Updating a Hydro Power Plant Monitoring System Through Failure Modes and Symptoms Analysis

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Considering the present energy generation scenario where a large number of hydro power plants (HPP) in Brazil have been in operation for quite some time now, and therefore need careful attention in order to have their useful life extended, the present work aims to identify critical component faults that cannot be observed by the current monitoring system present in the power plant under study, and accordingly suggest updates in this system. Therefore, the developed method initially proposes a detailed study of the current hydro generator components using two techniques: Functional Tree (FT) and Internal Block Diagram (IBD), the latter from Systems Modelling Language (SysML). The results obtained with these techniques indicate the functions of all hydrogenerator components and the interfaces between them. Next, the method proposes the use of the Failure Modes and Symptoms Analysis (FMSA) technique, in order to analyze if the monitoring technologies present in the system under study can properly diagnose and prognose any fault in an optimized way. The results obtained through the application of FMSA were able to identify the weak points of the current monitoring system and therefore contributed to the addition of new monitoring points in the plant that will maximize the confidence interval in both the diagnosis and prognosis processes.

Keywords: Failure Modes and Symptoms Analysis, Functional Tree, SysML, Hydro Power Plants, Prognosis, Diagnosis, Monitoring System.

1. Introduction

Brazil always had an *avant-garde* position in electricity production from sustainable sources, since the country's energy expansion has been based for decades on a model that highlights the predominance of hydro generation in the energy matrix. As presented by Ayres (2009), it all started more than 130 years ago with the small self-generation hydro power plant (HPP), Ribeirão do Inferno, built in the state of Rio de Janeiro in 1883, just one year after the world's first hydropower plant (a private unit in Appleton, Wisconsin, USA).

In the following years, the first hydroelectric projects that served the general population were carried out in the state of Minas Gerais, mainly by initiative of the textile and mining sectors, and in 1889 the first public utility HPP, Marmelos-Zero, became operational.

With the first National Development Plan, in the early seventies, the small private facilities made room to gigantic public enterprises, such as Tucuruí, Itaipu and Ilha Solteira (Souza 2008). In

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fact, since Brazil has one of the greatest hydraulic potentials in the world, even today, with the development of new energy sources, more than 65% of the electricity is generated by hydraulic power, as shown in Fig. 1 (Brazil (2018)).

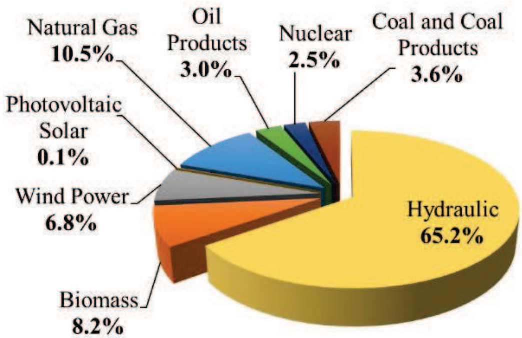

Fig. 1. Brazilian Electricity mix in 2017

However, many of the existing HPP were built decades ago and some of them have been operating for more than half a century. So, to extend their useful life, several of those plants are gradually undergoing a process of rehabilitation and modernization. This provides a good opportunity for updating and improving the hydro generator's Supervisory Control and Data Acquisition (SCADA) and Condition Monitoring and Fault Diagnosis (CMFD) systems, responsible for monitoring some of the plant's most critical operation parameters, and therefore revealing any condition changes that may be caused by components' faults.

Nowadays condition-based maintenance (CBM), which developed as a natural evolution of modern maintenance practices and techniques, constitutes an important field of both research and application where, by means of the active condition monitoring of parts, it is intended to perform not only the diagnostic of their current health, but also come up with prognostics for future defects. Kothamasu (2009), among others authors, even claim that the only way to minimize both maintenance and repair costs and the probability of failure occurrence is to perform online system health monitoring and ongoing predictions of future failures. Accordingly, CMFD systems in HPP have great importance, being basically designed to perform three functions: fault detection, fault isolation, and fault identification (Mino-Aguilar 2014).

