PRACTICAL APPLICATION OF STATOR WINDING ON-LINE PARTIAL DISCHARGE MONITORING IN THE PETROCHEMICAL INDUSTRY

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E. Bispo dos Reis
Iris Power-Qualitrol
3110 American Drive
Mississauga, ON L4V 1T2
Canada

M. Sasic
Senior Member IEEE
Iris Power LP
3110 American Drive
Mississauga, ON L4V 1T2
Canada
msasic@qualitrolcorp.com

G. Stone
Fellow IEEE
Iris Power LP
3110 American Drive
Mississauga, ON L4V 1T2
Canada
gstone@qualitrolcorp.com

***Abstract* -** The stator winding insulation in petrochemical plant motors and generators have been assessed using routine on-line partial discharge (PD) testing for at least 20 years, starting in chemical plants in the US Gulf Coast. PD are small electrical sparks that can occur in the winding insulation system due to poor manufacturing of the stator winding; or due to aging of the stator. In on-line PD monitoring the PD current pulses are detected by either capacitive sensors or high frequency current transformers that are mounted in the motor terminal boxes. To ensure reliable results, attention must be paid to reducing the risk of false positive indications due to electrical noise. The methods that are most successfully used employ time-of-pulse arrival, pulse shape analysis and the optimal selection of the measurement frequency range. Since the early days, great progress has been made with interpretation. Case studies from petrochemical industry machines are presented to show how machines with insulation problems can be identified using both the trend in PD over time and the absolute magnitude of the PD. However, experience shows that the trend itself, as well as the absolute magnitude can sometimes give a misleading indication of the stator winding insulation condition.

Index Terms –

INTRODUCTION

Partial discharges are small electrical sparks that occur in deteriorated or poorly made stator winding insulation systems in motor and generators rated 3.3 kV and above. Over the past 20 years on-line partial discharge (PD) monitoring has become the most widely applied method to determine the condition of the electrical insulation such petrochemical plant machines [1, 2]. PD testing detects most (but not all) of the common manufacturing and deterioration problems in form wound stator windings, including:

- Poor impregnation with epoxy
- Poorly made conductive and silicon carbide electric stress relief coatings
- Insufficient spacing between coils in the endwinding area or leads in the terminal box
- Loose coils in the slot (for non-global VPI machines)
- Long term thermal deterioration
- Winding contamination by moisture, oil, dirt, etc
- Poor electrical connections.

In general, for machines rated 3.3 kV and above, over 50 years of experience in the utility business with PD testing of motors and generators has shown that months, if not years of warning is often given before winding failure is likely [1, 2].

There are many methods available to detect the PD activity in operating motors and generators [1,2]. The electrical techniques rely on monitoring the current or voltage pulse that is created whenever a partial discharge occurs. The earliest methods measured the PD pulse currents by means of a high frequency current transformer (HFCT) at the neutral point on generators [3]. HFCTs have also been placed on the ground side of motor surge capacitors to detect PD [4]. One of the first applications of on-line PD to off-shore platforms in classified areas used a special type of HFCT, called a Rogowski coil, and such sensors are still used in the North Sea [5]. These latter sensors tend to require considerable skill on the part of the test operator, since the PD signals tend to be obscured by noise. By far the majority of motors and generators that are equipped with on-line PD monitoring use 80 pF capacitive sensors installed on the machine terminals, since such sensors, with appropriate instrumentation, yield a practical compromise to PD sensitivity with a low risk of false indications [6].

A key challenge with PD measurements is encountered when the motor or generator is monitored during normal operation. Since the machine is connected to the power system, electrical interference (noise) is often present. Noise sources include corona from the power system, slip ring/commutator sparking, sparking from poor electrical connections, arc welder operation, switching noise from variable speed drives and/or power tool operation. This electrical noise masks the PD pulses, and may cause an inexperienced technician to conclude that a stator winding has high levels of PD, when it is actually the noise. The consequence is that a good winding is incorrectly assessed as being defective, meaning that a false alarm is given suggesting that the winding is bad, when it is not. Such false alarms reduce the credibility of on-line PD tests. This paper briefly describes objective methods that separate PD from noise in motors and the high-speed generators that are often associated with petrochemical facilities.

