# METHODOLOGY FOR FAILURE ANALYSIS INTEGRATING OF VIBRATION ANALYSIS AND THERMOGRAPHY

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***Abstract.*** *In large machines such as hydraulic turbogenerators, the operating cost of maintenance is high, mainly due to low productivity during the maintenance period. The fault detection at an early stage aims to make it simpler and efficient system maintenance, avoiding the extra time and the aggravation of problems. Modern plants use monitoring systems in real time, providing knowledge about the machines in its overall activity of operation and transient conditions, from stops,to overspeed, allowing decision making based on the condition of equipment and generating machines. These systems are based on measurements of electrical and mechanical parameters of the equipment such as voltage, current, frequency, vibration, rotational speed, specific temperatures, displacements, among others. In this study an innovative methodology was developed, aiming hydraulic turbo bearings failure analysis and its consequences, through the integration of field research and laboratory, through fault simulation on a specially designed bench, using techniques for nondestructive testing based thermography and evaluation of vibration levels. The test bench generated from the experiments carried out also allowed the study of signal processing techniques applied to dynamic analysis of structures and contributes to the diagnosis of faults in the future. For the application of the methodology in the field, it developed a thermal analysis software, able to monitor in real time the electrical and mechanical components of the power generation system. Finally, the methodology was implemented on the premises of UHE- Peixe Angical of Enerpeixe, seeking thereby provide greater power generation control conditions and increased system reliability.*

***Keywords:*** *Maintenance, thermography, vibration.*

## 1. INTRODUCTION

The demands of the consumer market coupled with the development of new maintenance technologies requires the companies to generate electricity with quality, security, economic production management, increased productivity, etc. The growing demand for power generation coupled with increased productivity requires the decreased of stopping risks and a higher degree of automation in the operation of hydroelectric power plants (HPPs). Maintenance based on condition also known as predictive maintenance is one of the effective tools that can be applied to optimize the management of hydropower plants operation, aimed at reducing maintenance costs and higher productivity (Randal,2011). Systems integrating monitoring, diagnosis, maintenance and management of HPP's, increased the machines availability, improved performance and efficiency. The most common maintenance schedule found in the plants of electricity generation is the SM, where the physical structure and equipment are periodically reviewed and repaired second "check-list" standardized. Frequency varies for each building and equipment of the plant, according to the standards of manufacturers involved in the construction and supply of equipment. The most modern plants use on-line monitoring systems, which provide real time information about the operating conditions of the machines. This information is analyzed by operators, and those responsible for starting or off the generating units in accordance with required by the ONS (National System Operator). The analysis of the different monitoring systems installed throughout the plant allows the plant maintenance scheduling based on the needs, thus increasing machine availability by reducing forced stops for repairs. These systems are based on measurement magnitudes of engineering equipment and machinery installed in the plant, such as voltage, current, frequency, vibration, rotational speed, specific temperatures and displacements, among others. The ultimate goal of a condition-based maintenance and historical data is to reduce or even eliminate routine maintenance and allow them to carry out maintenance operations only when the system indicates the need of the operation.

Despite such periods of scheduled maintenance always occur in drought or low historic production periods, the fault detection at an early stage aims to make more efficient the operation of the corrective maintenance of the system, thus avoiding unplanned downtime and aggravation of faults. Thus, working mainly in high severity defects, where it does not affect the protection logic and can worsen if the generating unit is not removed from the system. The combined use of vibration analysis and thermal analysis can be an excellent solution for the detection of these faults. In this study, we propose a methodology for analyzing failure of hydraulic turbo bearings, from the integration of field research and laboratory where it was integrated the use of non-destructive testing techniques (NDT) based on thermography and levels of vibration, using principles of virtual instrumentation, through known flaws in a specially developed test bench and after tested in Hydroelectric Power Plant Peixe Angical of Enerpeixe on the Tocantins River, through the Research and Development Project (R & D). The contact temperature sensors were not used in this study because the goal of it is to evaluate the efficiency of techniques that applies optical devices.

