MONITORING PARTIAL DISCHARGES ON 4 KV MOTOR WINDINGS

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***Abstract*—Partial discharges are a symptom of most of the stator winding insulation deterioration mechanisms found in motors and generators rated 6 kV or more. Thus, partial discharge testing has been used for over 40 years as a means of determining the maintenance requirements of such high voltage stators. As the benefits of such testing have become more widely known, there has been an interest to apply partial discharge testing to 4 kV motor and generator windings.**

This paper discusses the theoretical reasons which may limit testing of 4 kV stators. The results of an extensive series of off-line partial discharge tests are presented which indicate that partial discharges indeed do occur. The results of a series of on-line partial discharge tests conducted on about ten 4 kV motors over the past two years show that partial discharges may only occur for a short time prior to failure with some types of failure mechanisms. Thus to prevent in-service failures, continuous monitoring is necessary. An inexpensive continuous partial discharge monitor is described. It seems that partial discharge monitoring will only be cost effective for very critical process motors and generators where in-service failures may have large financial consequences.

Introduction

Twenty years ago, many companies in the petroleum and chemical industry practiced preventive electrical maintenance which consisted of shutting down all equipment on a regular basis and taking every critical motor to a shop for cleaning and overhaul ... money was no object.

About ten years ago, vibration measurement became an accepted tool to decide when it was time for mechanical work on rotating machinery. On the critical machines, permanent vibration monitors became a standard feature, which minimized or avoided mechanical damage by shutting down the equipment before pieces actually started to fly apart.

A few years later, affordable frequency spectrum analyzers became readily available, and with them, the possibility to diagnose problems before even getting close to failure. That gave us some lead time to organize repairs. In addition to finding mechanical problems at an early stage, spectrum analyzers with suitable software could also pinpoint induction motor rotor problems such as broken rotor bars [1]. This is done by measuring a frequency spectrum of the phase current, and looking for sidebands of specific amplitude at the fundamental frequency plus and minus slip. Thus, both mechanical problems (usually with bearings) and rotor problems could be detected in normal motor service, that is without having to shut down the motor.

For decades, the only means of assessing the condition of a motor's third major component, the stator winding, was to shut the motor down for an insulation resistance test (IEEE Standard 43) and a visual inspection. More recently, an on-line partial discharge test has been used to detect stator winding problems on motors rated 6 kV or more [2]. However, many older critical machines, being 2.4 or 4 kV, do not fit in that category.

As our critical motors are getting over 25 years old, we are facing increasing risks of unexpected failures, or costly rewinding on a preventive (i.e. time-based) basis. Obviously, a method that could measure the "health" of our stator windings on line, in a similar fashion to vibration measurement for bearings and rotors, would be a very useful tool to get maximum life from aging motors.

This paper describes research into the effectiveness of extending on-line partial discharge tests on 4 kV motor stator windings, and discusses when such testing may be useful for anticipating stator winding problems.

Failure Processes

Most stator winding failures are a result of deterioration of the insulation from various factors, mainly: thermal stresses (overheating); chemical attack from the environment; and abrasion due to excessive coil movement in the slot or endwindings. Upon the action of these stresses, the epoxy or polyester resin loses its bonding properties, and air pockets will be created in the windings, allowing conductors to vibrate against each other, eventually leading to turn-to-turn and ground faults. A further problem occurs when partly conductive pollution from moisture and/or oil in combination with dirt, settles on the coil surfaces outside of the slots. This leads to electrical tracking which eventually punctures the insulation.

Recent papers have also reported that partial discharges occurring during voltage surges can lead to failure, even in low voltage, random wound motors. Thousands of such surges can be produced by the new generation (IGBT) of pulse width modulated drives [3, 4].

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Partial Discharges As A Symptom Of Deterioration

For motor and generator stator windings rated 6 kV and above, it has been known for decades that these failure processes give rise to partial discharges (PD). PD are small sparks that occur in high voltage insulation wherever small air pockets exist. Thus, since overheating, coil vibration and pollution create air pockets, PD is a symptom of most high voltage stator winding failure processes [2, 5].

