IMPLEMENTATION OF PARTIAL DISCHARGES MEASUREMENTS FOLLOW-UP ON E-MOTORS WITH PREDICTIVE MAINTENANCE TARGETS

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Abstract - The purpose of the paper is to present the implementation of PD measurements on HV E-motors within Air Liquide production plants.
We will explain why it was decided to implement the PD measurements on the MV E-motors and which steps were followed from the first measurements to the strategy of using them for predictive maintenance and to correlate them with additional data.
The implementation started in 2002 on motors in France and Belgium, then gradually on a world wide scale.
On-line measurements were first performed twice a year on each motor.
Need of qualified people for measurement, analysis and data management was identified; training modules were created and R&D projects initiated.
The targets of these projects were to identify the noise to be filtered and the correlation between PD and other motor parameters.
Success stories but also doubts from management will be presented.
The conclusion will explain what is the current situation and what will be the next steps.

I. INTRODUCTION

Availability of Medium Voltage motors at Air Liquide Large Industry is critical to provide reliable gas supply to customers. First return of experience in 2002 for France and Benelux perimeter pointed out a failure rate of 3 stators per year (since 1994 considering a 260 motors fleet). Later, based on the world wide perimeter statistics in 2009 (considering a 1500 motors fleet), there were around 20 incidents per year. The average cost is 1 M€ per incident, which includes direct cost of 100 – 500 k€ for repairing and indirect cost for penalties, production loss, and other disturbances to the supply chain. Two particularities about these incidents are their premature occurrence compared to the expected Mean Time Between Failures (MTBF) for such equipment and mismatch with manufacturers announced performance. Due to the high financial stakes, improving the monitoring of motors' condition so as to provide better information for predictive maintenance is a major path to product availability.

During the three last decades, competition between manufacturers has led them to increase rotating machine design stresses in order to reduce costs, i.e. increasing motor power ratings while maintaining the same stator frame, or reducing the stator dimension at constant power. This trend is increasing the machine failure risks as such increases the occurrence of the three major causes of stator failure: (i) electrical stress coating degradation, (ii) end winding partial discharges and (iii) loose coil into the slot. The following figure (Fig. 1) shows peak PD activity of 13-15 kV air-cooled machines, as a function of the manufacturing date (measurement made within the three years following the installation) for nine of the major manufacturers in the world. A significant raise of PD activity is observed for four of the manufacturers from 1995 to 2003.

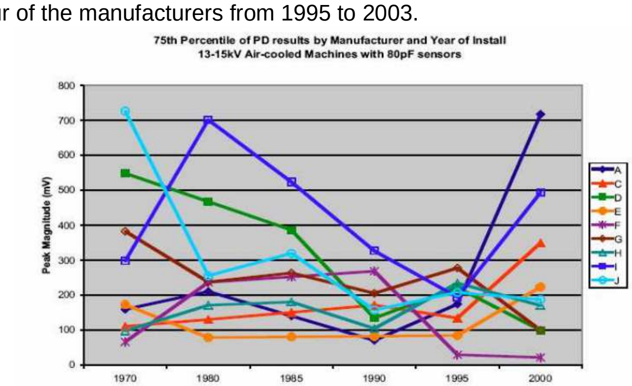


Fig. 1 Peak PD activity vs. year of manufacture for 9 major manufacturers[1].

[1] Examples of premature stator winding failure in recently manufactured motors and generators. G C Stone Iris Power Engineering, Canada, pp. 217-220.