## 2. FAULT MECHANISMS

### 2.1 The origin of fault mechanisms

The sources of faults in generating units are results from mechanical origin, nature forces, hydraulic, electric and magnetic. The action of these forces may result in deformation or damage of structural and operational elements of the generating unit. The forces can be permanent or transient (Vladislev, 1979). The forces of permanent regime can be periodic or stochastic (random in nature). The transient forces are not of periodic nature and occur in the form of pulses. The origin of mechanical forces may occur as a result of unbalance, misalignment, self excitation due to dry friction between rotating parts, and the internal friction of the material deformation. With regard to hydraulic forces when the system operates under steady state conditions, in the range of normal operation, appear periodic hydraulic components, which have frequencies related to machine speed due to their construction. On the other hand, if the system operates under transient conditions and outside its normal operating range, then stochastic components will emerge in the signals, thus generating a spectrum of excitation floating broadband frequency and amplitude, and reaches its maximum values near the rotation frequency of the machine. In steady state condition of the vibration spectrum showed multiple periodic components of the turbine speed, on the other hand the transient condition spectrum is characterized by a random variable signal amplitudes with maximum values near the turbine rotation frequency. The characters of fluid dynamic excitations are generally related to the frequency of rotation of the machine, with the blade passing frequency and frequency sidebands. The blade passing frequency is defined as the number of blades multiplied by the speed of the machine. Vibrations related to electric excitation source may occur in hydraulic turbogenerators in mechanical energy transformation process into electrical energy in the generator. The types of forces occurring in normal operation of the generator under steady state condition are due to the production of the magnetic field that interacts with the field generated by the stator, clearance between the rotor and the stator, forces due to partial short-circuit the coils of the rotor poles or stator, load with generator operation asymmetrical. Usually the disturbing source forces electromagnetic are insignificant at first, but become more severe due to corrosion, deformations and enlargements of generator components. The vibration monitoring is critical to the diagnosis of the condition of hydraulic turbo systems, and the use of diagnostic techniques applied, in particular in the dynamic aspects, is an important tool to understand the causes and consequences of faults that generate vibration.