For 40 years PD testing has been a common method for evaluating the condition of high voltage stator windings, especially in generators [6]. More recently, reliable methods have been developed to allow plant personnel to measure the PD activity during normal motor and generator operation [2]. The methods involve detecting the current (or voltage) pulses which are created every time a partial discharge occurs. Such PD testing, when combined with bearing and rotor monitoring, has enabled effective condition-based maintenance of high voltage machines.

PD testing has not been widely applied to 4 kV windings, primarily because conventional wisdom suggested PD activity is usually very low, at least for internal defects within the groundwall insulation. In particular, PD is the result of the electrical breakdown of a small air gap within the insulation. Electrical breakdown requires a minimum electrical stress of about 3 kV/mm before it occurs. Since a 4 kV stator has a voltage to ground of only 2.3 kV, it is somewhat difficult to obtain the required minimum electric stress to cause the spark, unless a considerable portion of the insulation has been damaged. This implies that before significant PD occurs in internal voids, the insulation is already substantially damaged or was poorly impregnated, and close to failure. Note however, discharges can occur for many months or years prior to failure if electrical tracking on the coil surface due to contamination is the cause.

To collect some data on the PD activity that can occur on 4 kV motors, "off-line" PD tests were conducted on several motors that were temporarily removed from service.

Experience With Off-Line PD Tests

Two types of PD detectors were used in the off-line PD test studies. The first type of test employed various brands of commercial conventional PD detectors. These detectors consisted of a high-voltage capacitor (usually about 1000 pF) connected to additional filters and an oscilloscope and/or pulse height analyzer to record the activity [7]. The bandwidth of the conventional detector was usually 10 kHz to 1 MHz. The results were measured in picoCoulombs, i.e. the number of electrons in the discharge.

The second type of PD measurement system used an 80 pF capacitor to detect the PD in the hundred megaHertz range with a pulse height analysis instrument called the TGA [2]. This type of instrumentation has been optimized for on-line tests (see later), but can also be used off-line. The magnitude of the pulses in the latter test was measured in millivolts.

A series of off-line PD measurements were performed on twenty-one 4 kV motors with ratings in the range of 250 to 3500 HP at a nuclear generating station. Of the twenty-one motors tested, nineteen had measurable PD at rated line-to-ground voltage (2400 V rms) on all three phases. PD magnitudes ranged from 50 pC to 5000 pC. While the absolute magnitudes were not high in comparison to tests on 6.6 kV motors, and other tests and inspections indicated that the windings were in acceptable condition, the large percentage of windings which exhibited PD at nominal line-to-ground voltage was surprising. Clearly, these results show that PD can be an aging factor on 4 kV stator winding insulation.

On a discarded motor stator rated 4 kV, 200 HP with varnish cambric insulation, PD levels of about 300 pC were measured with a conventional PD detector. The motor was energized to 2300 V. Measurements with the TGA and an 80 pF capacitor indicated PD magnitudes of about 40 mV. The winding had severely delaminated insulation, and the