In the following items a method is presented aimed at indicating the functions of all hydro generator components and the interfaces between them, as well as assessing whether the monitoring technologies present in the system under study can properly provide diagnosis and prognosis information for any fault in an optimized way.

2. Failure Modes and Symptoms Analysis

Failure Modes and Symptoms Analysis (FMSA), as presented by Nuñez and Borsato (2017), Blancke et al. (2015), Vogl et al. (2014) and Bencomo (2012), is essentially a modification of the well-known Failure Mode, Effects and Criticality Analysis (FMECA) technique with a focus on the symptoms produced by each failure mode identified. Its objective is to assist with the selection of monitoring techniques that provide the greatest sensitivity to detection and rate of change of a given symptom.

According to standard ISO 13379-1:2012(E) (ISO (2012)), FMSA analysis can be developed for a system by:

- Listing the components involved;
- Listing the possible failure modes for each component;
- Listing the effects of each failure mode;
- Listing the causes of each failure mode;
- Listing the symptoms produced by each failure mode;
- Listing the most appropriate monitoring technique;
- Ranking each failure mode by detection, severity, diagnosis confidence and prognosis confidence resulting in a monitoring priority number (MPN), obtained by multiplying each of these ratings;
- Listing the most appropriate correlation techniques;
- Listing the frequency of monitoring for the correlation techniques.

ISO (2012) provides ratings from 1 to 5 which estimates the likelihood of detection, the accuracy of diagnosis and the accuracy of prognosis. It should be remarked, however, that differently from what is prescribed in ISO (2012), in this paper the following criteria were used for ranking severity:

- 4 means "any event which could cause degradation of system performance function(s) resulting in negligible damage to either system or its environment, and no damage to life or limb."
- 3 means "any event which degrades system performance function(s) without appreciable damage to either system or life or limb."
- 2 means "any event which could potentially cause the loss of primary system function(s) resulting in significant damage to the said system or its environment and negligible hazard to life or limb."
- 1 means "any event which could potentially cause the loss of primary system function(s)

resulting in significant damage to the system or its environment, and/or cause the loss of life or limb."

In so doing, the authors' purpose was one of keeping in line with the idea that the lower the MPN, the lower the "confidence level for detection, analysis, and prognosis with the nominated monitoring technique and frequency."

3. The Proposed Method

The objective of the proposed method is, in a first phase, to provide a structured way of carrying out a detailed study of the hydro generator components in a Brazilian HPP by means of Functional Trees (FT) and Internal Block Diagrams (IBD), the latter borrowed from Systems Modeling Language (SysML) (Delligatti 2014). In a second phase, to apply FMSA in two different fronts: first, to investigate the capability of the installed monitoring technologies, and then to advance maintenance and monitoring improvement actions.

The results obtained with FMSA on these two fronts (prior and posterior) are compared and the differences found indicate where improvement actions would need to be prioritized. The failure modes with the greatest differences found indicate where improvements would have more significant effects. Additionally a cost analysis can be done, complementing the previous analysis.

The advantage of initially using both FT and IBD techniques is the fact that, although extremely useful, FT diagrams do not show the relationship between monitored parameters and the operational status of a system and its subsystems. So, IBDs are used in order to expand the knowledge about how the system works, and allow potential observation points, in which parameters monitoring is possible, to be highlighted, thus leading to a better application of FMSA. The method framework is illustrated in Fig. 2.

4. Case Study

A case study is considered in order to illustrate the proposed method. The analyzed system is the shaft of a 150 MW Kaplan hydro generator from a hydroelectric power plant located in the north of Brazil.

