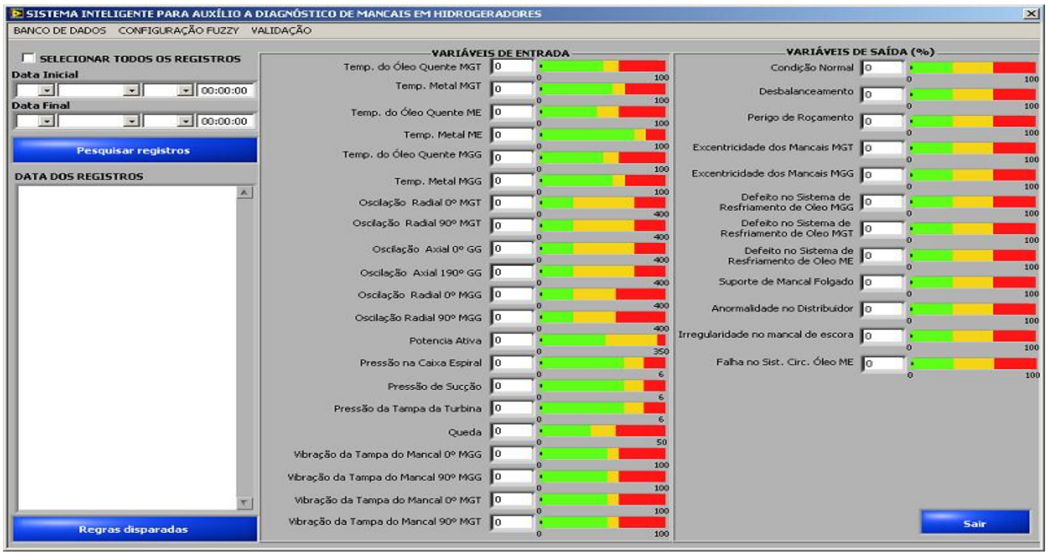

FIGURE 2 – Diagnostic system

Through the connection to the database made after starting the system, recording dates of the variables are available on the screen. When choosing a date, the variables are updated on the screen and the

rules activated by the variables are displayed along with the possibility of the defect, providing the diagnosis based on stored knowledge.
In addition to aiding diagnosis, you can also see the proximity of the value of each variable with is pre-set limits, through the colors used in the indicators: green, yellow and red. It is considered the normal state value that is in the green region; alarm state the value that is in the yellow region and the critical value that is in the red.

4.2. Simulation Module

The simulation module, see Figure 3, allows the user to validate the rules entered into the system by simulating the values of input variables. These values are entered manually by the user, which is free to choose any range of values that it considers valid.

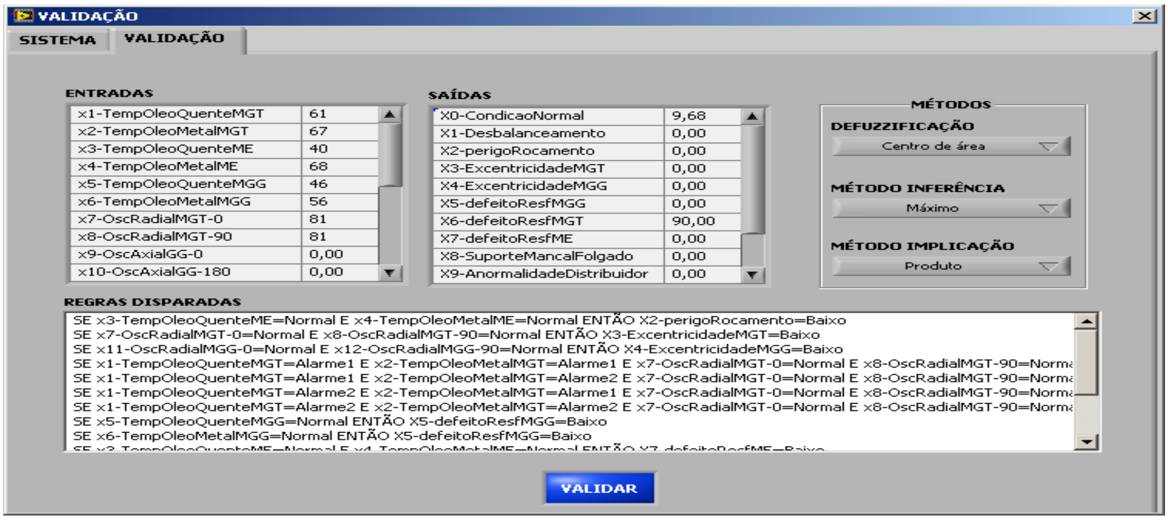

Figure 3 - Simulation Interface

The simulation interface allows the user to enter values of input variables and also a choice of defuzzyfier, inference and implication methods to be used for diagnosis. After choosing these parameters, the user enters the command to test the values entered and in the same interface are displayed the rules that were acted for the diagnosis result.
This module is very useful both in the initial validation of the rules that have just been prepared by experts and in the refinement phase of the new rules, which eliminates inconsistencies in the rules for the diagnosis of defects and permit to obtain results much more reliable.