### 2.2 The analyze of the mechanisms

The monitoring of vibration levels in hydraulic turbogenerators allows relating the origins of the intensities and frequencies of excitatory forces with the behavior of the generating unit and its components under the action of these forces (Suyi,2006). The evaluation of the relative vibration in rotating machines is determined in accordance with ISO 7919/1 (1996), from which the radial extent of displacement in two orthogonal directions are calculated maximum displacement of the axle, and are controlled values peak to peak X shifts and YA signal analysis in the frequency domain is a form of alternative signs description, given that in many situations it is impractical show complex phenomena in the field of time. In the monitoring machine area, the differential in the analysis of the signals in the frequency domain when compared to the analysis in the time domain is the possibility of the diagnosis of the causes associated with faults of the various components of a machine. The unbalance of a rotor is one of the most common machine faults, and occurs when the center of rotation does not coincide with the center of mass of the rotor. The unbalance can result from design defects, manufacture, assembly or improper operation, such as, for example, lack of rigidity of the axes of the units, wear or loss components due to cavitation, inaccuracies in the manufacture of components, material in homogeneities, improper assembly, misalignment, inlays, etc. ISO 1925(2001) four types of standard classifies unbalance: static, binary, quasi-static and dynamic. The static unbalance occurs when the principal axis of inertia of a rotor is displaced, however, parallel to the rotation axis thereof. This effect is caused by an unbalanced mass located at the same axial position of the center of gravity (CG), or two masses equal and equidistant CG. The unbalance torque occurs when the shaft cutting the main inertia axis of rotation in the center of gravity. This condition occurs when two equal mass unbalance are placed axially equidistant from the CG, but opposite 180 ° around the axis of rotation. The quasi-static unbalance occurs when the main axis of inertia cuts the rotor rotational axis at a different point CG. The dynamic unbalance is the most common type found on the machines. It occurs when the main axis of inertia of the rotor does not touch the axis of rotation. In generating units components are susceptible to unbalance the rotor of the turbine generator rotor and the armature driver. The unbalance can be detected by the occurrence of large vibration amplitudes, synchronous with the rotational speed (1xRPM) and predominant direction of vibration, typically radially. The misalignment between the axes is coupled to the unbalance, one of the most common defects in machinery. The types of misalignment are angled, parallel or a combination of both. The misalignment constitutes loss centricity axes, ie center line of axis deviation, which may occur due to: the existence of an angle between the center lines of the axle shafts, the lack of perpendicularity between line shaft center and the surface plane of the axial bearing or anchor, the unit's tilt and when bearing guide is not coaxial with the shaft. A misaligned rotor generates forces in the bearings and excessive vibrations. Factors affecting the degree of alignment machines can be temperature variations, inadequate foundations, uneven load distribution, among others. The vibration analysis caused by misalignment It presents high vibrations in the axial direction of frequency components at once with the axis of rotation (1xRPM), and in more severe cases of misalignment twice rotation of the shaft (2xRPM) or even frequency Vibration three times the axis of rotation (3xRPM) .The rubbing is a mechanical source failure resulting from metal to metal contact and can cause high levels of vibration. The state of the surfaces and the nature of the materials in contact have an influence on the intensity of the frequency of vibration. The rubbing causes are: lack of lubrication, war page of the shaft, assembly errors, deformation of the substrate, unevenness of the supports and damage the foundation or base of the machine. The friction in bearings, as well as electric source flaws allow generate increasing temperature, thus allowing the application of thermography to monitor the behavior of this parameter by using stationary infrared cameras and mobile, which can in the case of a hydroelectric plant, They are installed in the generator and transformer region of Generating Unit. According to Bortoni (2010), there are countless potential use of infrared thermal imaging in colorimetric method for determining the efficiency of synchronous hydro machines. It is clear that radiated losses are only a small part of the total losses, being generally less than 10% of that. It has been shown that machines with large exposed area such as large hydro power plants generators are more sensitive to these losses than small hydroelectric generators. Moreover, this is the most time consuming task to perform determination tests efficiency in the field. The application of thermography techniques dramatically reduce the man-hours needed for field trials. It has also been shown that the values of heat transfer coefficient suggested the most common patterns must be revised to give physical quantities studied the machine and the ambient conditions. Conduction loss in the machine shaft was also considered, but in fact was often overlooked because of measurement difficulties and also because of their small value. The results demonstrated the applicability of the proposed method, leading to a very good agreement when compared with the standards. Diagnostic work to characterize the faults were developed from data collection and analysis on the operational records of equipment, circumstantial conditions of the occurrences in specialized laboratories materials analysis and inspections during the dismantling process of each. The results of this study are to contribute to the development of fault classification criteria in transformers, improve parameters for assessing susceptibility to faults from specific types of transformers as well as initiating the development of a database on faults power transformers in the Brazilian electrical system. In the study by Pacholok (2004), it was possible to investigate whether scaling relation between the heat generation in the flexible element of a rotary shaft coupling and the extent of misalignment, being able to confirm the central hypothesis established that a relationship exists linear range between the heat generation in the flexible coupling element and the amplitude of misalignment, as well as the need outlet temperature of angulations in some situations. In cases he studied, it was found 3,1ºC maximum increase in the flexible coupling element of the electric motor while the increase was up to 24 ° C. In the analysis by thermography, the images of efficient processing can contribute substantially in reducing the availability of equipment, since the system can monitor on a daily basis the points of interest, the early identification of likely failure points.

## 3. DESCRIPTION OF THE TESTS BENCH

Based on studies, a bench was developed in which it was possible to simulate faults in a system similar to a turbo-generator, where it was possible to measure the electrical parameters, vibration and temperature in real time. This developed bench, consisting of a shaft supported by two bearings. The axis can install up to three drives with different moments of inertia.

They were designed three sets of bearings to be used in supporting the shaft, two rolling and four slip, targeting new future studies.