4.1 *Functional tree*

Initially, a functional diagram was proposed for the hydro generator, presented in Fig. 3. Five major systems were considered: the excitation system, the generator, the shaft (including the bearings), the turbine (including suction and the draft tube) and the speed governor. As an example, Fig. 3 shows the further development of the functional tree for shaft system. Next, some components presented in Fig. 3 are considered to build the IBD

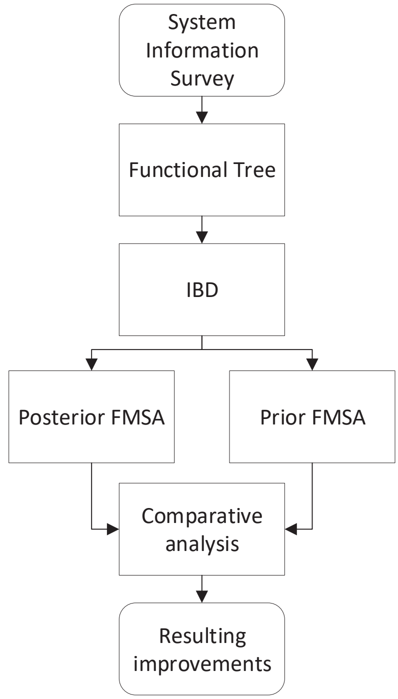

Fig. 2. The proposed method.

4.2 *Internal Block Diagram*

Considering the shaft major components (generator shaft, turbine shaft, coupling elements, lubrication system, guide bearings and thrust bearing) presented in the FT, an IBD can be built, showing the interaction and item flows between each component, as presented in Fig. 4.

According to Melani et al. (2018), the construction of the IBD has the purpose of defining the interfaces and types of information exchange between the components of any system. This diagram highlights the monitored parameters and their relation with the operating condition of the subsystem under analysis (Delligatti (2014)).

In addition, twelve points (named from A to L) were highlighted in the IBD, in which, potentially, one or more parameters could be monitored. The analysis of such points can be considered the key of the method, since from there the FMSA can be correctly developed.

The considered points, with their location and the observed flow from the IBD are listed below:

- Point A: radial oil film pressure between the turbine guide bearing and the turbine shaft;
- Point B: radial oil film pressure between the generator guide bearing and the generator shaft;

- Point C: axial oil film pressure between the thrust bearing and the generator shaft;
- Point D: oil supply between the lubrication system and the turbine guide bearing;
- Point E: oil supply between the lubrication system and the generator guide bearing;
- . Point F: oil supply between the lubrication system and the thrust bearing;
- Point G: oil return between the turbine guide bearing and the lubrication system;
- Point H: oil return between the generator guide bearing and the lubrication system;
- Point I: oil return between the thrust bearing and the lubrication system;
- Point J: cold water collected in the river and used in the lubrication system;
- Point K: hot water, returning from the lubrication system;
- Point L: electric power, from auxiliary power system of the plant providing electrical power to the lubrication system.

