# INSTRUMENTATION FOR MONITORING AND ANALYSIS OF PARTIAL DISCHARGES IN ROTATING MACHINES – BRAZILIAN EXPERIENCE

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**Abstract**: This paper describes the recent Brazilian experience on Partial Discharges (PD) measurement and analysis in rotating machines, including the development of IMA-DP (Instrumentation for Monitoring and Analysis of Partial Discharges), designed by Eletrobras to monitor the generators 1 and 2 of Tucuruí, the biggest Brazilian hydro-power plant. The proposed system includes high speed digitizer cards on a PXI industrial computer and is designed to operate off line or on line, remotely logging statistical maps of PD over time. IMA DP has been validated by comparison with other traditional PD instrumentation, and has proved to be an economic alternative to monitor high voltage equipment, including rotating machines insulation.

## 1 INTRODUCTION

For many years Eletrobras (Cepel) has been dedicated to research monitoring systems that aim to improve the development of computational tools for measurement, data storage and analysis as well as models for evaluation and operative diagnosis of rotating machinery.

Besides the traditional thermal and mechanical analysis, performance aspects of stator insulation has grown in interest, leading to measurement and evaluation of PD by electrical methods.For many years Eletrobras (Cepel) has been dedicated to research monitoring systems that aim to improve the development of computational tools for measurement, data storage and analysis as well as models for evaluation and operative diagnosis of rotating machinery.

This work presents the current state of art regarding PD monitoring, and describes the main boundary conditions where this technique can be used. It also describes IMA-DP, a modular instrumentation system that has proved to be an economic and effective tool for PD analysis.

The measurement of partial discharges in rotating machinery has always caused intensive discussions and differing opinions on specialized technical groups. The state of the art, which has evolved very little in recent years in terms of effective diagnosis of the machines, failed to produce more universal recommendations and regulatory procedures. This technology stabilization results in a diversity of referrals of diagnostic and monitoring solutions as the philosophy of maintenance and technical expertise of each company.

There is, however, one common point to most experts in this area: the consideration of the PD measurement as an essential tool to establish a robust assessment of electrical performance of stator winding.

Initially we tried to describe the main factors that affect the quality of analysis and diagnosis of operating machines based on a collection of PD acquisitions. Among these factors are the electrical characteristics of the couplers, their quantity and location; the measurement bandwidth, the storage form of the acquired signals, etc. The simultaneous acquisition of PD signals with the operating conditions of the machine, such as operating power and distribution temperature of the bars are other factors to consider.

Based on these initial reports it was decided to develop a system that could be flexible to the point of provide a degree of adaptation to the characteristics of each machine.

Notably, the measurement bandwidth and amplitude limits of PD signals are examples of parameters which may be different for different stator windings.

From the analysis viewpoint, a procedure was developed that facilitates the tracking of evolution of partial discharges at various levels, such as the global average in a given period for each measuring point, etc.

The formulation of a single database combining electrical, thermal and mechanical quantities provided more versatile analysis for each user.

Another important goal was to use commercial modular equipment easily obtainable on the market. It greatly reduced the final cost of the system, facilitating the maintenance processes and the future repairs and upgrades. With modular virtual instrumentation, a single hardware can monitor up to 60 couplers, reducing greatly the cost by channel.

## 2 MEASUREMENT CIRCUIT

PD activity inside an electrical equipment shows itself as a sequence of high frequency pulses over the applied voltage. Figure 1 shows a PD electrical pulse from a generator insulation. At the right, the sequence of pulses is shown along one cycle.

