MEASURING PARTIAL DISCHARGE ON OPERATING MOTORS WITH VS-PWM DRIVES

H.G. Sedding*, G.C. Stone* & C. Chan*

***Qualitrol – Iris Power, Canada**

ABSTRACT

Partial discharge (PD) testing is an important tool for assessing the condition of the high voltage insulation in motor and generator stator windings. In the past several years, many motors have been powered from inverters which facilitate variable speed motor operation. The most common type of drive being used nowadays is the voltage source, pulse width modulation (VS-PWM) type. Drives rated up to 13.8 kV are becoming more common in natural gas compressor plants, as well as other petrochemical facilities. Such drives generate high voltage spikes in the kV range with rise times in the sub-microsecond range. These high voltage spikes are a form of severe electrical interference that can make the detection of partial discharge difficult, due to the overlapping frequency content in PD and in the spikes that are 1000 times higher in magnitude. Thus, PD detection on medium voltage VS-PWM systems has been a challenge, in spite of the serious stator winding insulation ageing that the impulse output such drives may cause to their driven motors.

This paper discusses the stator winding failure mechanisms which produce PD, particularly the insulation problems that VS-PWM drives can accelerate. A prototype on-line PD monitoring system suitable for motors fed by VS-PWM drives was developed to address the difficulties associated with making reliable PD measurements on such drives. Results from the application of this system on a number of such motors are presented and discussed.

INTRODUCTION

Partial discharges (PD) are small electrical sparks that can sometimes occur in insulation systems. In switchgear, power cables and transformers, there should be no PD in new equipment. If for any reason PD does occur, the PD attacks the organic insulation in such apparatus and can often cause failure in a few weeks or months. In contrast, stator windings, due to the inclusion of mica in the insulation, are much more resistant to PD degradation. Most stator windings rated 3.3 kV and above have low levels of PD activity, and still can operate for 30 years or more without any incident [1]. However, if there are large defects in the stator winding insulation caused by the manufacturing process or ageing, the PD activity will increase over time [1-3]. By monitoring the trend in PD, machine owners can plan maintenance as required.

Partial discharge tests may be performed on-line or off-line. In the latter case, when the motor is shut down, and isolated from the bus, a power frequency high voltage transformer, capable of energizing the stator winding capacitance is used [1,2]. Such tests tend to be done infrequently, so it is hard to establish a trend. On-line PD testing is carried out with the motor in normal operation, using previously installed PD sensors [3-5]. The advantage of on-line PD testing is that the data can be collected more frequently and at any time, and the motor is operating under consistent voltage, load and winding temperature conditions. The disadvantage of on-line PD testing is that the motor is connected to the power system and, therefore, many sources of electrical noise and disturbances are present, including transmission line corona, sparking from poor electrical connections elsewhere in the plant, etc. This noise may be higher in magnitude than stator winding PD and lead motor owners to believe that the stator winding insulation is failing, when, in fact, it may be in good condition. Such false positives tend to decrease confidence in PD testing. Several methods have been developed to minimize or reject this interference, which then reduces the risk of false positive indications [1, 3-5]. These methods have enabled routine application of on-line PD testing on over 16,500 conventional 50/60 Hz motors and generators around the world and the creation of limits for acceptable PD levels in operating equipment [5].

There are many applications where it is advantageous to vary the speed and power output of a motor, to improve processing and to reduce electrical energy costs [6]. Several methods exist to electrically change the motor speed. Most of the methods use some form of convertor that rectifies the normal 50/60 Hz voltage, and then inverts the dc voltage into a voltage of any desired frequency. Of the several inverter topologies [6], the two oldest are load-commutated inverters (LCI) and current source inverters (CSI). More recently, voltage source - pulse width modulated (VS-PWM) inverters have become more popular; due to lower cost and a smaller footprint. VS-PWM drives inherently produce thousands of voltage impulses per second, which are caused by the switching of transistors within the drive [6-8]. In machines rated 3 kV and above, the impulses may be more than 2000 V and have rise times shorter than several hundred nanoseconds. These transients have frequency characteristics similar to stator winding PD, yet they are 1000 times larger than the PD magnitudes. Thus, these transients make reliable on-line measurement of PD much more difficult.

INVERTER DRIVE EFFECTS ON STATOR INSULATION

Experience over the past decade indicates that the voltage impulses from the VS-PWM inverters can age each component of the stator insulation system differently.

Turn Insulation Deterioration

Voids in the turn insulation may result in PD if the interturn voltage is of sufficient magnitude. This mechanism is less of a concern in form-wound stators designed specifically for VS-PWM applications if mica paper turn insulation, which is very resistant to PD, is used.