With thousands of machines being monitored for many years, together with occasional direct observation of the insulation condition by visual observation during plant turnarounds, it has been possible to establish what levels of PD should trigger maintenance intervention. This paper presents the latest analysis of more than 270,000 test results, and other data to aid in the interpretation of results. Finally the paper will present case studies of deteriorated machines that were identified by on-line PD testing.

NOISE SEPARATION METHODS

Over 25 years ago, the North American utility industry sponsored research to develop an objective on-line PD test for machines that could be performed and interpreted by plant staff with average training. The PD test that was developed emphasized separating PD pulses from electrical noise pulses. In fact the techniques developed during this research depends on 4 separate noise separation methods – since no one method was found to be completely effective on its own:

- Frequency domain filtering
- Surge impedance mismatch
- Pulse shape analysis.
- Time of noise and PD pulse arrival from a pair of sensors

Practically, to reduce the risk of false indications to less than a few percent, at the least 3 of the 4 methods must be implemented. In high noise environments, all four must be implemented.

Filtering

As part of the utility research project, surveys were performed of the noise environment in typical plants. It was found that noise tended to produce the greatest signals at frequencies below 10 MHz or so [2, 6]. In contrast, when measured close to the stator winding, PD produces frequency components up to several hundred megahertz [1, 2]. Thus the highest PD signal to noise ratio (SNR) and thus the lowest risk of false indications occurs if the PD is measured in the very high frequency (VHF) range of 30-300 MHz. A simple single pole, high pass filter can be realized with a 50 ohm input oscilloscope or measurement instrument with a high voltage capacitance of about 80 pF. The capacitor is the same capacitor as is used for the PD sensor.

Surge Impedance Mismatch

In many cases a generator is fed by air-insulated bus. In general such busses have a characteristics (or surge) impedance of about 100 ohms. In contrast, the surge impedance of a coil in a stator slot is much lower – typically on the order of 30 ohms. A noise pulse from the power system that travels along the air-insulated bus sees a source impedance of 100 ohms, and then encounters the coil impedance of 30 ohms. Using transmission line theory, the first peak of a fast risetime noise pulse is attenuated to about 25% of the original magnitude. A PD pulse originating in the winding has a source impedance of 30 ohms, and then encounters the 100-ohm impedance of the air-insulated bus. From transmission line theory, a reflection and superposition occurs that results in the first peak of the PD pulse current being amplified by about 50%. The high speed traveling wave properties of PD and noise pulses amplifies the PD and suppresses the external noise, enabling another method of increasing the SNR. To use this method, the noise and PD pulses must be detected with their original risetimes of <5 ns, and the PD sensor must be within 1 m or so of the coils.

Pulse Shape Analysis

A third method of separating PD from noise depends on the time-domain characteristics of the PD and noise pulses [2, 6]. Short risetime current pulses, no matter what their source, are modified as they travel along a power cable from the power system. There are two types of modification: attenuation and dispersion, where the latter refers to the frequency dependent attenuation of the pulse. The longer the distance the pulse must travel, the greater is the attenuation and dispersion encountered. Fig. 1 shows the effect of these two properties as a voltage pulse propagates along a power cable. As the pulse propagates farther, the magnitude of the pulse decreases due to attenuation and the risetime of the pulse lengthens due to dispersion.

If a PD sensor is installed very close to the stator winding (say less than 1 m), then any PD pulses from the stator winding will undergo negligible attenuation and dispersion as the PD pulse travels to the sensor. However, if a noise pulse from the power system first has to propagate through many meters of power cable, then the noise pulse will be significantly reduced in magnitude and have a longer risetime. By digitally measuring the risetime, PD can be separated from noise on a pulse-by-pulse basis using risetime or pulse width. Although intended to separate PD from noise that must travel along a power cable, pulse shape analysis is also effective in separating sparking sources on the machine rotor (for example sparking from shaft ground brushes or slip ring sparking in synchronous machines), since such noise tends to have a slower risetime when coupled to the stator.