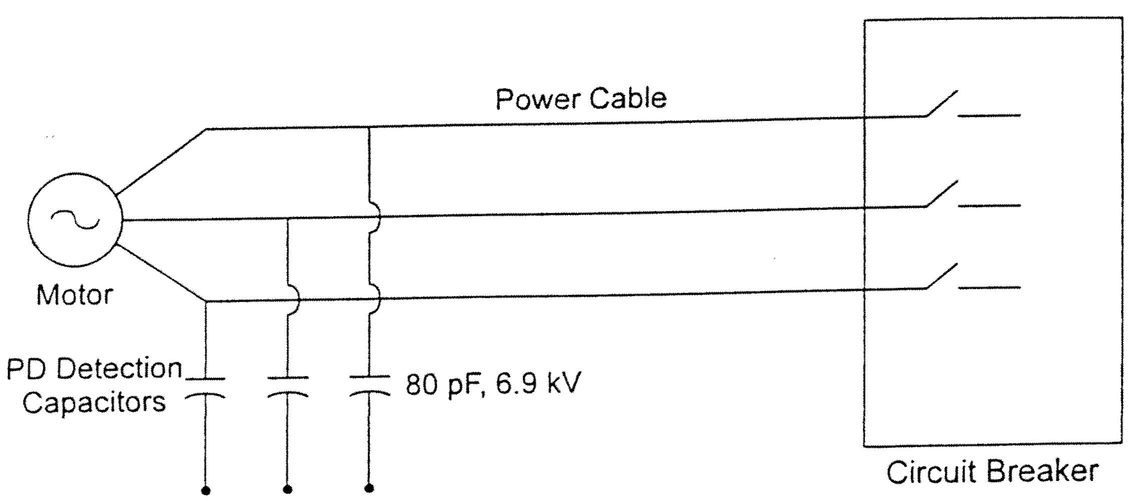

Fig. 1: Schematic of 80 pF capacitive couplers on the phase terminals of a 4 kV motor to detect PD.

insulation was very "spongy" just outside of the slot. Although classic PD was detected, the magnitudes were much lower than magnitudes that would have occurred in a 6 kV motor with similar voids in the insulation. For comparison, an 11,000 HP, 6.6 kV motor had PD magnitudes in excess of 100,000 pC by conventional tests, or greater than 2000 mV by the TGA test, with the winding energized to normal line-to-ground voltage (4 kV).

The conclusion from the off-line PD tests is that 4 kV stator windings in good condition may have no or very low levels of partial discharge. Secondly, the PD magnitudes for machines with significant deterioration are much smaller at rated line-to-ground voltage for 4 kV machines than for 6 kV and above windings. Furthermore, since the groundwall insulation is relatively thin when compared to higher voltage motors, less insulation material needs to be digested in a 4 kV stator to result in winding failure. Thus if large magnitude PD does occur in a 4 kV stator, then the insulation will take less time to fail due to the thinner groundwall.

Experience With On-Line Testing

Over the past two years, about 10 motors have been equipped with either 80 pF high voltage capacitors on the motor terminals, or RF current transformers on the ground side of surge capacitors mounted in the motor terminal box (Fig. 1). The pulses from the sensors were measured with the TGA instrument described above. In most cases, the PD activity has been low in comparison to the PD levels typical in higher voltage machines, that is less than 25 mV or so. Fig. 2 shows a typical result.

The highest PD levels were measured in a one year old utility motor insulated with epoxy mica insulation. The readings reached 300 mV (see Fig. 3). Unfortunately, there has not been an opportunity to examine this motor to determine the source of the PD and the insulation condition. It is expected that the PD is due to contamination of the endwinding by partly conductive pollution, leading to electrical tracking.

80 pF capacitive sensors were also installed on four 4 kV motors, rated 3500 HP in a refinery application. One motor had been recently rewound and was presumed to be in good condition. Essentially no PD was detected. Two others had PD less than 25 mV. One 22 pole, 26 year old motor had PD levels up to about 30 mV (Fig. 4). From the three-dimensional pulse phase analysis plot, it is apparent the pulses are clumped with respect to the 60 Hz ac cycle. Furthermore, the pulses have the same phase position and polarity as expected from PD. Since the positive and negative PD have approximately equal magnitude, experience shows that the source of the PD is delamination of the groundwall insulation [8]. Several weeks after these measurements were taken, the motor stator failed. The failure occurred in the second coil from the phase terminal, in the phase with the highest PD activity. Dissection of the coil showed the insulation was poorly impregnated and poorly bonded (Fig. 5). Small burn holes were found through some layers of the insulation, indicative of PD attack.