Ground and Phase Insulation

The short-rise time switching voltage and associated transmission line reflection effects may lead to voltage doubling, which in turn, results in the peak-voltage to rms-voltage ratio being higher than the 1.4 ratio that is present with sinusoidal voltage [7]. The higher peak voltage will increase the repetition and magnitude of groundwall insulation PD and thus accelerate ageing. Further, the number of PD pulses may also be higher than that for a conventional 50/60 Hz motor since the switching frequency is 1000 Hz or higher and each resulting impulse may create PD in a void.

Stress Relief Coatings

Since inverters generate high-frequency voltages, the capacitive currents through the ground insulation are relatively high compared to power frequency. The high-frequency capacitive currents will result in high local I^2R losses in the coatings compared to power frequency windings [1, 7]. The result is that the stress control layers in VS-PWM inverter fed motors are likely to deteriorate much faster than the layers in 50/60 Hz windings due to the resulting higher temperature. As the stress relief coatings deteriorate, they will create PD activity.

ON-LINE PD MEASUREMENT

Conventional PD Measurement

There are several different PD detection methods that may be applied to operating motors fed from the 50/60 Hz power system [3]. Probably over 95% of the motors with on-line PD sensors use high voltage capacitors, with a capacitance of 80-1000 pF, that are installed at, or very close, to the stator terminals. A partial discharge pulse from a stator winding operating in air at atmospheric pressure is shown in Figure 1. Inspection of Figure 1 shows that the rise time of the pulse is about 3 ns, which has an equivalent (Fourier) frequency content up to 100 MHz.

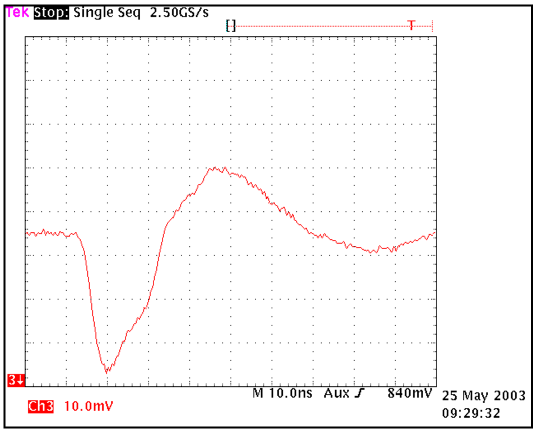

Figure 1 Oscilloscope image of a single PD pulse measured by an 80 pF capacitive PD sensor, on an operating stator winding in air. The pulse is measured across a 50 Ω resistor. The vertical scale is 10 mV per division while the horizontal time scale is 10 ns/division.

Figure 2 shows a typical output from an on-line PD measurement instrument where the positive and negative PD pulses are recorded [3-5, 9]. The higher the PD magnitude, the larger the defect, giving a relative indication of the risk of stator winding insulation failure [3]. The PD pulse repetition rate indicates the density of defects there are in the winding. If a single dominant insulation ageing mechanism exists, then the pattern of the PD with respect to the ac cycle can sometimes indicate the root cause of the PD, thus aiding maintenance planning [1, 3, 9].

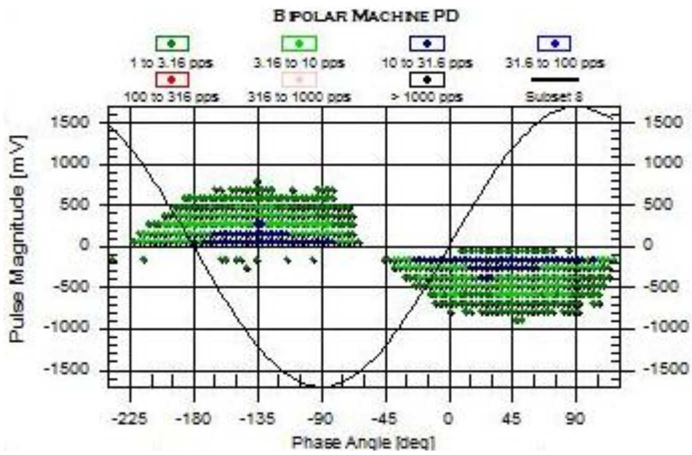

Figure 2 Phase resolved PD (PRPD) plot of data from an operating conventional 11 kV, 4.9 MW, 50 Hz oil pump motor. The vertical axis is the PD magnitude (in mV) while the horizontal axis is the

phase angle of the 50 Hz ac voltage. The colour of the dots indicates the PD pulse repetition rate.