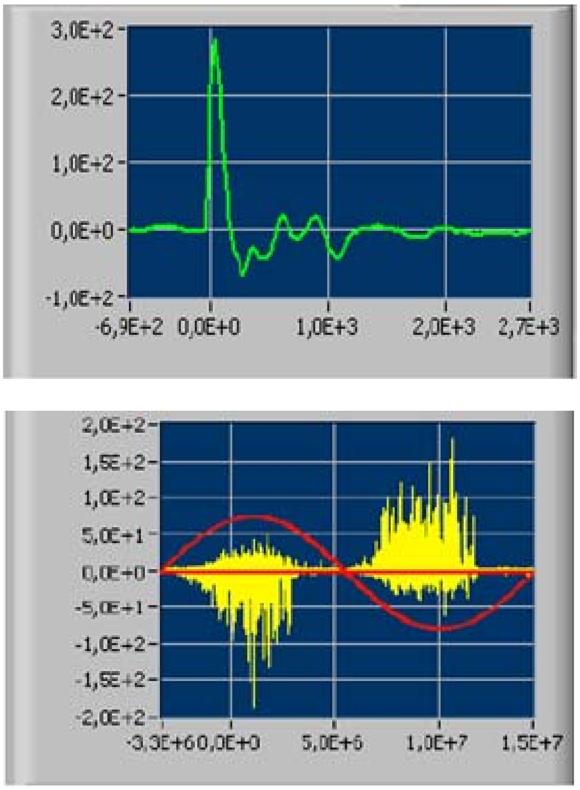



**Figure 1:** PD electrical pulse

As a high frequency signal, the PD pulse can be measured by the circuit in Figure 2. The PD pulse is driven through the Coupling Capacitor C1, and measured over the shunt impedance Z. Note that C1 and Z form a High Pass filter, eliminating the low frequencies and making possible the PD measurement.Specific details are provided in the following sections.

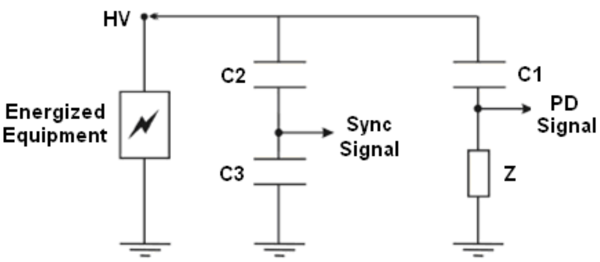



**Figure 2:** Circuit measurement of partial discharges

To identify the insulation defect, is convenient, however, to record PD pulses with the information of the correspondent applied voltage. For this purpose we take a voltage reference signal from the capacitive divider C2 – C3, in order to synchronize the measurement with the applied voltage.

Both signals, PD and Voltage are acquired and processed by the Measurement Instrument.

The PD pulses are thus measured from coupling capacitors connected in predefined points along the phases of the stator winding. Depending on the characteristics of the generator and the philosophy of measurement, various couplers can be installed per circuit. There is no way need to define a minimum number of couplers, because, regardless of possible criterion adopted, it would not be possible to quantify accurately the level of discharges nor establish their relative position within the stator.

This behavior implies that the PD signals will have different waveforms according to their sources positions and the relative position of the coupler where the measurement is being performed.

The conclusion is that the PD measurement should give us a statistical behavior of the welling as a whole, and track the evolution of the PD levels. According to the kind of analysis performed, it is also possible to evaluate the kind of defect that would be present at the wheeling.

With these assumptions, some flexibilities can be considered in the measurement of PD's:

- A greater number of couplers will not necessarily bring more confidence and efficiency in diagnosing or provide the location of the most critical region in terms of occurrence of PD;
- The value of capacitance of the coupler is not very important (may be used couplers of 500 pF, 145 pF, 80 pF, among others);
- The calibration of the test circuit is not very important, since discharges in different parts of the winding are translated into different ranges of discharge at the measuring points;
- The most important thing is to follow the evolution of discharges in the same geometric position;
- It is possible to make different adjustments of the measuring circuit and the instrumentation for different couplers installed in various points along the winding - the measurement sensitivity settings can be defined for each coupler;
- It is enough to distribute couplers in winding regions with the largest

concentration of electrical field (high voltage side) and, if appropriate, in positions of strong coupling between bars of different phases.

The diversity of possible assemblies of the test circuits allows to perform measurements in various frequency bandwidths. Thus, it is possible to adjust the frequency bandwidths in order to get more sensitivity for each type of winding and, if applicable, for each installed coupler on each measurement point.

## 3 PD STATISTICAL MAPS

Since this is a statistical phenomenon, to characterize satisfactorily the occurrence of PD, it is necessary to acquire the signal over several cycles of the network. However, because the signal is of high frequency (typically up to several tens of MHz), by the Nyquist theorem, to avoid incurring aliasing errors, the signal should be digitized with a sample rate at least equal to twice its largest frequency component. These two facts lead to a storage problem, as illustrated below.

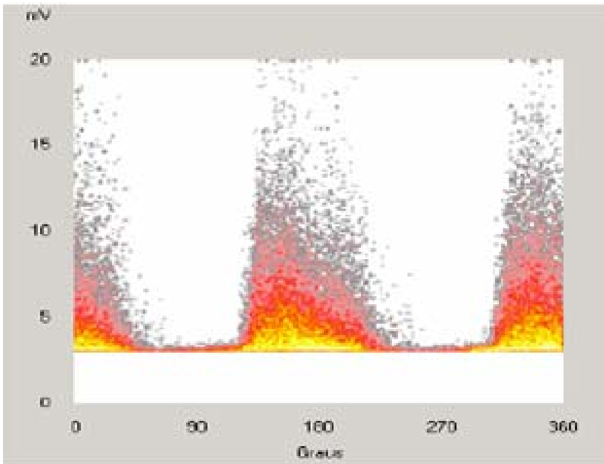
Suppose a signal up to 50MHz is digitized with a sample rate of 100MHz. To register this signal for 16.6 ms, it would be necessary to store an array of 1,660,000 points, which correspond to only one cycle of a 60Hz sinusoidal voltage. As we see, the record of the signal over several cycles would require a large amount of memory and disk storage, which would overload the entire measurement system, increasingly slowing the acquisition process.