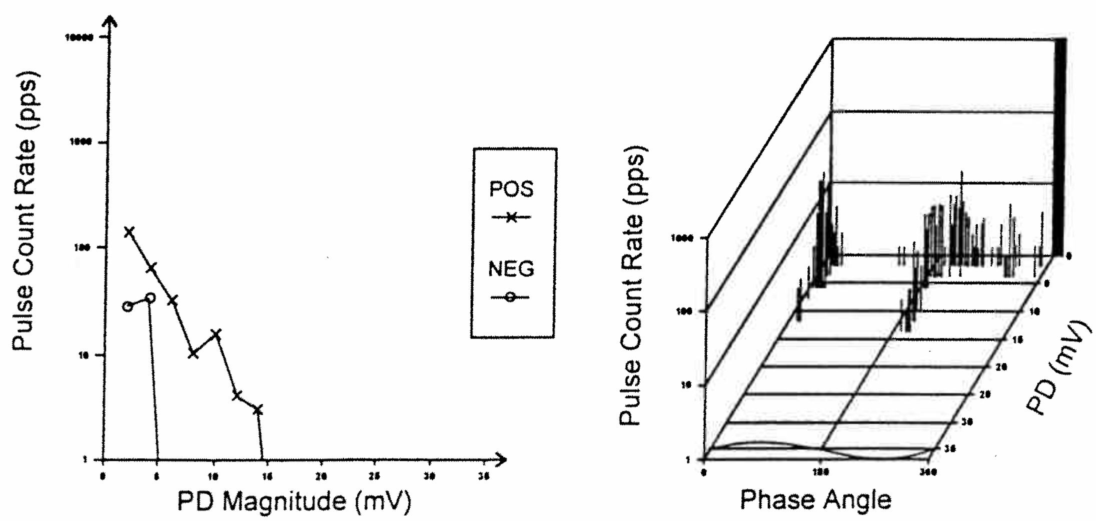

Fig. 2: PD activity in a 4 kV, 1750 HP stator measured on-line. The 2D plot shows the "pulse height analysis" where the pulse magnitude is displayed on the horizontal scale. The vertical scale is the number of PD pulses per second at the corresponding magnitude. The 3D plot shows the "pulse phase analysis" where the number of pulses per second (vertical scale) is plotted against the pulse magnitude (scale coming out of the page) and the 60 Hz ac cycle position (horizontal scale). The peak PD magnitudes are less than 15 mV, which is low.

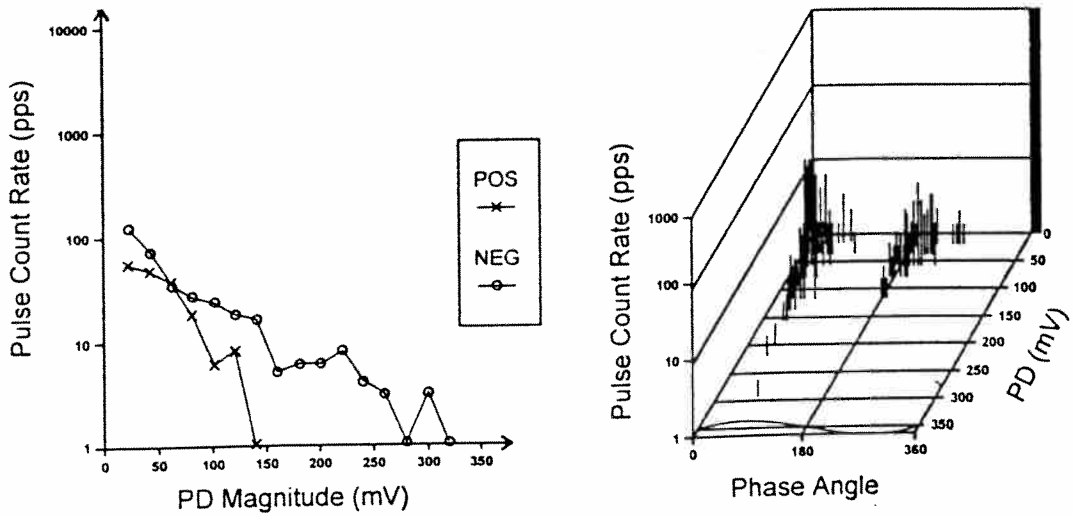

Fig. 3: Pulse height analysis and pulse phase analysis plots of the highest PD levels ever recorded on a 4 kV, 1750 HP motor. The motor is only one year old.