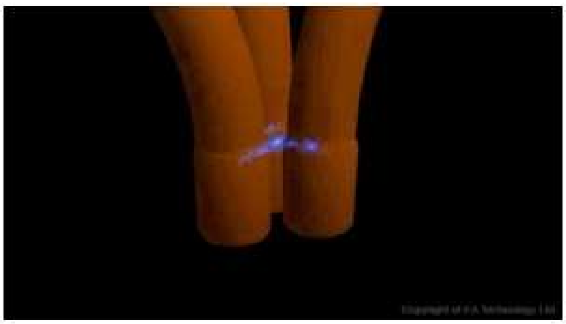
II. PARTIAL DISCHARGES THEORETICAL DATA

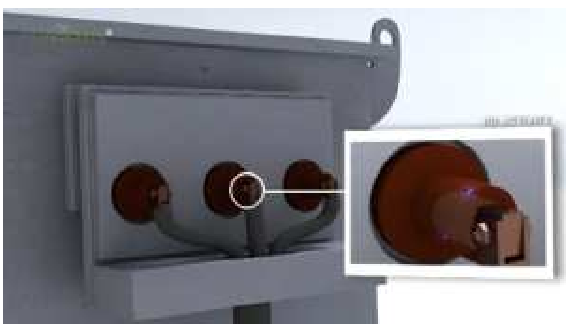
Partial Discharge (PD) is a breakdown of a fraction of the entire insulation system or insulated media.
PD activity is a symptom of electrical deterioration and also a cause of Insulation Degradation.
PD activity can occur at any point in the insulation system, where the electric field strength exceeds the breakdown strength of that portion of the insulating material. PD emit energy as:

- Electromagnetic emissions, in the form of radio waves, light and heat

- Acoustic emissions, in the audible and ultrasonic ranges
- Ozone and oxide of nitrogen gases

PD usually begins within voids, cracks, or inclusions in a solid dielectric, at conductor-dielectric interfaces within solid or liquid dielectrics, or in bubbles within liquid dielectrics. Since PDs are limited to only a portion of the insulation, the discharges only partially bridge the distance between electrodes. PD can also occur along the boundary between different insulating materials.





PD can occur at any point in an insulated system.

A. PD IN HV MOTORS

Induction/Generation under HV conditions requires an insulation system with sufficient dielectric strength. The General purpose of an HV Insulation System:

- forming an insulated barrier between HV-potential and Ground potential
- being PD resistant during many years
- reduce heat transfer from the inner conductor to the core (heat-sink).

Various insulation materials have been used in the past causing an improved PD stability:

- Organic materials (cotton, silk, …)
- Inorganic materials (glass fibers, asbestos,...)
- Fibrous papers (Nomex, still in rotor windings)
- Mineral (Mica).

The bonding of insulation materials is made by impregnation; several insulation materials have been developed during the time:

- Polyester resins,
- Bitumen,
- Asphaltic resins,
- Varnishes,
- Epoxy resins.

The most common aggregate is today epoxy resin and mica combination.

B. CONSEQUENCES ON MOTORS

Once begun, PD cause progressive deterioration of insulating materials, leading to electrical breakdown. The effects of PD within high voltage cables and equipment can be very serious, ultimately leading to complete failure. The cumulative effect of PD within solid dielectrics is the formation of numerous, branching partially conducting discharge channels, a process called treeing. Repetitive discharge events cause irreversible mechanical and chemical deterioration of the insulating material. Damage is caused by the energy dissipated by high energy electrons or ions, ultraviolet light from the discharges, ozone attacking the void walls, and cracking as the chemical breakdown processes liberate gases at high pressure. The chemical transformation of the dielectric also tends to increase the electrical conductivity of the dielectric material surrounding the voids. This increases the electrical stress in the unaffected gap region, accelerating the breakdown process. A number of inorganic dielectrics, including glass, porcelain, and mica, are significantly more resistant to PD damage than organic and polymer dielectrics.

Fig. PD activity on HV induction motor (Air Liquide)

PD can usually be prevented through careful design and material selection. In critical high voltage equipment, the integrity of the insulation is confirmed using PD detection equipment during the manufacturing stage as well as periodically during the equipment's life. PD prevention and detection are essential to ensure reliable, long-term operation of high voltage equipment used in the plants..

III. PD MEASUREMENTS IMPLEMENTATION

A. HISTORY [80's - 2006]

Partial discharges measurements within Air Liquide started in early 80's on around 40 high rated power motors under continuous operations for 10-15 years and that were driving large centrifugal compressors at some ASU (Air Separation Unit) plants in France and Belgium. At this period of time this technology was under development and proposed as pilot to industrials by motors specialists and research engineers working for the main motors' manufacturers. It appeared to be an alternative to the Qm(U) metrology which was also practiced during the same period but that had brought to the destruction of several stators. Measurements were usually performed off-line and during major overhauls into workshops. Without significant benefit, measurements' interpretation remained fuzzy and led to neglect the practice in 1990.