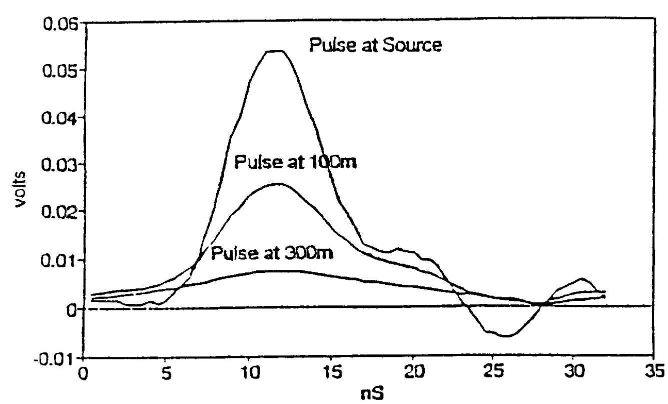


Fig. 1: Attenuation and dispersion of a pulse as it travels along a cross-linked polyethylene power cable of different lengths.

Pulse Time of Arrival

Where the connection to the power system is via air-insulated bus or very short power cables, and thus the pulse shape is not sufficiently different between noise and PD, an additional noise separation method based on using two sensors per phase has been implemented (Fig. 2). If the sensors are at least two meters apart, a pulse from the power system will arrive at the 'S" sensor before they are detected by the 'M' sensor. Similarly, if the pulse is due to stator winding PD, the pulse will first arrive at the 'M' sensor before it arrives at the 'S' sensor. With fast responding digital logic, the pulses can be classified as noise or PD based on which sensor detects the signal first.

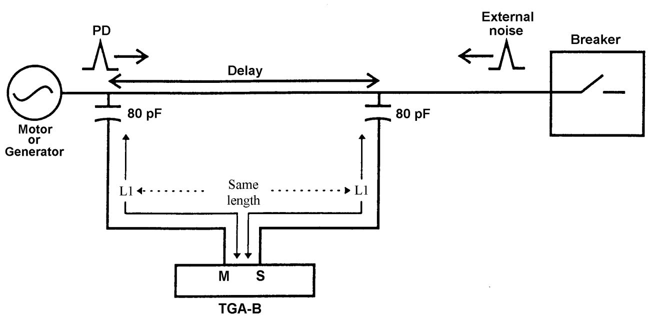


Fig. 2: Use of two capacitors per phase to separate PD and power system noise based on the direction of pulse travel. Two sensors are only needed if the there is less than about 30 m of power cable between the switchgear and the motor.

INTERPRETING PD DATA

The basic guidelines for interpreting PD data are presented in IEC 60034-27-2. To identify stator windings that may have serious insulation problems, two methods can be used:

- Trending the peak PD magnitude (Qm) over time
- Comparing the Qm of a machine to other similar machines.

Trending of Qm has long been the primary method for determining which machines need maintenance attention. Doubling of Qm in 6 to 12 months, under the same operating conditions, normally implies that rapid insulation deterioration is occurring [1,2]. It is important to measure the trend at approximately the same operating voltage, winding temperature, ambient humidity and load, since PD can be affected by these conditions. Note however that the PD does not continuously increase in magnitude until failure occurs. Instead empirical evidence suggests that after a period of rapid increase, the Qm will level off and not increase, even though the insulation continues to age (Fig. 3). In fact in some cases, the PD has been noted to decrease dramatically just before failure. Thus if PD sensors are applied late in the life of a machine, the PD may not increase, even though the winding is very close to failure. Therefore it is better to install the PD monitoring when the winding is new. The reasons for the leveling off are not clear, but they may involve high space charge content or carbonization in voids and/or conductive particles mixed with oil that suppresses surface PD [1].

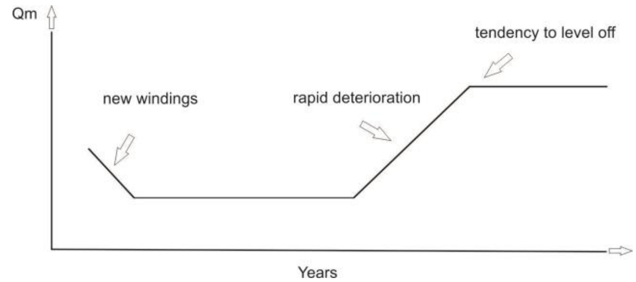


Fig. 3: The trend in PD magnitude may stop increasing (or even decrease) near the end of winding insulation life.

Regrettably the IEC technical specification for on-line PD testing does not gives indications for what is "high" PD activity [2]. One set of tables has been developed for high PD activity which depends on the nature of the PD measurement system and the operating voltage of the motor or generator [6]. Table 1 shows PD alert levels for air-cooled motor and generators that is based on over 270,000 PD measurements, where visual examinations of many of the stator windings indicated that Qm in excess of the limits shown usually have serous insulation problems.