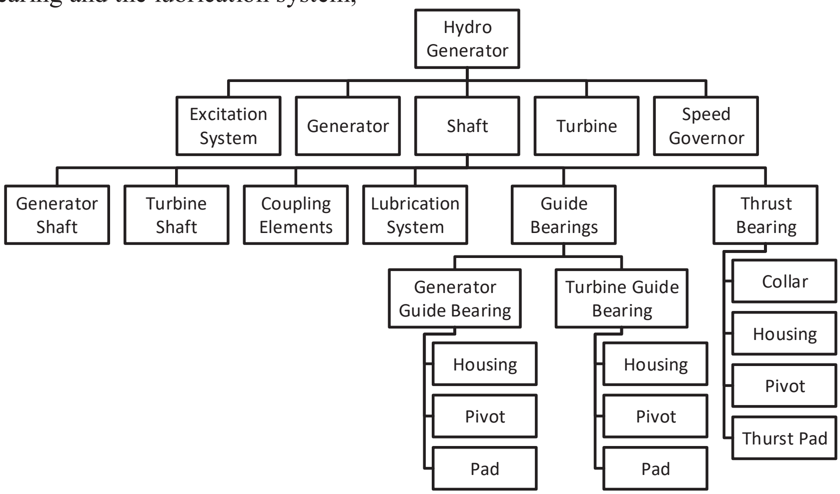

Fig. 3. Part of the Hydro generator functional tree

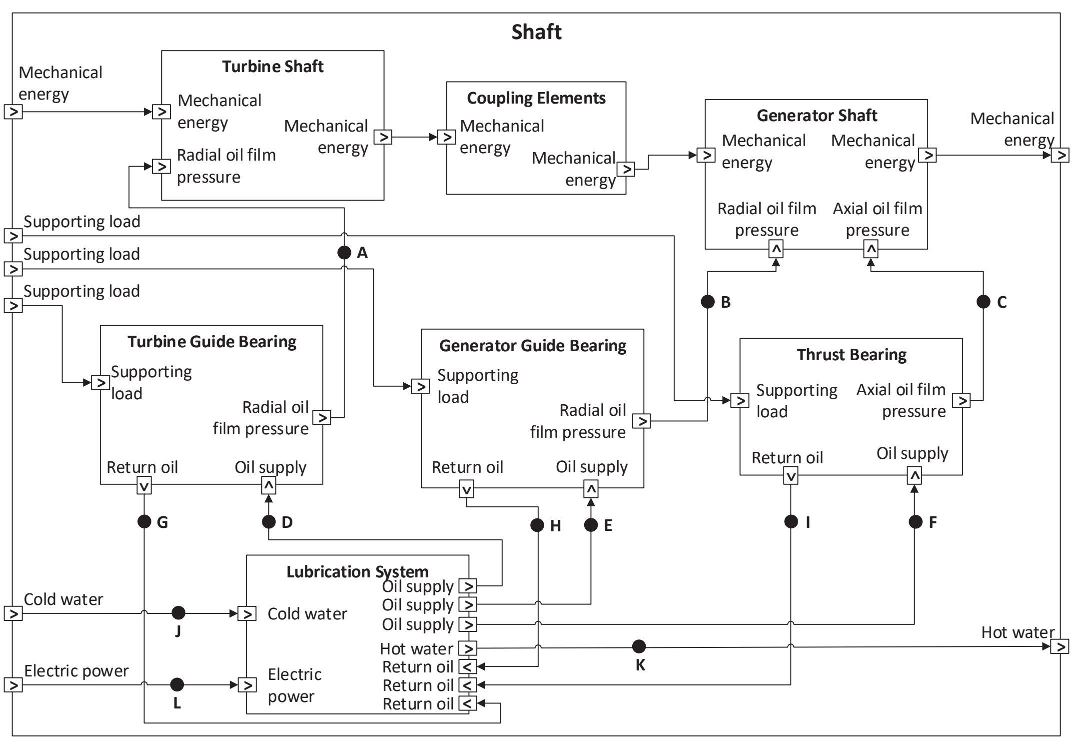

Fig. 4. Shaft IBD

Considering that any deviation in the item flow associated with each point could indicate a component failure, some parameters could be monitored in each case.

Points A, B, and C have the same item flow, and deviations in oil film pressure could indicate shaft or bearing problems. However, direct monitoring of oil film pressure can be very difficult, but monitoring of shaft vibration in the bearings (displacement) and bearing housing (acceleration) can be a good guide for fault diagnosis in this case.

Likewise, points D, E and F were analyzed together. In this case, the oil supply to the bearings is the key point. Variations in this supply may indicate problems in the lubrication system or in the specification of the oil itself, for example. In this case, parameters such as temperature and oil pressure could be monitored.

The analysis of the return oil, related to points G, H and I, is important since it could indicate bearings' problems. Variations in the oil flow could be related to leaks in the bearings, and variations in the temperature could indicate an excessive load in the same component.