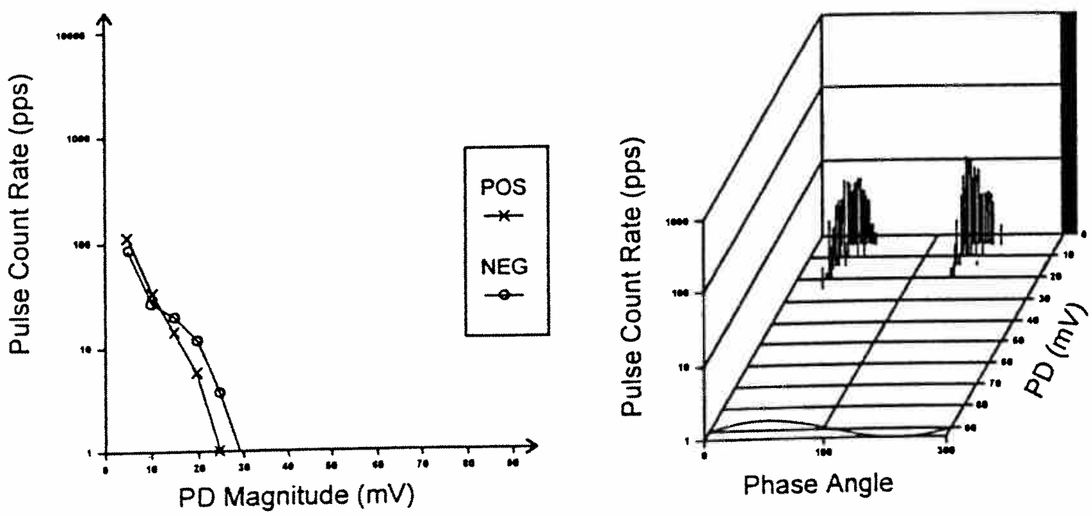

Fig. 4: Pulse height analysis and pulse phase analysis plots of the PD activity in a 4 kV, 3500 HP motor which failed only a few weeks after the PD test. The test was performed during normal operation of the motor.

Although this is a single example, when compared with the off-line tests, it seems that a 4 kV motor with significant insulation deterioration will produce low level PD. However, the degree of PD deterioration evident upon dissection indicates that very substantial PD must have occurred just before failure. Since PD readings only several weeks prior to failure indicated a relatively low activity, then this activity must have occurred after the PD test was done. Clearly, with the delamination failure mechanism due to overheating, significant PD may only occur for a few weeks or months prior to failure. Thus to be alerted of imminent failure, the PD activity needs to be almost continuously monitored. This led to the development of a continuous on-line PD monitor.

Requirements for a Reliable Continuous On-Line Monitor

As with any on-line system which is designed to provide information on the need for maintenance of a critical piece of equipment, the system must have the following attributes:

- no false indications. Since motor stator windings are usually very reliable, with lifetimes commonly exceeding 30 years, it is very important that the monitoring system not give false indications of stator winding problems. If false alarms are more likely to occur than genuine warnings, plant personnel will lose confidence in the system.
- the ability to actually detect most of the problems that can occur. If only a few of the possible failure mechanisms are

detected, then "unexpected" failures will occur, again causing the plant to lose confidence in the system.

- the monitor itself must be reliable, i.e. not lead to motor failure, nor should the monitor be inoperative for any significant period.
- the monitor output must be easy to interpret, preferably with a simple alarm, but with sufficient data being available so that a person with the proper expertise could extract more information about the condition of the winding.
- the system must be economical to install and operate. Although motors are important, the risk of stator winding failure at any one time is low, and thus plant management will not be prepared to make an unwarranted investment in an expensive monitor.

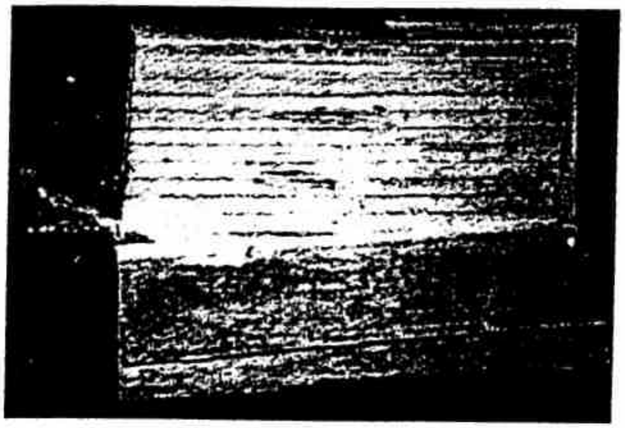

Fig. 5: Photograph of a motor coil dissected shortly after failure. The taped insulation layers separated easily, and there was considerable white/light brown powder at the copper conductors.