Difficulties in Measuring PD on VS-PWM Fed Motors

Most types of inverters such as LCI and CSI drives usually do not produce significant high voltage and short rise time transients. Thus, they do not present any particular problem for the measurement of stator winding PD. On-line PD measurement has been done on motors supplied by CSI and LCI drives for almost 20 years without any need of special provision or modification to conventional measuring equipment [1, 10].

Figure 3 shows the voltage waveform measured at the output of a voltage divider on a nominal 3 kV motor fed by a VS-PWM inverter. The oscilloscope had a Fourier transform function, which showed that the transients had frequency content up to 18 MHz. The transients caused by the inverter switching can result in high frequency "noise" that is 1000 times higher than the mV PD signals that are typically measured from stator windings. These transients are not sufficiently reduced in magnitude by the high pass filter formed by the PD detection capacitor because of their high-frequency content. Even after high pass filtering using 80 pF PD sensors that have a lower cutoff-frequency of about 40 MHz, the inverter transients at the motor are still in the order of tens of volts (Figure 4), which is almost 100 times the magnitude of significant PD.

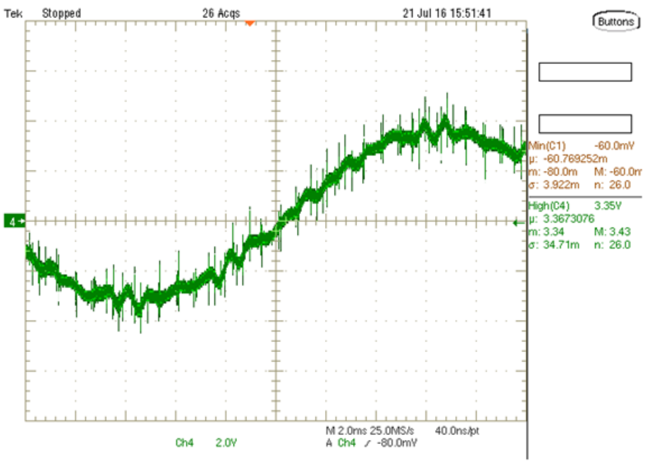

Figure 3 Waveform of the voltage at the motor terminal of a nominal 3 kV rated motor. The fundamental voltage frequency is about 40 Hz. The voltage was measured by means of a capacitive and resistive voltage divider.

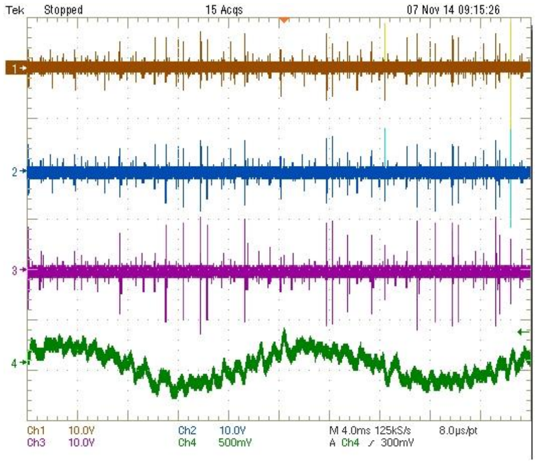

Figure 4 Oscilloscope traces of the output of 80 pF PD sensor feeding 50 Ω (top three traces, one per phase) vs. the ac fundamental voltage (bottom trace) in the 12.5 MW motor. Phase 3 is indicating nearly 15 V pulses (0 to peak) on the output of the PD sensor.

In addition to better means of suppressing the switching noise detected by the PD sensors, there are two other challenges in reliably detecting and measuring PD on VS-PWM drives. As indicated in Figure 2, it is traditional to display the stator PD activity with respect to the 50 or 60 Hz ac cycle. Thus, the electronics needs to synchronize the PD to frequencies other than 50 and 60 Hz. Changes were needed to permit the test instrument to operate over a desired fundamental frequency range of say 20 to 120 Hz. An additional problem is detecting the start of each fundamental ac cycle. Often, this is done using a voltage "zero crossing" detector that is fed from the small (usually 100s of millivolts) residual 50/60 Hz ac voltage from the PD sensor. With a sinusoidal ac voltage, this circuitry is trivial, since there is only one positive voltage zero crossing per ac cycle. However, as shown in Figure 3, there may be hundreds of positive zero crossings overlaid on the fundamental ac cycle caused by the switching events within the VS-PWM inverter.