Incorrect flow of cold water, related to point J, can be a problem for the lubrication system, since oil cooling may not be performed correctly. On the other hand, the analysis of hot water output, related to point K, could indicate several failures. High temperatures in this case may be related to a very hot oil in the bearings. A lower than normal flow, on the other hand, could be related to leaks in the heat exchangers of the lubrication system.

The electric power supply, related to point L, could be monitored as well. Current and voltage may be the parameters considered, and its variation is undesirable as it affects the oil and water pumps of the lubrication system, for example.

Next, FMSA was elaborated from the current situation of the monitored components of the hydro generator and then the analysis considering improvements in the monitoring system.

4.3 *Prior and Posterior FMSA*

In this section, so as to illustrate the use of FMSA in this method, only the generator and turbine shafts will be considered, in a joint analysis.

Some typical mechanical failures related to the dynamic behavior of a rotating machinery shaft were considered (Walker, Perinpanayagam and Jennions 2013).

The prior FMSA is presented in Fig. 5. The table presents some variations in relation to the typical table, but the core of the method was preserved and, mainly, the MPN was obtained for each case.

Item	Function	Failure Mode	Cause of Failure	Effect of Failure	Failure Symptoms	Primary Technique	Monitoring Location	Monitoring Frequency	Det.	Sev.	Dgn.	Pgn.	MPN
Turbine and Generator shafts	Connect the turbine to the generator, transmitting the movement from the first to the second and allowing the electric power generation.	Fracture	Cracks propagation due to mechanical fatigue or overload	Immediate loss in the generation capacity and trip of the generating unit	Noise, excessive vibration and loss of synchronism	Active power and Noise	Phase bus	Continuous	2	1	4	5	40
						Noise	Local	Inspection round	1	1	4	5	20
		Excessive vibration	Bearings lubrication failure (lack or loss of oil properties)	Gradual loss in the generation capacity and trip of the generating unit in the most severe cases	Excessive bearing vibration and temperature, noise	Noise	Local	Inspection round	1	2	3	1	6
			Mechanical unbalance						1	3	2	2	12
			Electromagnetic imbalance						1	3	2	2	12
			Shaft misalignment						1	3	1	1	3
			Misalignment between bearings						1	3	1	1	3
			Shaft bow						1	3	1	1	3
			Cracks propagation in the shaft						1	2	2	1	4

Fig. 5. Prior FMSA

It is important to notice that for the considered power plant, since there is no dedicated CMFD system, but only a SCADA system, failures whose symptoms are related to the machine dynamics behavior can be very difficult to diagnose, differentiate, and quantify. The experience of the plant maintenance team ends up being a crucial factor in the process, making the attempt of any deeper analysis extremely subjective and imprecise. The very low scores of the resulting MPNs reflect this reality.

Another interesting point is that, since FMSA is mainly related to the ability to monitor and diagnose faults, catastrophic failures often end up receiving a larger MPN than simpler failures that could have their degradation monitored. The point is simple: there is not much to be done after a catastrophic failure, in addition to corrective actions, since diagnosis and prognosis are already known.

Considering now the monitorable parameters, defined from the IBD analysis, and the faults listed in the prior FMSA, the subsequent FMSA can be elaborated, presented in Fig. 6.

In this case, in addition to the large variation of the obtained results, which will be analyzed in the next section, two points changed significantly in relation to the prior FMSA: first, the fault related to the shaft fracture, which initially had detection techniques with different frequencies, and is treated as a single technique in the Posterior FMSA; secondly, the fault related to cracks propagation in the shaft goes through the opposite process, being analyzed in the later FMSA by two different techniques.

4.4 *Comparative analysis and suggested improvements*

As presented in the previous section, the results obtained with the FMSA were very different for the two cases considered. In some cases, the later MPN came close to being 30 times larger than the prior MPN.

The greatest differences are related to mechanical faults that are relatively usual in rotary machines, such as unbalance (Silva (2013)). Faults such as unbalance can be easily identified from vibration signal analysis in the frequency domain.