The most critical aspect affecting the credibility of on-line monitors to detect PD, is the handling of electrical interference [2]. Electrical interference, or noise, can obscure legitimate PD pulses. Sources of interference include arcing slip rings and commutators in electrical machines (especially hand tools), corona from switchgear and electrostatic precipitators, and arcing from poor electrical contacts anywhere in the plant. The noise sources are external to the motor.

Although PD testing has been applied for many decades for high voltage motors and generators, and the noise environment was extensively investigated in such environments, there was little experience with medium voltage motors. Thus, considerable research was undertaken to determine the characteristics of PD and noise on medium voltage motors, prior to the development of a continuous on-line monitoring system.

Differences Between PD and Noise

Sensors essentially identical to those installed in high voltage machines were installed on many 4 kV motors in several generating stations. The sensors were usually 80 pF high voltage capacitors (Fig. 1). These sensors detect the high frequency pulse currents or voltages which accompany PD and noise pulses. The signals were measured with spectrum analyzers and digital oscilloscopes.

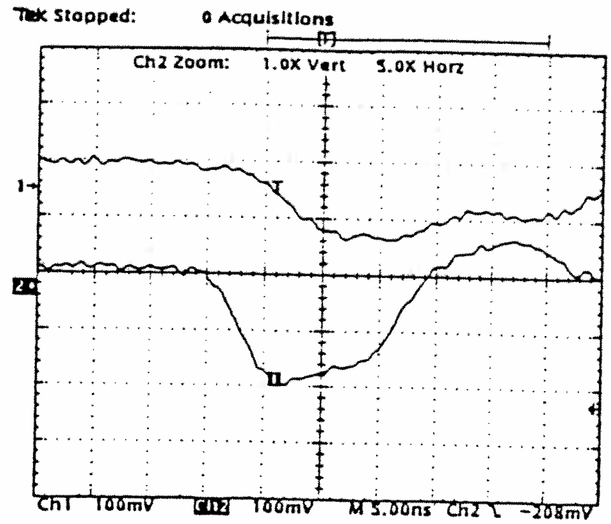

Fig. 6: Oscilloscope recordings of partial discharge pulses measured on the terminals of a stator winding with 80 pF sensors.

Fig. 6 shows the detected voltage pulse at the motor terminals as a result of a partial discharge. The pulse has a risetime (defined as 10% to 90% of peak) of 4 ns. The frequency content of this pulse extends to over 100 MHz, thus an 80 pF capacitor installed on high voltage machine terminals can be used as the coupling device [1].

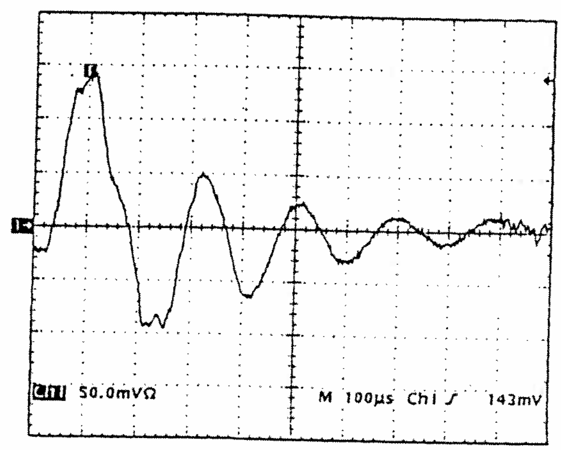

Fig. 7: Oscilloscope recording of electrical noise. The noise pulse was detected at a 4 kV, 3217 HP cooling water pump motor.