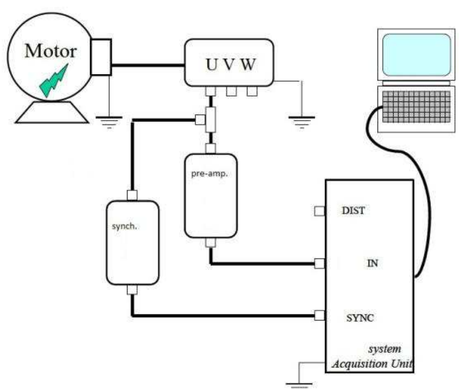
Ten years later, in 1999 - 2000, as measuring devices had considerably been improved making their use more friendly, and as new specialized companies had appeared, making the technology more visible and the deliverables more interesting, the project was reactivated. It was pushed and sponsored by industrial departments in the context of the business development leading to operate more MV motors with a broad variety of insulation system, and which were forced to recognize that motors' failure was increasingly undergone without giving any pre-warning. The stakes justifying significant investments were:

- unavailability of the production plants
- direct and indirect costs
- maintenance strategy

In 1999, the French and Belgian operation entities were still acting as a pilot, even if benchmarking with North America's plants, but the sensors' type was not imposed. This brought technical departments to set-up Rogowski coils for one part and capacitive couplers for the others. On-line measurements started to be performed by third-parties who were providing services on site.

In 2002 it was stated that Rogowski coils and associated measurement device were not accurate enough and led to widespread the sole capacitive couplers.

The solution which was chosen privileged one PD sensor type and correlation with other data (temperature, load, moisture..…..).



Picture: 16 MW synchronous motor connections hall, ROGOWSKI coils at the top and divisive capacitors at the bottom

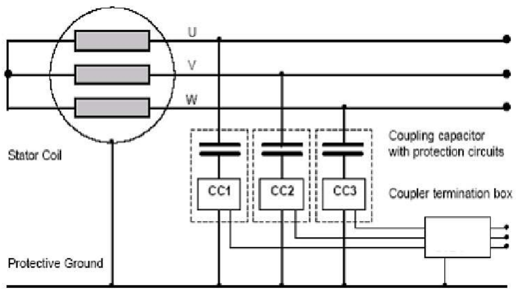
B. CORE MODEL

As the first return of experience had been consolidated between Western Europe countries and North America, the organization took shape. The European entity decided to invest in sensors and in PD analyzers with the aim of training technicians and engineers in-house while North America took the path with subcontracted service. Both organizations have in common to implement on-line measurements binded with actual operating conditions (temperature, load, moisture, grid) in running mode whenever surrounding noise might disturb measurements. A dozen of people in Europe attended basic training organized by the selected vendor, they gradually set-up couplers, performed an average of two measurements per year and have sought to benchmark the results by themselves. People in North America systematically relied on their partner expertise who populated his own worldwide database and provides risks assessment based on wider statistics.

Outsourcing the decision making for a major overhaul is questionable considering the financial impact. It is therefore recommended to develop the own database and to endorse the full decision processus.

Between 2002 and 2005, in Europe, 150 to 200 motors [Power range: 1 to 24 MW - Nominal Voltage: 5,5 to 13,8 kV] (≈ 1 third of the fleet) have been equipped with divisive capacitors, 5 PD analyzers have been purchased, the whole for an approximative amount of 800 k€.

Picture: General view of on-line measurement with a portable acquisition unit.

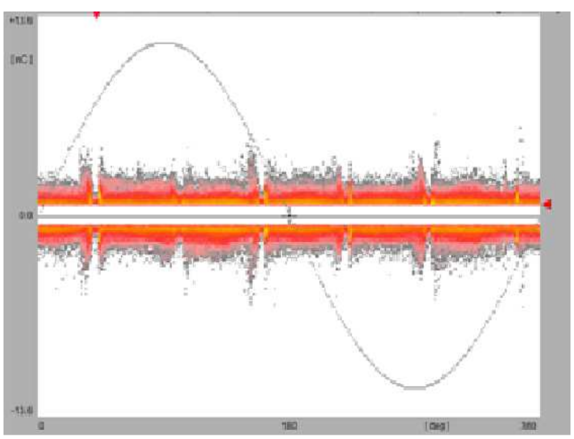


Picture: capacitive couplers and termination box as fixed equipment on the motor for scheduled on-line measurements