Currently, the hardware needed to perform the signal acquisition is already commercialized in large scale and relatively low cost. Likewise, commercial signal analysis tools already have in most cases the features necessary to perform the processing required to detect this type of fault.

Such arguments only corroborate the obtained results, since the benefits of vibration monitoring systems for large rotating machines are already widely reported in the literature.

Item	Function	Failure Mode	Cause of Failure	Effect of Failure	Failure Symptoms	Primary Technique	Monitoring Location	Monitoring Frequency	Det.	Sev.	Dgn.	Pgn.	MPN
Turbine and Generator shafts	Connect the turbine to the generator, transmitting the movement from the first to the second and allowing the electric power generation.	Fracture	Cracks propagation due to mechanical fatigue or overload	Immediate loss in the generation capacity and trip of the generating unit	Noise, excessive vibration and loss of synchronism	Active power and Vibration measurements (proximeters and accelerometers)	Phase bus and Shaft	Continuous	3	1	4	5	60
		Excessive vibration	Bearings lubrication failure (lack or loss of oil properties)	Gradual loss in the generation capacity and trip of the generating unit in the most severe cases	Excessive bearing vibration and temperature	Vibration measurements (proximeters) and Temperature	Shaft and Bearings	Continuous	3	2	3	2	36
			Mechanical unbalance		Excessive vibration in 1X rotation	Vibration measurements (proximeters)	Shaft	Continuous	4	3	4	3	144
			Electromagnetic imbalance		Excessive vibration in 1X rotation and 120Hz	Vibration measurements (proximeters)	Shaft	Continuous	4	3	4	3	144
			Shaft misalignment		Excessive vibration in 1X, 2X and 3X rotation	Vibration measurements (proximeters)	Shaft	Continuous	3	3	3	3	81
			Misalignment between bearings		Excessive vibration in 1X, 2X and 3X rotation	Vibration measurements (proximeters)	Shaft	Continuous	2	3	3	3	54
			Shaft bow		Excessive vibration in 1X rotation	Vibration measurements (proximeters)	Shaft	Continuous	3	3	3	3	81
			Cracks propagation in the shaft		Excessive vibration at various frequencies	Vibration measurements (proximeters)	Shaft	Continuous	2	2	2	4	32
					Presence of cracks in the shaft	NDTs	Shaft	Scheduled	3	2	5	3	90

Fig. 6. Posterior FMSA

However, the method is not limited to predictive maintenance techniques. In the case of crack propagation fault, for instance, non-destructive testing (NDT) techniques, widely used in preventive maintenance, present a more significant MPN increase than the use of a vibration monitoring system. Since stress points can be easily identified on such shafts, periodic NDT may be the tool required to evaluate this fault.

This example can be considered even more interesting if the cost factor is added. The ideal would be the implementation of both techniques. In this case, the results obtained with continuous monitoring would serve to determine the periodicity of NDTs. However, if only one technique could be implemented due the associated cost, the results of the method would help in such a choice.

5. Conclusions

In this work, a methodology based mainly on IBD and FMSA, capable of identifying the weak points of the current monitoring system of any system was presented.

The method was initially oriented to hydro generators, given its importance in the Brazilian electric sector, and a case study was considered.

Although it seems an extreme case, since in the considered power plant there is no dedicated CMFD system, it can be said that this is a typical case in many smaller plants in Brazil.

In addition, the validation of the method is not diminished for this reason, since it is not limited to the analysis of monitoring and diagnostic systems, but to the monitoring techniques incorporated into the maintenance routines of an equipment.

In fact, even with a simple example, the method presents several virtues, clearly indicating the possible ways that can be taken to improve the techniques of detection and fault diagnosis.

The application of the method in a broad case, considering all the principal items of a machine or an entire power plant, for example, has great potential and can at least provide a priority analysis, indicating where efforts and funding should be applied to improve the detection and diagnosis of faults. Considering a hydro generator rehabilitation and modernization planning, such gain can be the difference between success and failure.

Acknowledgement

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