Fig. 7 shows the typical response to a noise pulse detected at the motor during normal operation. The noise pulse risetime is about 50 ms. Relatively slow risetimes are characteristic of noise pulses detected at the motor. Noise pulses must either propagate from the power system to the motor along the power cable, or they couple onto the metal motor enclosure by a radio-type pick-up through the air. The latter is well known to yield relatively slow risetimes, since the motor enclosure was not designed to be an efficient high frequency receiving antenna. The slow risetime response that occurs from a pulse which travels through a power cable to the motor is caused by the frequency-dependent attenuation properties of the cable [9]. Specifically, as a fast risetime pulse propagates along a power cable, say from sparking at a poor electrical connection in the switchgear, the pulse risetime lengthens, and the magnitude of the pulse reduces. The result is pulse distortion, which gets worse as the cable gets longer. Power cables can considerably distort a pulse since the semiconductive conductor shield is a strong absorber of high frequency energy [9]. Fig. 8 shows how a PD pulse is attenuated and its risetime is lengthened as it travels through a power cable. The PD pulse detected at the motor has a risetime of about 3 ns. However, after traveling through about 1000 feet of cable, the pulse magnitude is reduced by about 10 times, and the risetime is lengthened to 15 ns.

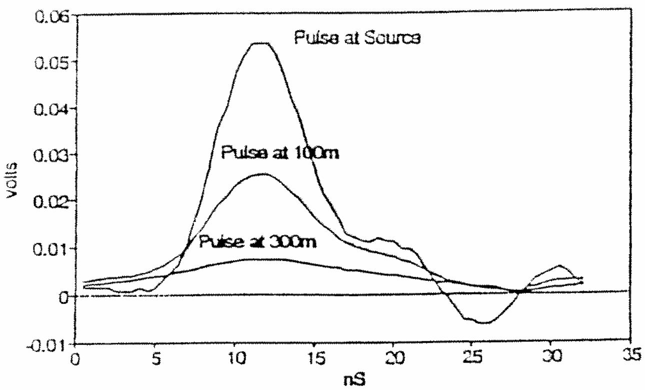

Fig. 8: Effect of power cable length on the PD pulse shape. The longer the power cable, the longer the risetime of the pulse, and the lower the pulse magnitude.

The difference in magnitude and risetime between noise and PD, when detected at the motor terminal, enables the development of a reliable, on-line, continuous PD measuring system. By taking into account the different pulse shapes, PD can be distinguished from noise on a pulse-by-pulse basis, and thus the risk of false indications of stator winding problems caused by noise is greatly reduced.

The critical aspect of implementing such a system is that the PD pulses must be detected at the motor terminals, since this will ensure that the PD pulses will have the maximum amplitude and shortest risetime, and noise pulses will be distorted the most since they have to propagate through the maximum length of cable. In addition, the PD sensors must have a very wide bandwidth, typically 100 MHz, so that the differences in pulse shape in the nanosecond range are measurable. Sensors such as Rogowski coils will not enable reliable noise rejection, since their bandwidth can not exceed a few hundred kilohertz, due to the lack of a ferrite core and their large size. A 3 ns risetime pulse and a 25 ns risetime pulse produces the same response from any practical Rogowski coil.

The key result of these investigations is that PD can be distinguished from noise using a single sensor per phase, based on pulse shape and amplitude. Furthermore, when PD does occur in medium voltage motors, the PD will exhibit the same pulse patterns as PD from high voltage motors, with the exception being that the normal PD magnitudes are lower for good motors. This information provided the scientific basis to develop a continuous PD monitoring system for medium voltage motors.

Description of the PD Monitoring System

The system developed consists of two main components: PD sensors mounted in the motor terminal box (Fig. 9); and an electronic instrument mounted in a convenient location adjacent to the motor or within about 50 m of the motor (Fig. 10). Both components are permanently installed.

To ensure maximum sensitivity to PD and maximize noise rejection, it is important for the sensors to be installed as close as possible to the stator winding.

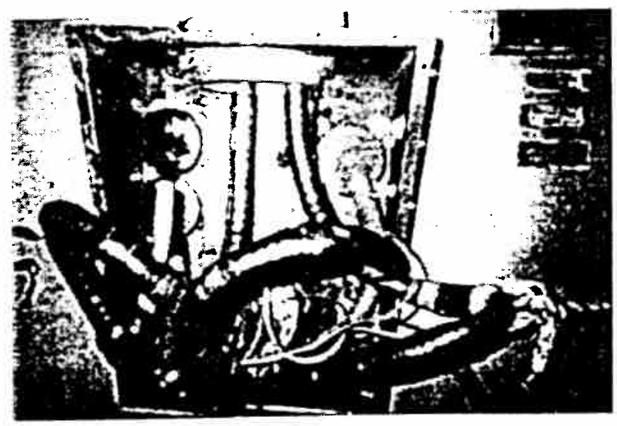

Fig. 9. Photograph showing the installation of 6.9 kV PD capacitors within the terminal box of a 4 kV motor.