C. Lessons learnt

In 2006, after 4 years of measuring, especially in Europe, it is stated that the PD measurements do not meet the original expectations for several reasons:

- the installation of the couplers is sometimes not well completed, leading to signals attenuation or noise
- capacitive couplers have not always been calibrated from the beginning leading to distorted references
- the PD analyzers, bearing a significant cost were shared between production plants and led to mis-tuning operations.
- “test acceptance criteria” does not exist formally and the interpretation of peak values is subject to question
- when in best case half/year measurements are available, it remains difficult to compare them over the time without processing the data



Picture: PD signal is embedded into noise and measurement settings are not well tuned in

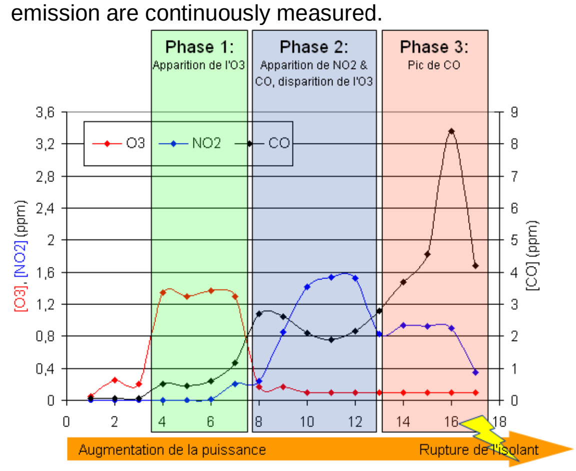
IV. REEXAMINATION FROM EVERY ANGLE

In 2006, it was decided using the available data and internal state of the art to check if the measurements were correct and if the methods and tools were suitable with what- was expected to achieve in term of results.
There were some doubts on the accuracy and interpretation of the recorded data; the management was challenging the results interpretation as well as the action plans launched accordingly.
The decision was taken to start a R&D project with a well known engineering school and a french electrical manufacturing company as a co-sponsor. The project mainly consisted in:

- laboratory simulations by reproducing typical PD in motors (on a stator bar)
- showing the PD analyzer was capable of detecting and quantifying PD type and magnitude
- evaluating the impact of the surrounding noise
- giving guidelines for measurements and interpretation
- creating a database in order to follow the PD evolution and give a risk assessment
- looking for new PD measurements’ methods like gas detection

In parallel, some investigations were done around the methods which could help measuring PD or other parameters linked to PD. Bibliography study was done and contacts with other end-users (e.g EDF) were taken. For example acoustic method was investigated and HV tests method (with a laboratory in Montpelier).
Finally, the major investigation was driven by one knowledge of the company which is gas detection and analysis. The R&D engineers were finally working on correlation between PD emission and Gas presence in the motor. The main finding was that different gases appear when PD phenomena is present and the type of gas as well as the level change during the evolution of PD in time.
The results were promising and the R&D team worked on specifying and finding a gas detector on the market able to measure the gases based on the concentration which can be in the motor casing.
The 3 gases which appear are O3, NO2 and CO.

The gas measurements gave the following results:
MV motor stator bars were put in voltage and current conditions as a motor in operation. PD level and gas emission are continuously measured.



Phases of apparitions of different gaseous species

The tests demonstrate there are 3 different phases in the PD cycles which can be correlated with gas emission:

- Phase 1: start of insulation damage and increase of O3 emission followed by a plateau of O3
- Phase 2: sudden drop of O3 level and NOx emission.
- Phase 3: NOx emission and appearance of CO. This step is irreversible.

The various tests and experience demonstrated that the critical point is the crossing of the decrease in O3 emissions and the increase in NOx. After this point, CO appears and the stator insulation is definitely damaged (white powder on the coils and varnish residues can be observed). The results have been repeated several times in laboratory.

This allow to save one motor on a Canadian plant; the machine was stopped just before crossing the O3/NOx critical point.