In addition to determining which machines have insulation problems, PD testing has been shown to identify the root cause of the insulation deterioration, as long as only a single mechanism is dominant. See References 1 and 2 for further information on this aspect of interpretation.

Table 1:
Qm alert levels vs. rated voltage of the stator winding

Voltage Class	PD Magnitude (mV)
2-4 kV	274
6-8 kV	276
10-12 kV	401
13-15 kV	461

CASE STUDIES

The following are several case studies of problems identified in refineries, petrochemical plants and air separation facilities.

Insuffcient Spacing Between Phase Leads

An 11,000 HP, 13.8 kV motor operating in the Northeast USA to compress air had PD levels up to 800 mV, which greatly exceeds the "alert" levels in Table 1 for a 13.8 kV motor. The PD patterns indicated that the cause of the PD was phase to phase PD, either between coils in the endwinding, or between the leads. As a result, during a short turnaround, the motor was inspected. Very clear signs of PD (white powder and some pitting of the insulation) were found between motor leads in the motor terminal box. Since the lead insulation was rubber, which has a relatively low resistant to PD in comparison to epoxy mica, phase to phase failure could have occurred in less than one year. However, the leads could be easily separated, preventing the PD. Fig. 4 shows the reduction in PD after the repair, indicating that the repair had been successful.

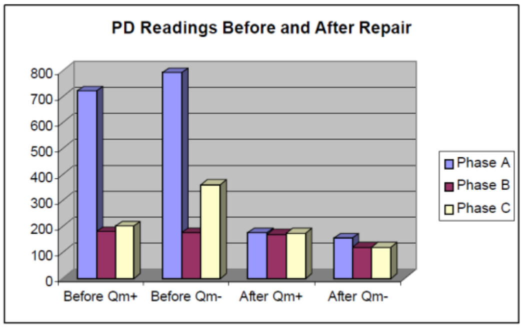
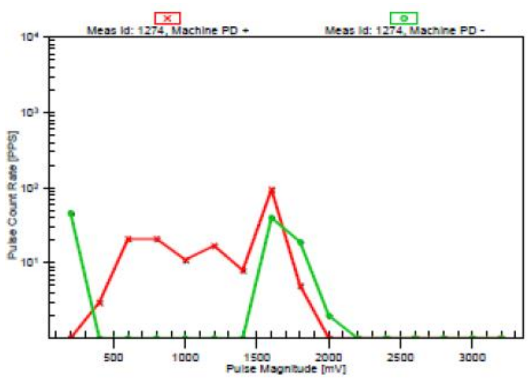


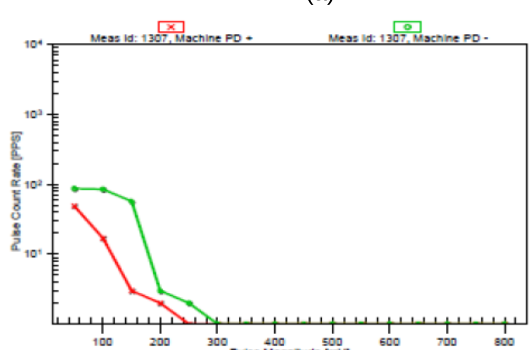
Fig. 4: Effect of separating motor terminal box leads on PD activity

Poor Circuit Ring Bus Lead Placement

In another compressor motor rated 10 MW at 10 kV, installed in Finland, the peak PD magnitude on one phase reached as high as 1800 mV (Fig. 5a) and the PD was in the classic phase position – that is the PD was between phase and ground (not phase to phase). The PD level greatly exceeded the alert level of about 400 mV. During a convenient shutdown, the winding was subjected to an off-line PD test, and audible discharging could be heard and visually located. A circuit ring bus lead had been inadvertently placed against the steel motor frame. The lead was easily shifted to prevent the discharging. Fig. 5b shows that the peak PD magnitude was reduced by 9 times.



(a)



(b)

Fig. 5: PD activity on a compressor motor (a) before repair and (b) after repair

Overheated Connections

A 20.5 MW, 13.8 kV motor in a US refinery started to exhibit high PD activity (Fig. 6). The Qm was 445 mV, again higher than the alert level in Table 1. During a convenient shutdown, the motor was visually examined. There was clear signs of overheating of the insulation at the connection leads (Fig. 7).