The system is driven by an electric motor of 1.5 HP, whose rotation is controlled by a frequency converter. The drive of the bench are used three engines one at no fault condition and the others failed and shorted rotor bars break. The “Figure 1” illustrates the bench developed.

The bench also has a clamping device of a thermal imager to assess the condition of the critical points of the system by thermal analysis. A device for handling and fixing of the thermographic camera is designed so as to operate the thermographic monitoring system over a number of points machine. This system allows the camera to be moved horizontally by hand through a spindle nut. The spindle attached to a fixation device can undergo a swivel at an angle of 120 ° by means of an electric actuator. The camera also has rotational movement around the spindle via a servo motor drive system. From preliminary tests with the counter rotation under different conditions, it was observed high levels of vibration in the resonance regions. This operating condition presents risks severe damage to the machine and operator safety. To minimize this problem was a device designed to limit excessive movement of the shift shaft out of the rotor center of mass. The "Figure 2" illustrates two devices bushing at the side of the disc. This system does not limit the rotation of the shaft in the normal operating condition, but the resonance condition restricts excessive deflections of the shaft, minimizing the risks of operation. This device may also be used to simulate the rubbing condition, when the system operates in the regions of resonance. The measurement and analysis of vibration magnitudes were structured in monitoring and diagnostic system Automatic MDM made by M&D Company.

Figure 1. Side view of test bench.

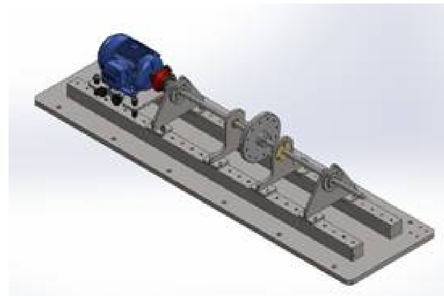


Figure 2. Limit device of excessive deflections of the shaft in resonance condition.

This system is structured from the LabVIEW platform and uses hardware from National Instruments (NI). The data collection system is integrated via the network, performs processing digital signals and applies artificial intelligence techniques to aid in the diagnosis of machine condition. MDM system comprises a data acquisition unit with an eight channel analog module Current measurement (4 to 20 mA), where the proximity sensor and also a four analog input module for measuring with accelerometers are installed. Evaluation of machine vibration levels involves absolute and relative quantities.

The measuring absolute vibration is performed through four accelerometers fixed at strategic points of the machine, such as the bearings in radial and axial directions. Four proximity sensors (non-contact sensor) are used for assessing the relative radial axis (XY) and a proximity sensor and timing (trigger). The thermal monitoring module that is independent of the MDM system comprises a thermographic camera, the camera tracking system and a system of collection and image processing. The MDM system allows the issuance of various graphical reports to support the diagnosis.

The developed mathematical model was applied for the UHE SINOP case study – expected for the Teles Pires river, in the northern of Mato Grosso State and located at Amazonas' river basin – that provides the application of 3 Kaplan turbines with 24.5 m of available head, 596.20 m³/s of unitary nominal flow and 400 MW of optimum total installed power.

They were adopted 95% and 96% as efficiency values for Francis turbines and Kaplan turbines.

The utilized values for monthly flows were the average flows of Teles Pires river at location of the installation, during the period between 1931 January and 2006 December

The adopted electricity sell price was 259.19 R$ / MWh while the adopted monthly operating hour load was 660 h.

It was made the application of the mathematical model for the analysis of three different scenarios: all 3 generating units using Kaplan turbines (according real project), all 3 generating units using Francis turbines and finally an optimized combined application scenario with these two types of turbines.

## 4. THERMAL ANALYSIS MONITORING SYSTEM

The system developed for temperature monitoring in the field, in the case of applied study in the field, refers to the mapping of generator and transformer of hydroelectric plant, analyzes predefined regions of a target object electric, set up and configured previously, and produces a diagnosis. The system also allows a custom thermographer perform inspections within the field of view of the cameras remotely since the system can be accessed remotely and be operated manually. This makes the system attractive for inspection in hard to reach areas, installations in hazard areas or remotely operated facilities, since the thermographer need not be present, being able to access the cameras remotely through an internet connection or connected to network company.