V. IMPLEMENTATION (2006-2012)

After closing the R&D project, the implementation was officially announced by the Operations management. PD transducers implementation on all MV motors above 1MW was announced as mandatory and systematically required in motors Invitation To Bid.

A. The implementation of PD transducers

PD transducers implementation was enlarged to all LI entities (it was mainly done in France and Belgium from the time being) and the best practices were shared through a company experts group.

The deployment of the solution was done following the below steps:

- Issuing of documents for operators training on PD measurement device calibration and best practices to carry out the measurements
- Issuing documents for measurement interpretation assistance
- Setting up of a database to store all measurements (data base located and managed in R&D department)
- Purchasing of measurement device by region and build of a strategy for equipment choice (transducers and measurement device)
- Training of Operators for installation and measurements best practices.
- Training of the leaders for data interpretation,
- Set-up of a database for sites data collection and appointment of a leader to manage it,

B. Implementation of gas monitoring

The correlation between gas emission and insulation wearing was found of a deep interest and led to further monitoring in parallel of the systematic implementation of PD transducers for new motors and the installation of some on existing plants (during major turn-around). The solution of the gas tele-monitoring system was validated and an industrialization plan was launched (after having filed a patent to protect the idea).

The first idea to perform a gas monitoring with sustainable costs, was to have a plug and play solution but it appeared that the budget was not sufficient. In addition to that, to measure the gas inside the motor, a hole must be made in the motor casing.

On a target of 100 installations, 106 have been delivered, 70 were installed and 49 remain in operation. This low availability is mainly due to installation constraints and the low reliability of the device itself.

The telemonitoring systems are capable to perform a basic detection of O3 or NO2 (but not CO). The limit of the gas monitoring system is the sensor's life cycle. . Due to the non-mastery of sensors, this detection capacity is decreasing with the sensor age.. Furthermore, this detection was considered inopportune because 74% of the followed motors show a high risk due to NO2 concentration, this was due to the non reliability of the sensor. . It is thus not possible to confirm the ability of the sensors to detect a change in time of concentrations. Similarly, it is not possible to deduce an assessment of the health of the motors or a clear indicator to trigger further investigations using the PD measurement.

Monitoring system and measurement range and accuracy must be enhanced. The next step should be to perform accurate measurement on targeted motors to assess concentration level and behavior.

The gas monitoring system includes:

- One humidity sensor
- One temperature sensor
  (both for correction in the detection algorithm)
- 2 gas sensors (one for O3, another one for NOx and CO).

C. Lessons learnt

A large amount of motors were equipped by both systems and the following lessons learnt are to be considered:

- Some success stories: the measurements gave the good information and allow some plants to stop the installation just on time to avoid the catastrophic event.
- The gas monitoring system was not heavy duty enough and some disadvantages were discovered:
  - communication problem (with the modem) in countries where the communication systems were not developed
  - the fact that the gas sensors accuracy was decreasing after 12 to 18 months (yearly replacement must be foreseen).
  - batteries duration
  - the device was not really plug and play and motor must be stopped prior to any installation or modification.

The next step was never validated and the project was unfortunately stopped for the moment due to lack of management budget and support.

The gas monitoring system was considered by the management as non sustainable. Further investigations were not supported and the next steps are still pending.(industrialization of the new solution). No decision was taken today.

VI. MANAGEMENT SPONSORING

In the beginning, the PD measurements implementation was supported by asset managers of operations and was presented to the management as a method aiming to reduce the motor failure rate. Budget was allocated conditioning to pay-back and success story in the coming years. The first implementation period in Europe did not allow any spectacular demonstration to clear all doubts from management. Being pioneers in inaccurate science was not a strength.

As a second step, the intention was to use the equipment and tools already invested to go further in the analysis. Steering committee was put in place to follow the progress and ensure financial result in terms of profitability.

When additional budget was required for prototype industrialization, it was strongly challenged and not accepted because of low return of investment

VII. ONE STEP FURTHER (AFTER 2015)

All studies and experiments led with key partners, the last 15 years, demonstrated that PD measurements applied to MV motors were all the more relevant when they were correlated with other significant and influencing parameters which are electrical and operational. Moreover PD must be categorized as they do not all present the same dangerousness. Nobody can predict an imminent failure just relying on a PD magnitude in the present knowing that some motors can be running for years with a relative high level of partial discharges.