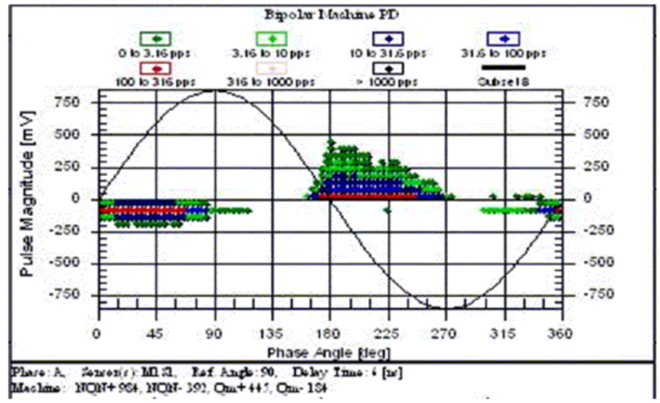


Fig. 6: Phase-resolved PD plot due to thermal deterioration of the insulation at a poor electrical connection.

Figure 7: Overheated motor terminal leads

Winding Contamination

A 15.6 MW, 13.8 kV gas compressor motor in the Middle East was monitored with a continuous PD monitor. For most of its life the motor PD levels were low (<100 mV) and stable. However in September 2006, the Qm suddenly increased over 3 times for no apparent reason (Fig. 8). An inspection revealed that the stator was heavily contaminated – which can lead to electrical tracking of the end windings.

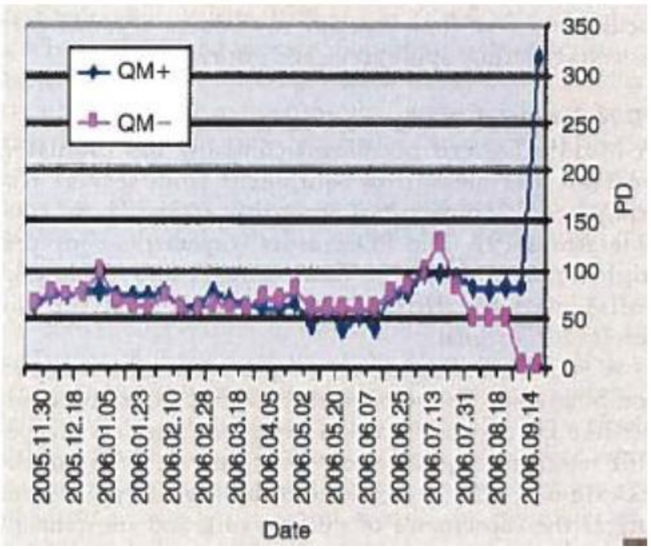


Fig. 8: Sudden increase in PD that was visually conformed to be caused by winding contamination.

LIMITATIONS OF ON-LINE PD TESTING

Given the 20 year history of on-line PD testing on machines in petrochemical plants, experience shows that there are several limitations of the test:

1. On-line PD testing is not able to predict when failure of the stator winding will occur.
2. Not all failure processes can be detected. For example end winding vibration and debris within the machine usually will not produce PD for any significant time before failure.
3. The IEEE and IEC standards have no generally-agreed limits for safe PD levels. This can create disagreements between machine manufacturers and users
4. With present technology, when multiple failure processes are occurring in a winding at the same time, there is no objective evidence that the different failure processes can be correctly identified with high confidence.
5. Some diligence is needed to ensure that the installation of PD sensors do not themselves lead to motor or generator. This limitation is effectively eliminated if the sensors meet the requirements identified in IEC 60034-27-2.

CONCLUSIONS

On-line monitoring of PD in motors and generators is now well-established with over 15,000 machines being equipped with the necessary sensors for the test. IEC has published a standard for measuring PD in machines on-line [2], and the test is now an optional test in API 541 and API 546. Some monitoring systems have been certified for use in Zone 2 hazardous locations.

Interpretation of PD results has improved significantly in the past decade. Case studies on the application of the technology in petrochemical facilities show that the test can give warning of stator winding insulation problems, and enable plants to determine if machine repairs have been effective.

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