On-Line PD Measurement System for VS-PWM Drives

A measurement system has been developed to enable PD detection on VS-PWM driven motors that addresses the issues discussed above. The PD sensors are the same 80 pF capacitive sensors used on many thousands of conventional motors. These sensors meet the reliability requirements of IEC 60034-27-2, and have already been certified for use in ATEX hazardous locations, where many VS-PWM drives are situated. Their use also permits the employment of PD severity tables compiled for power frequency applications since they have the same impedance and frequency range [1, 5]. Thus a new database for PD interpretation is not required to be assembled – which could take tens of years of comparing PD levels with the observed condition of the stator winding as determined by visual inspection.

Two basic methods are used to minimize inverter noise while minimally affecting the stator winding PD. The first is to use multi-pole filters to strongly suppress signals below about 30 MHz, where the inverter transients have most of their energy. As new types of switching devices, such as silicon carbide transistors that can switch in less than 20 ns, become more prevalent, these filters may need further adjustment. In addition, the instrumentation can measure the rise time of each detected pulse, amongst other features, and digitally classify pulses with a rise time longer than 6 ns as noise [2, 5].
For the reasons described above, a separate voltage divider to provide the fundamental frequency synchronization signal is required. The advantage of the divider is that its response is independent of frequency, and so higher frequency signals from switching transients are not accentuated compared to the much lower fundamental frequency. After the divider, additional filtering is used to suppress the switching transients.

Figure 5 shows the block diagram of the on-line PD measurement system applied to VS-PWM drives. Figure 6 shows a photograph of an installation inside the terminal box of an inverter fed motor.

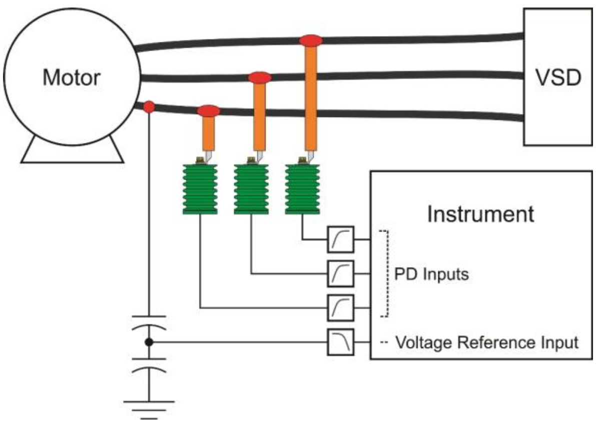

Figure 5 Schematic of the PD measuring system for motors rated 3 kV and above.

Figure 6 Installation of 3 PD sensors and a voltage divider in the terminal box of an IFM.

FIELD EXPERIENCE

The prototype system was first installed in 2007 on LNG compressor motors supplied from VS-PWM invertors. Many adjustments have been implemented over time to make the system functional with advances in inverter technology. Presently, the technology has been applied to about 100 motors around the world.

45 MW, 7.2 kV Compressor Motor

Figure 7 shows the fundamental frequency phase-resolved PD plot for the first installation on a 45 MW LNG compressor motor fed by a VS-PWM inverter that operates at a fundamental frequency near 100 Hz. The PRPD pattern is consistent with deterioration of the stress relief coating deterioration [9]. PD on the surface of high voltage coils just outside of the stator slot is more likely to happen when the motor is fed from a VS-PWM drive [7, 8]. Peak PD magnitudes (Q_m as defined in IEC 60034-27-2 and IEEE 1434) above 336 mV using an 80 pF PD sensor are considered significant for a motor of this voltage class [5].

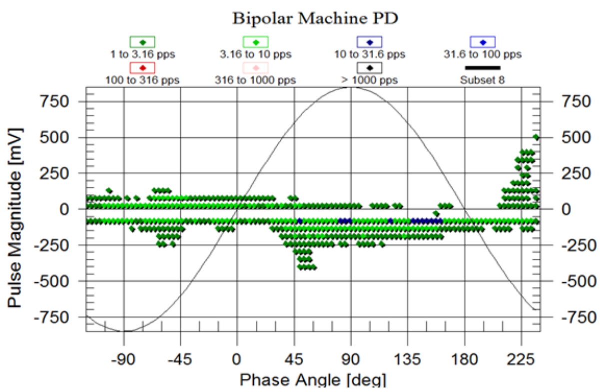

Figure 7 PRPD plot showing classic surface PD in a 45 MW, 7.2 kV motor operating at 100 Hz.

Figure 8 shows the PRPD pattern recorded from another phase on the same motor. In this case, the pattern is not as amenable to interpretation suggesting that further work is required to improve the assessment of PD data obtained on motors driven by such drives.