The stakeholders coming to this statement after questioning the practice all along this period,the vendors gradually came with new solutions that supplement or replace on-line spot measurements with/by continuous on-line monitoring systems including analog inputs for load and temperatures acquisition, and sometimes advanced software supporting the interpretation of the PD patterns.

Such solution which still needs to be tested during a significant period (Proof of Concept) offers several advantages:

- replaces people or service on the field for measurements
- makes reproducible the measurements
- cancels the management of the portable devices when owned by operation team
- processes external data and/or communicates with other data acquisition systems
- one monitoring system as a fixed equipment can acquire data from several motors (2 to 4)

A few monitoring systems have been put in operation the last year, they are stand alone systems, correlation with process parameters are done manually a posteriori and the vendor provides service on request by connecting remotely. Next implementation shall include the synchronisation of PD signals with all available data coming either from the DCS or from the electrical protective relays.

If the PDs reflect a very slow phenomenon of insulation wear, the need to correlate it with other PDs measurements, or operational data, or environmental data, makes spot measurements inefficient, which imposes the extra cost of -line PDs monitoring and then expertise in data processing.

VIII. CONCLUSIONS

It took 15 years of investigation, brainstorming and communication to reach the current situation.

According to Air Liquide experience with PD measurements on MV E-motors, this technology requires from the end-user to have a clear view of his expectations and of the means he will have to deploy to meet them.

Experts at Air Liquide are still convinced that PD measurements are the main indicator to assess a stator condition that is running in its environment. Measurements which quality is good in terms of signal amplification and noise, added to tendencies, are used for:

- without warning, postponing major overhauls of the motors on a yearly basis in order to reduce maintenance costs or to schedule them in the same time with the driven equipment
- in case of warning, preventing of a sudden incident as there is not any available spare part or as the customers cannot manage the gas supply interruption. When the motor can be shutdown in advance for repair it sometimes allows a partial or temporary repair in order to save time, or in an extreme case to contain the damages to the stator’s windings only.

The management is not always as convinced as experts are because success stories are not that numerous or not enough shared between the operation entities. It becomes a vicious circle when PD measurements programs being not supported by the management, experts cannot show during the Root Cause Failure Analysis that PD activity was maybe at the origin of a possible failure. As long as relevant figures cannot be presented it is hard for decision-makers to invest in such technology still costly which remains a niche because of its complexity.

Nevertheless experts still believe they can contribute to the technology making steps forward and are ready to share their own experience with other end-users in order to better launch such program. In a few words some key questions and stakes must be considered before confirming, among which the starting assumptions (maintenance strategy, associated costs, criticality in case of failure), the motors’ fleet (number, power, voltage, service factor, hazardous area,...), the human resources for taking care of (in-house or subcontracting), the relationship with the vendor (skills, service), the methodology for measurements follow-up and the popularization of PD measurements.

Behind “popularization” there are two stakes, the first is to make such as PD measurements are mixed-up with all other on-line measurements like stators’ windings temperature for example. PD measurement must not remain something owned by a few experts and not

communicated to a centralized supervision system. Advanced interpretation is still possible by any specialist but there are simple KPIs that can be correlated with all other electrical and process factors. Taking the example of the stators' windings temperature which are supposed to prevent of a possible shutdown because of an overload or a cooling inefficiency, one knows that such signal will rarely warn the operator of an imminent failure, but nevertheless nobody question the relevance of this protection. So the same approach should apply to partial discharges and a stable PD activity continuously monitored should bring to the conclusion that there is nothing wrong with the stator's insulation.
The second stake of the popularization is the cost of the technology that is still too high because of the on-going developments and the niche effect.
When both, integrated system and cheaper solution, will be achieved, PD measurements will likely be part of the good practices for assessing the condition of MV motors.

The gas monitoring system is not totally excluded from future plan in the company.

The gas monitoring is definitely a complement to the PD measurements device, especially today where the continuous monitoring and digitalisation are under development.

IX. LIST OF ABBREVIATIONS

PD: Partial Discharge
HV: High Voltage
MV: Medium Voltage

X. ACKNOWLEDGEMENTS

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XII. VITA

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