The PD sensors are permanently connected to the electronic instrument via coaxial cables. The instrument is fully self-contained in a weather proof box, and designed for use in hazardous locations. The main functions performed by the instrument are:

- protect itself from voltage surges as can occur during motor switch-on.
- convert the pulses from analog to digital form.
- determine which pulses are noise, and which are legitimate PD on the basis of pulse shape.
- determine the positive and negative peak PD magnitudes, as well as the total PD activity. The quantities derived are called Qm and NQN, to be consistent with other PD measuring instruments [2].
- Ensure that the pulses have a pattern consistent with stator winding PD, i.e. the correct polarity and ac phase relationships.
- statistically analyze the pulse activity over time to ensure that it has a pattern consistent with PD. Discard unlikely data.
- store the PD data in on-board memory, with decreasing temporal resolution as the data gets older. Up to 2 years of data can be stored.
- display the present and any selected past PD data on an alphanumeric LCD.
- provide a set point for a PD alarm. For example, if very severe pulses are detected which meet the pulse shape, pulse pattern and statistical criteria for PD, turn on a light,

and close a relay contact to signal an alarm for plant maintenance personnel.

- provide an RS232 port so that stored data can be downloaded to a portable laptop computer.

By incorporating three different methods of separating noise from PD (pulse shape, pulse pattern with respect to the power frequency cycle, and activity trend over time), the risk of a false indication of a stator winding problem is greatly reduced.

Where possible, much of the same technology that is used in the portable PD instruments is applied to the continuous monitoring instrument. However, to reduce costs and size, the pulse phase analysis and pulse height analysis plots (Fig. 2) are not produced. Only the summary quantities Qm and NQN are stored.

The monitor incorporates a microcontroller to control its operation, enable the settings (such as sensitivity) to be customized for each motor, control what is displayed, and facilitate the RS232 link.

Initial Experience

To date the continuous monitoring system has been installed on 6 motors. Relatively little experience has been collected to date, and unfortunately, none of the monitored motors has failed! Fig. 10 shows the trend in the peak PD activity over a several month interval. The PD activity is relatively constant.

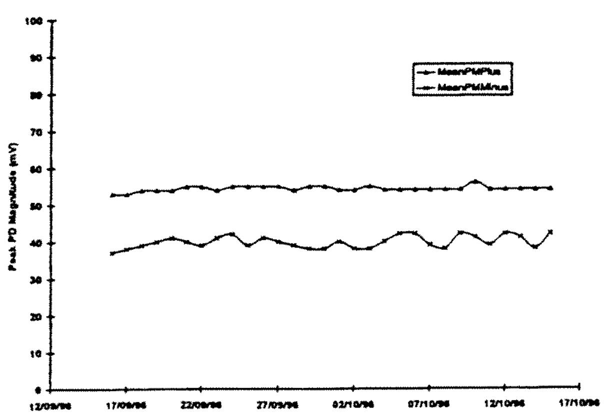

Fig. 10: Trend in positive and negative peak PD activity on one phase over a 1 month interval with a continuous PD monitor on a 1750 HP, 4 kV refinery motor.

Conclusions

1. There were no in-service methods to detect incipient problems in 4 kV stator windings. The stator winding is the only machine component therefore that requires an outage to determine its fitness for continued operation.
2. Research has been conducted to determine if partial discharge testing can be a practical means to detect stator winding problems.
3. Both on-line and off-line results indicated that, at least for some types of failure processes, the time between the occurrence of very active PD and failure may be only a few weeks.
4. To improve the chance of detecting stator winding problems, a system which continuously monitors the PD activity has been developed, with special attention being devoted to eliminating false indications from electrical interference.
5. Since the warning time is relatively short, when PD occurs, it seems that the winding may be already significantly deteriorated, and the only effective maintenance is probably a rewind. Thus PD monitoring of 4 kV windings is probably only useful in process or safety applications, where an in-service failure will result in significant losses of production, or would compromise the integrity of associated plant equipment.

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