4.3. System Configuration

A feature of great importance by this system for the diagnosis is its flexibility to change the system parameters without requiring any changes to software source code. This is possible through the configuration interface of the *fuzzy* system. Here the user can do the addition, deletion and modification of input and output variables of *fuzzy* sets, and rules for diagnosis.
In the setting of *fuzzy* sets, as shown in Figure 4, we select the input and output variables, and for each one are defined type, name and range of values of the *fuzzy* set.
For the step of setting the rules must be entered both the input and output variables, *fuzzy* sets as already defined in previous steps. In this interface are still used to the rules composition connectors "AND" and "THEN".

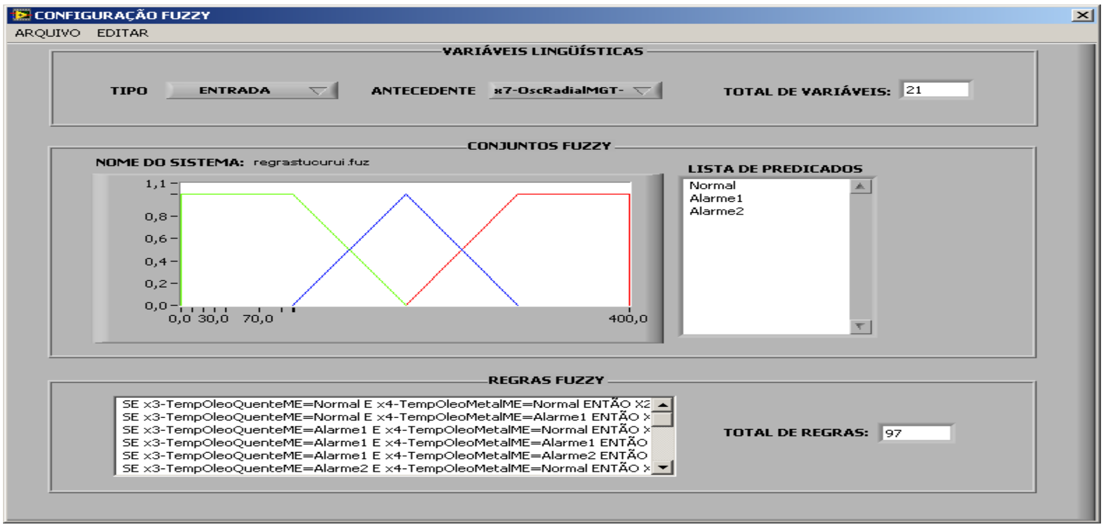

FIGURE 4 - Configuration Interface

Thus, experts have been created several rules that form the basis of knowledge of the system and that reflect the experience of professionals in the area. Some rules used to characterize the defects in the bearings are described below:

- IF (hot oil temperature of thrust bearing is in alarm2) AND (metal temperature of thrust bearing is in alarm2) THEN (danger of rubbing is high).
- IF (radial oscillation at 0 degree angle of turbine guide bearing is in alarm2) THEN (eccentricity of it is high)
- IF (oil temperature of generator guide bearing is in alarm2) AND (metal temperature of generator guide bearing is in alarm2) AND (radial oscillation at 0 degree angle of generator guide bearing is normal) AND (radial oscillation at 90 degree angle of generator guide bearing is normal) THEN (cooling oil system defect is high)

The following are some rules to diagnose defects in the insulation of the stator:

- IF (winding temperature is in alarm2) AND (growth of PD`s in alarm2) THEN (losses level of insulation is high)
- IF (winding temperature is in alarm2) AND (ar temperature is in alarm2) AND (core temperature is in alarm2) THEN (stator overheating is high)

Now, exemple of rule to diagnose the risk of slip ring :

- IF (slip ring temperature at determined current is in alarm2) THEN (burning risk for the slip ring is high)

The rules used by the diagnostic system are stored in text file, not taking up too much disk space as well as provide fast access to data when editing the configuration data. Unlike the measurements made by the monitoring systems that are stored in SQL Server database.

The access to the configuration of the *fuzzy* system is restricted, or is done by users who have permission to access it, which further enhances the integrity of the data since there is little risk that any users will inadvertent changes to system setup.

5. RESULTS

This section presents the results from the application of this diagnostic system in hydro generator based on knowledge obtained from experts.

The results were discussed using data created by a fictitious bank. This bank was created because they were not found in the databases available on the company, with real and synchronous data records that could generate a fault diagnosis. In addition, records of events with real data may take some time to occur. Therefore, this database was created with data that simulate events for the rules used by the diagnostic system to be validated.