To overcome this problem, the construction of the PD statistical map was proposed. Also known as a Phase Resolved Partial Discharge representation, it is shown in Figure 3. Those statistical maps are commonly used as a form of DP representation on many digital measuring instruments.

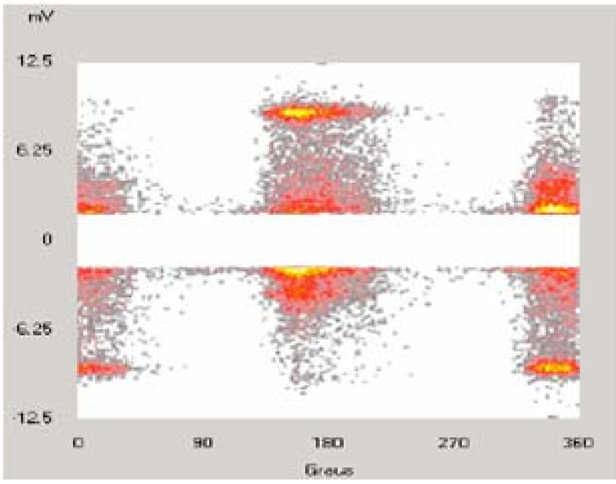
Given the impossibility of registering multiple pulses over several cycles of the network, the acquisition system, each cycle, catches a train of pulses and records them on a surface chart. In this graph, the horizontal axis represents phase, the vertical axis represents amplitude, and color indicates the number of occurrences of PD (with a certain amplitude and at some phase) over several cycles of acquisition.

Note that in the construction of the statistical map, each vector with a train of pulses is processed and discarded shortly thereafter, so that information about the occurrence of PD is extracted and condensed, saving disc space and memory storage.

The acquisition of a statistical map of PD involves, after the digitization of pulses, a second discretization of the values of phase and amplitude, according to the dimensions of the matrix representation of the map.




(a)




(b)

**Figure 3:** PD statistical maps: (a) Unipolar Map; (b) Bipolar map.

Although this process involves some loss of information, the statistical map of PD is a form of representation quite similar to the measured phenomenon.

## 4 MEASUREMENT HARDWARE

IMA-DP is a PD virtual instrument built over a modular hardware platform. IMA-DP is designed so that virtually there were no limitations on the number of measurement points monitored. All the measurement hardware can therefore be scaled, so that the number of measurement channels can be expanded indefinitely.

The measurement hardware will consist of one or more independent units of measurement: a PXI chassis with an embedded processor unit. Each PXI chassis has a module controller, and several high speed digitizers, and some modules switches, as shown in Figure 4.

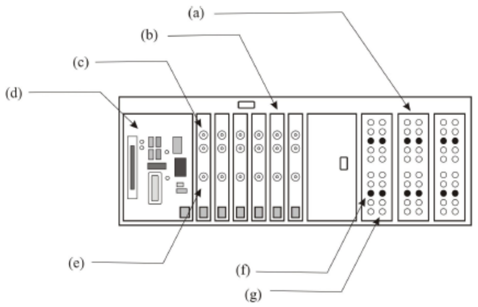



**Figure 4:** Unit of measurement hardware: (a) modules of the commutator switches. (b) card scanners high speed. (c) Scan channels. (d) controller module. (e) input sync signal. (f) output channel of a commutator switch in black. (g) four input channels of a commutator switch in white.

The digitizers have 8-bit of resolution, with the potential sampling rate of dozens of MHz. Besides the digitizer cards, the chassis of Figure 4 also contains some switch modules. The function of these modules is to expand the number of acquisition channels. The reference voltage signals used for timing on PD measurement can feed the external trigger inputs of the acquisition boards. The measurement process is controlled by the controller module, which runs an acquisition and signal processing software developed in C + + over a Windows 2000 OS.

When performing a measurement, the system initially search the database and the configuration files for all the necessary parameters, then switches the hardware to the correct channel. Then it performs the acquisitions and process data from the corresponding data acquisition board. The result of each measurement – the correspondent statistical map - is finally recorded in the database.