The system also allows the thermographer perform manual inspection, analysis using their knowledge through a remote positioning of the cameras. Making attractive system for monitoring areas of difficult access installations in hazard areas or operated remotely, since the thermographer need not be present and is able to access the cameras remotely through an internet connection or connected to a local network of the company. The obtained images are processed and the resulting temperature is calculated and corrected by the environment data supplied from the temperature and humidity sensors.

The new values are then stored in a database, such as average temperature, maximum temperature, minimum temperature and the average temperature for each acquired image are stored together with the current temperature values of current, active power , reactive and power factor target element. A priori, an artificial neural network (ANN) is trained for each region to estimate the mean temperature for that region according to the prevailing conditions.

The RNA output value is compared with the stored average value of the temperature obtained in actual image region if the difference is greater than the tolerance data likely to be reliable. The maximum temperature is compared with the mean temperature and with the maximum permissible temperature for the material of the analyzed region. According to the defined rules, a fault diagnostic report is generated, as well as a diagnosis by comparing regions of different images.

For example, the switchgear installed in all three different stages of the electric system. Once the system is subjected to the same conditions and equipment have the same specifications, the temperature difference between said regions should be very small. If the temperature difference between those regions is greater than a set value, a fault diagnostic report is generated [7].

## 5. METHODOLOGY DEVELOPED FOR FAULT DIAGNOSIS INVOLVING BEARING TURBO GENERATORS

In order to the vibration and temperature data, got by monitoring system of the generating unit, being useful for the fault diagnosis they must be accurately analyzed.

Within the trends of failure of the turbo generator operations, it is evidenced in the tests, the correlation between variation in temperature and vibration, but the correct fault finding must follow certain steps for proper procedure.

Considering size, difficulty and risk to perform the tests described here, in a real size generating unit, it was clear that the best option to create a database which will act as a source of temporal data Unit operating status of generating as a whole.

Thus, questions related to how much each error factor on the bearing shaft, will influence the malfunction generating unit in question will be solved and can be provided with the analysis of history.

Then as described was prepared one diagnosis methodology failures involving turbo bearing.

Assuming that a machine is characterized in that its moving parts, vibrate according to the characteristic frequencies of the components and each kind of machine has a unique spectral signature. Vibration analysis is the process by which the flaws in moving parts of equipment are discovered by the rate of change of the dynamic forces generated.

These forces affect the vibration level that can be evaluated at accessible points in the machines without interrupting the operation of equipment, according to the installed sensors.

As to the vibration in thermography is also needed a thermal signature operation referenced to system load, which may be divided into intervals commonly used in the generation, for example, 50%, 75% and 100% load.

The monitoring of the operation with that signature is the process of discovering and analyzing changes in the pattern of the signature according to the wear or sporadic fact.

Through the spectrum analysis process to vibration and variation in temperature applied to the entire thermographic system, it is possible to identify the thermographic and vibration characteristics of each individual component to monitor their condition.

From the moment in which the machine is set signature, it is necessary to create the database according to the fault has occurred.

Thus, the occurrence of a fault is stored in reports containing the vibration analysis, and thermal analysis of the state of operation.

Recalling that the digital data, for example, thermographic (FPF) images to the thermal camera, and points to generate the charts are extremely vibration needed for diagnostic analysis of future failure.

Thus will begin the creation of a comprehensive database of machine operation, which for a long period of time will make it possible to diagnose with greater veracity the operating situation, predicting the failure point, or rather the future point of failure closer.

On the other hand there is an immediate gain because once known the signature generating unit, you can not diagnose the momentary compliance, although not possible to identify the point of failure.

The described methodology was applied by means of tests conducted in the laboratory, the first test to validate the calculated resonance points. These points should be ignored in the operating system due to the high indict vibration.