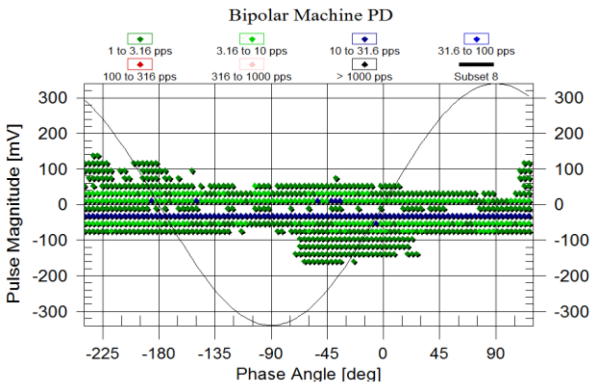

Figure 8 PD pattern recorded on another phase of the same 7.2 kV, 45 MW motor.

4000 HP, 4.1 kV Oil Pump Motor

Figure 9 shows the PRPD pattern for a 4000 HP, 4.1 kV motor fed by a VS-PWM converter. There appears to be little or no conventional PD occurring on the motor. According to the statistical PD database, PD activity on a power frequency 4.1 kV motor would have a Q_m value in excess of 214 mV [5] before concern would be raised. The activity present may be some residual transients from the drive. Alternatively, it is speculated that the PD may be occurring between the stator coil turns. It is known that turn-to-turn insulation failure has been precipitated by VS-PWM voltage transients [7, 8]. Such PD would be expected to occur across the fundamental ac cycle, since the PD is initiated by the drive switching transients rather than the fundamental frequency ac voltage.

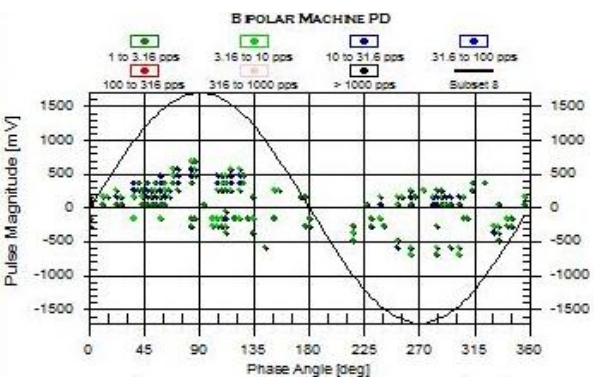

Figure 9 PRPD plot of measured activity in a 4000 HP, 4.1 kV motor fed by a VS-PWM drive.

3.1 MW, 3 kV Fan Motor

Figure 10 is the PD pattern from a new 3.1 MW, 3 kV motor fed by a VS-PWM inverter. Very little classic PD is detected on this motor. High PD measured using an 80 pF sensor would be above 214 mV for a 3 kV 50/60 Hz motor. Since the motor is new, and designed for VS-PWM operation, little PD is expected.

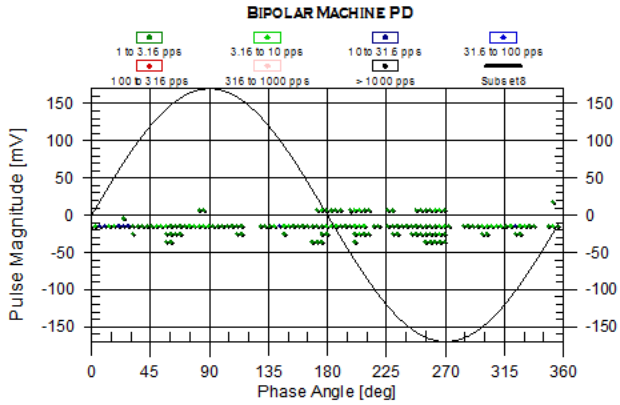

Figure 10 PRPD pattern from an operating 3.1 MW, 3 kV motor fed by a VS-PWM drive. No discernible PD is occurring.

CONCLUSIONS

On-line PD detection has been used for several decades to assess the stator winding insulation condition in motors rated 3.3 kV and above. It would be especially desirable to measure the PD on-line in motors fed from voltage source pulse width modulated drives because of the extra stresses imposed by the switching impulses on the groundwall insulation and the turn insulation and also on electric stress control elements outside the slots. However, it has proven difficult to do this due to the presence of short rise time voltage transients of many hundreds of volts from the drive. These transients are similar enough to PD, but hundreds of times higher, so it is a challenge to extract the stator winding PD from the switching transients. A system was developed to overcome this issue and has now been installed on many dozens of motors fed by VS-PWM drives. Both conventional and unconventional PD patterns have been measured on the stator windings. Further work is needed to refine the interpretation of the PD patterns resulting from motors fed from variable frequency drives.

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