The complete system is comprised of three integrated subsystems: besides the measurement system, there is an operation system and an analysis system.

The operating system is responsible for setting and adjusting the measurement hardware and request measurements. The analysis system includes tools for data visualization and processing of information in the database consolidated over time, in order to diagnosis of the monitored equipment.

The three systems communicate over a network by accessing a common database, as illustrated in Figure 5.

The configuration of the measurement hardware is completely remote, recorded by the operating system in the database. Each hardware unit starts the control of their instruments based on the previously specified settings recorded in the database.

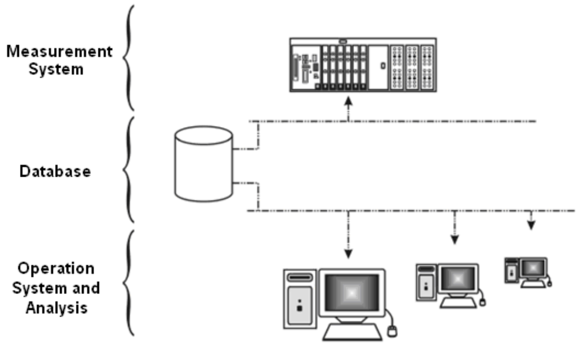



**Figure 5:** Architecture of the measurement system

In this layer of system operation, the system administrator configures the acquisition parameters of the data acquisition boards and the switches, specifying witch channel will monitor each available signal.

A major function of the hardware configuration layer is to make instrumentation absolutely transparent to the user who will later ask for the measurements. Thus, once configured the hardware, this user will simply specify the machine and the characteristics of the measurement without worry about the detailed configuration of the hardware. In other words, this makes the instrumentation 100% virtual, as shown in Figures 6 and 7.

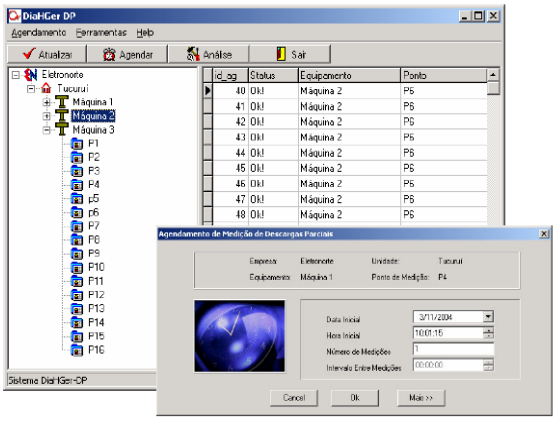


**Figure 6:** Program screen I

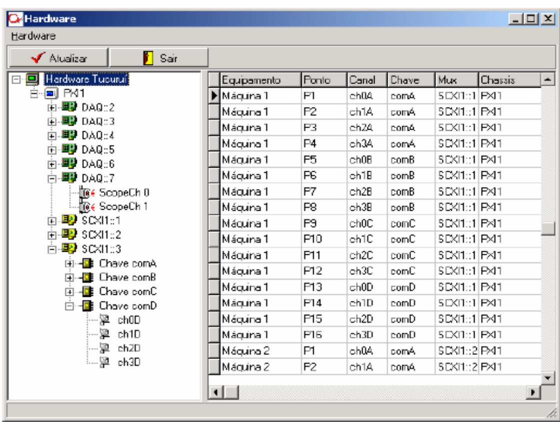
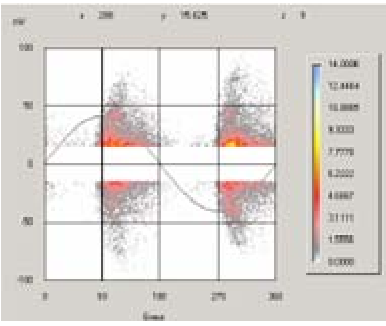


**Figure 7:** Program screen II

## 5 THE ANALISYS SYSTEM

The analysis system allows the user to view and handle the performed measurements stored in the database. The measurements can be treated separately or together.

Figure 8 shows the result of a measurement performed in phase C of the first UHG Tucuruí plant in December 2004. The measured statistical map can be viewed on a surface chart, as shown. From the statistical map, other information can be extracted, such as the total number of pulses recorded along the measurement, the number of pulses depending on the phase and amplitude, etc.