The signature of the machine running test was conducted in a range of frequency values, and thus it was possible to have patterns of vibrations and thermal, for the system making the exchange of bearings, brass and bearing.

Once unbalanced, the shaft system showed a considerable variation in its orbit, and an average variation of 10 ° C in temperature of the test modes: bearing, motor, and in case the cart axis. Therefore, a variation in shaft vibration generated in the system affecting engine temperature, which in turn will generate an increase in temperature of the gas around the engine and increased wear of the parts involved.

In misaligned system using the spectral amplitude axis, the misalignment in evidence the varying components synchronous rotation and is accompanied by a next variation of 10 ° C and coupled to the motor bearing, however the bearing free condition was observed a slight change in same.

In the case of rubbing, and a visible thinning of the components involved, the large increase in temperature due to the engine load, it is also possible to verify the occurrence of a particular orbit analysis. The external appearance of loops, indicating sub synchronous behavior.

In assessing the performance of the system based on electric drive system were conducted tests on the engine in faultless condition, motor with phase failure, motor with phase failure and unbalanced rotor, motor with short on housing and motor with short on housing and unbalanced rotor. The unbalance test was selected because of its importance and relevance in most operating conditions.

The current measurement for each value shows an increase in all operating conditions, and thus a slight increase in temperature, vibration view major differences were observed for each of the situations described. However, in the event of electrical faults, such as those of the engine, can be considered as a high level fault, easily diagnosed by means of thermography, since a failure in the temperature region will be completely changed, and for the vibration analysis Spectral denotes great variation.

The results obtained in the experiments can be seen in , "Fig.3,4,5" and "Tab.1, 2" .

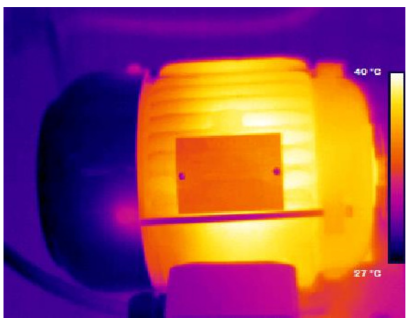



Figure 3. Motor thermal photo - rubbing condition

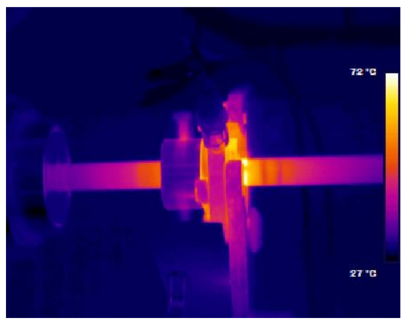



Figure 4. Thermal photo of the coupled bearing

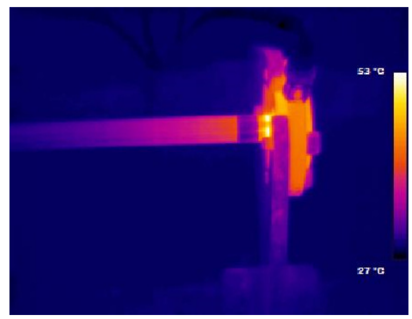
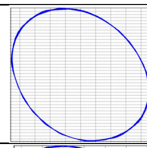
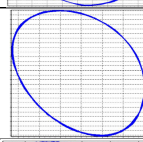
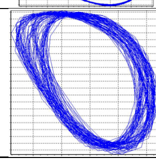
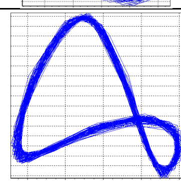
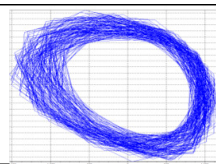
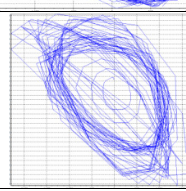
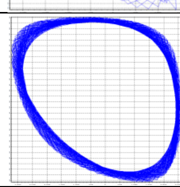
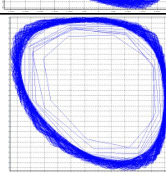