The system diagnoses the bearing as to the danger of rubbing defects, eccentricity and fault in the oil cooling system. The diagnosis of stator insulation is done by the system as the defects in high level of partial discharge, overheating of the stator winding and localized overheating. As for the slip ring, the diagnosis is made on the risk of burning the slip ring.
Based on the rules provided by experts and with possible values where these defects can happen, it was added to the database records with defects in the eccentricity of the guide bearings of the turbine and records with defects of over-heating of the stator winding. While the rule about the defect of eccentricity is based on the values of oscillation of the radial bearing of the turbine, the rule about the defect of over-heating of the stator winding is based on the maximum winding temperature, air temperature and the core temperature.
The system interface, see Figure 5 presents the input values from the database and the output variables with the values calculated. The item bearing eccentricity MGT (the turbine guide bearing) results in the value of 48.99, and watching the display is noted that the value is in the yellow region, alert, indicating that the equipment is not in perfect operating condition. In this situation, the hydro generator presents a defect that tends to worse if no intervention is made in the equipment.

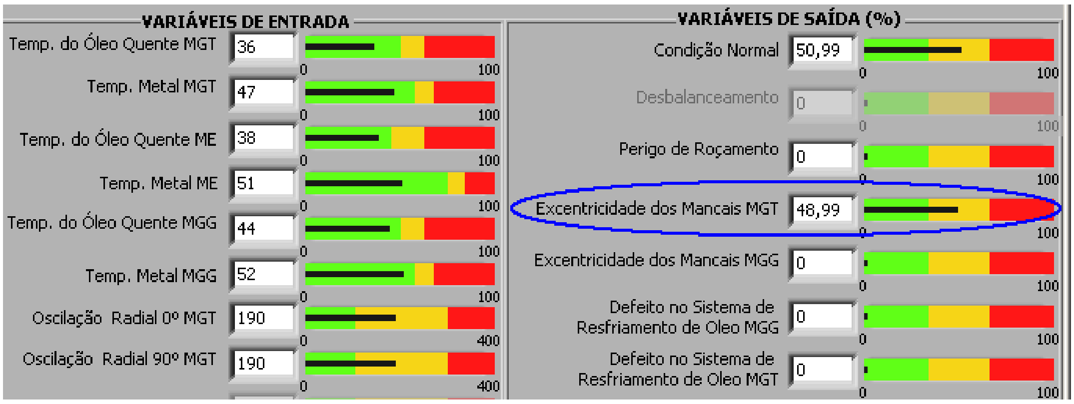

Figure 5 - Trend of eccentricity fault in the turbine

In Figure 6, the value of the stator winding overheating is 73.02, the display is in the red, indicating that the equipment already is in default.

Figure 6 - Failure of overheating of the stator winding found

6. CONCLUSION

Due to the constant load variations, generators intermittent operation and the increase in electricity demand, has been necessary to modernize the procedures for predictive maintenance.
The machine in operation emits numerous signals that indicate its operating condition; the problem consists, from these signals, to establishing a correct and reliable diagnosis. Signals such as vibration are made by several components with different frequencies and amplitudes. The determination of the

origin of these enables the elaboration of a proper diagnosis, contributing to the implementation of a satisfactory maintenance.

The diagnostic system consists of specialist software based on *fuzzy* logic that uses a knowledge base, formed by the experience of experts in the equipment. The use of the system contributes to increase reliability and safety of hydropower, which fully justifies its implementation, with the following advantages:

- Continuous monitoring equipment, providing information to operate and maintain.
- Schedule early to stop the equipment before defect, avoiding penalties and expenses with heavier maintenance.
- Improved scheduling of maintenance personnel tasks.
- Assist the predictive maintenance, filtering out redundant information and aiding in the diagnosis of defects.
- Reduced travel costs for the collection of signals, eliminating the time spent on travel expert.
- Anticipate the vast majority of defects, leaving the experts more time to analyze the more complex cases or wich were still not known.
- Facilitate decision-making of operators, thus tracking "online" the evolutions of the signals provided by the system diagnostics, helping maintenance and enabling the action of the maintenance team in a right time to resolve any problems that are evolving very quickly.

Finally, this system besides providing aid to the diagnosis of defects in hydro generator, help in training and getting better knowledge of the operational behavior of the machines, which could decrease the learning time of users, or can serve as a verification of new knowledge. Moreover, this system can help the production process, enabling the planning and providing explanatory view of the operating data of the equipment or part thereof, for risk analysis of possible intervention.

To improve the diagnostic rules, we have developed mathematic models for the main components of the machines, subject of this diagnostic. When one variable is going out of his normal condition, the formation of the consequent defect is simulated, and we verify if the diagnostic rules are well running; if not we adjust the rules or the models.

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