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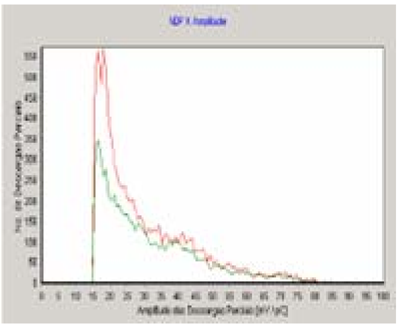

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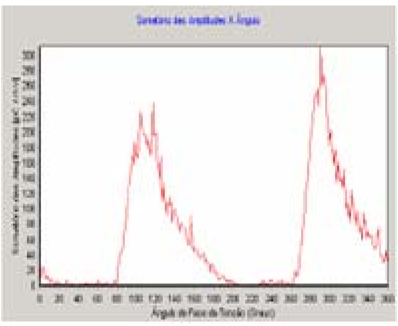
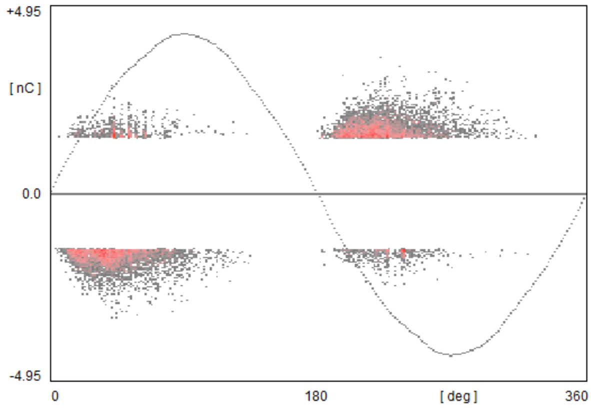


(c)

**Figure 8:** Result of a measurement in phase C of the UHG 1 Tucuruí plant: (a) Statistical map; (b) Histogram of the number of discharges depending on the amplitude; (c) Histogram of the number of discharges according to the angle.

## 6 VALIDATION

In order to validate the measurement instrumentation proposed, we performed in lab several simultaneous tests using modern commercial PD measurement systems and IMA-DP. We obtained exactly the same results measuring PD in mV or in pC, according with the instruments used for comparison, as shown in Figure 9. In some cases, we obtained results with a resolution 16 times larger than the traditional instrumentation.

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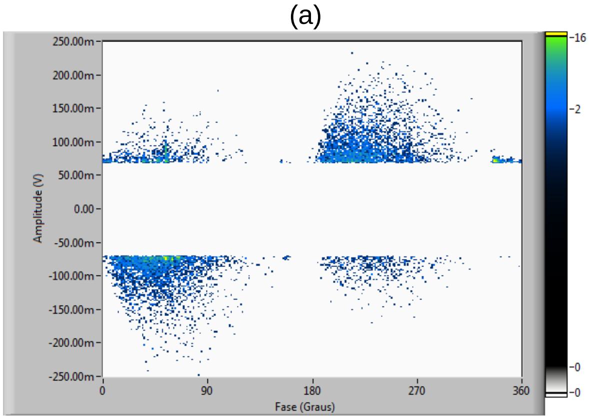


(b)

**Figure 9:** PD statistical maps: (a) ICM System; (b) IMA-DP.

Since 2004 IMA-DP has been monitoring 24 couplers on the machine UHG1 and 16 couplers on UHG2 of Tucuruí. Both machines are 350 MW hydro-power generators. Moreover, this system was also used to perform many off line measurements and analysis at some of the most important Brazilian power plants, including the Brazilian nuclear power plant at Angra dos Reis. Performing on line or off line measurements, the system has successfully tracked the insulation state of those machines with high reliability.

## 7 CONCLUSIONS

Among many existing monitoring methodologies, PD measurement is the only one able to give any indication on the electrical insulation of the bars and stator windings of high voltage rotating machines when it is in operation, performing on-line measurements.

Even though the lack of agreement among specialists for a general and standard implementation of this type of monitoring, it is not sufficient reason for not carrying out this procedure.

In favor of PD measurement is its feature to provide information on the deteriorating state of the dielectrics in the very beginning of the process, enabling maintenance engineers to plan interventions before the machines reach a failure condition.

The aim of this work was to inform professionals in the areas of maintenance and operation that PD measurement can be an important tool in prevention of failures, with direct results and of relatively easy implementation on the field.

The PD measuring system IMA-DP arises in this context as an effective tool, low cost, now validated at laboratory and on the field.

There was consensus among the professionals participating in this work that the IMA-DP and many others PD measurement systems showed very similar results. In the lab, arrangements were made under several different voltage levels, which caused different levels of DP with various intensities and repetition rates. In the field the results proved to be all the same satisfactory, validating the measurements performed by IMA-DP.

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