Figure 5. Thermal photo of the free bearing

Table 1. Temperature behavior results in relation to the simulated failure on the test bench.

| Failure | Temperature variation compared to Room Temperature | | |
|---|---|---|---|
| | Motor | Coupling bearing | Anchor bearing |
| No defect. (Machine signature) | 52,2 % | 43,5 %, | 52,2 % |
| Unbalance | 82,6 % | 82,6 % | 52,2 % |
| Misalignment | 86,9 % | 86,9 % | 17,4 % |
| Rubbing | 100 % | 45,8 % | 29,2 % |
| Motor with phase failure | 63,9 % | 65,7 % | 69,7 % |
| Motor with phase failure + Unbalance | 62,1 % | Not applied | Not applied |
| Engine with short circuit on housing | 62,2 % | Not applied | Not applied |
| Engine with short circuit on housing + Unbalance | 62,2 % | Not applied | Not applied |

Table2. Results of the Orbit , the frequency spectrum and behavior in relation to the simulated failure on the test bench.

| Failure | Orbit | Frequency Spectrum |
|---|---|---|
| No defect. ( Machine signature) |  | 1xRPM –pure component with an amplitude determined in accordance with the sampled machine; |
| Unbalance |  | 1xRPM – like “ no defects” condition;<br><br>2xRPM – appearance of a component with low amplitude; |
| Misalignment |  | 1xRPM – like “ no defects” condition;<br><br>2xRPM – appearance of a component with low amplitude; |
| Rubbing |  | 1xRPM – like “ no defects” condition;<br>2xRPM – component with approximately one third of the amplitude 1xRPM;<br>3xRPM – appearance of a component with low amplitude;<br>4xRPM – appearance of the component with a small amplitude, smaller than with 3xRPM; |
| Motor with phase failure |  | 1xRPM - Amplitude similar to “no defects” condition, but with noise components around low amplitude;<br>2xRPM – component with spaced noises; |
| Motor with phase failure + Unbalance |  | Appearance of noise before 1XRPM<br>1xRPM - amplitude similar to “ no defects “ condition, but with noise components around low amplitude;<br>2xRPM - component with spaced noises; |
| Engine with short circuit on housing |  | Appearance of noise before 1XRPM<br>1xRPM - amplitude similar to “no defects” condition, but with the enlargement of the wave;<br>2xRPM - small amplitude;<br>3xRPM - higher amplitude than 2xRPM; |
| Engine with short circuit on housing + Unbalance |  | Appearance of noise before 1XRPM<br>1xRPM - amplitude similar to “no defects” condition, but with the enlargement of the wave;<br>2xRPM - small amplitude;<br>3xRPM - higher amplitude than 2xRPM; |

## 6. CONCLUSION

To be able to study the mains aspects of the mechanics faults on hydraulic turbogenerators bushing, such as unbalance, misalignment, rubbing, and electric defects, it was necessary a big effort to the construction of the tests bench, that provide a significant knowledge evolution of the team involved.

The conception of the mechanical and constructives requirements of the system, as a particular solution for the installations location on field, or the position control system, allowed advance on the development of a comum solution, with easy replication to any monitoring area.

The developed methodology allowes the operator to create an operation pattern, that will help on the take of decisions and on the increase of availability of the Generator Unit.

The installations that were made at the plant involved a big technical challenge that propitiated a big knowledge evolution of the team who developed the study.

Due to the recent methodology implementation at the UHE – Peixe Angical, there were no historic conditions for analysis of its results, showing the benefits that will provide, as the necessary adjusts to its application. The lack of a data base whit the historic information of operation of the Plant, from thermal and vibrational point of view, increased the difficulty of creation and the comparative analysis with the developed tests bench, but once implemented the described methodology, it will lead to the acquirement of historical data as the natural failures occur and then it will be possible to define a real pattern of operation, thus, the deepening at real behavior of the UHE will be bigger, providing the upgrade of the developed methodology in this study.

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## 8. RESPONSIBILITY NOTICE

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