MEASURING PARTIAL DISCHARGE ON OPERATING HIGH VOLTAGE MOTORS WITH VS-PWM VARIABLE SPEED DRIVES

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Abstract - Inverter fed motors (IFMs) are now widely being applied in petrochemical plants to vary the speed and power of a motor to improve processing and reduce energy costs. IFMs of the voltage source, pulse width modulation (VS-PWM) type have become the most popular type of drive due to their relatively small size and low cost. Unfortunately, the voltage transients created by such IFMs are similar to the pulse signals caused by stator winding partial discharges, and thus distinguishing stator winding PD becomes harder. Several decades of experience indicates that the trend in PD activity over time can help users detect developing stator winding insulation problems in conventional motors rated 3.3 kV and above, and users can then plan maintenance actions based on the measurement findings. A multi-year research project was undertaken to develop an on-line PD monitoring system that can better detect PD in IFMs, without being overwhelmed by noise from the inverter. This paper briefly outlines the difficulties in measuring PD on IFMs of the VS-PWM type, describes the monitoring system developed, and gives case studies from installations around the world.

Index Terms — Inverter Fed Motors, Electrical Insulation Failure, Partial Discharge Testing.

I. 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 above a specified level 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 using epoxy impregnated mica paper tapes, are much more resistant to PD degradation, and most stator windings of 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, or the insulation ages in such a way as to create significant voids within the insulation, then the PD activity will increase over time [1-3]. By monitoring the trend in PD, machine owners can plan maintenance when it is needed.

Partial discharge tests can be performed on-line or off-line. Off-line tests are done when the motor is shut down, and a special 50/60 Hz transformer is used to energize the stator winding capacitance [1, 2]. Such tests cannot be done frequently, so it is hard to establish a trend. On-line PD testing is done 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, too many sources of electrical noise are present, including transmission line corona, sparking from poor electrical connections elsewhere in the plant, and sparking from slip rings on motors in power tools, etc. This noise can mask stator winding PD and lead motor owners to believe that the stator winding insulation is failing, when, in fact, it is in good condition. Over the years, multiple methods have been developed to suppress or avoid this noise, which then reduces the risk of false positive indications [1, 3-5]. These methods have enabled on-line PD measurements 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 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 called load-commutated invertors (LCI) and current source inverters (CSI). More recently, voltage source - pulse width modulated (VS-PWM) inverters have become more popular. Such inverters saw widespread industrial application in the late 1980s in low voltage motors. Since about 2000, VS-PWM drives rated 3 kV and above have become more common. 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 risetimes 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 the reliable on-line measurement of PD much more difficult. This paper discusses the results of a multi-year research project to develop a system that measures PD on-line in motors supplied by a VS-PWM inverter.

II. ON-LINE PD MEASUREMENT

A. Conventional PD Measurement

IEC 60034-27-2 discusses the many ways PD can be detected in 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 very close to the stator winding. This capacitance, in combination with the (typical) 50 Ω load inside the PD instrumentation, creates a high pass filter which strongly suppresses the 50/60 Hz sinusoidal high voltage from the power system. A partial discharge pulse from a stator winding operating in air at atmospheric pressure is shown in Fig. 1. It is clear from this oscilloscope waveform that the risetime (t_r) of the pulse is about 3 ns, which has an equivalent (Fourier) frequency content up to 100 MHz, since the frequency is approximately equal to $1/4t_r$. Hence, the capacitive PD sensor has very low impedance to the high frequency PD pulses, while strongly attenuating the high voltage ac from the measuring instrumentation.

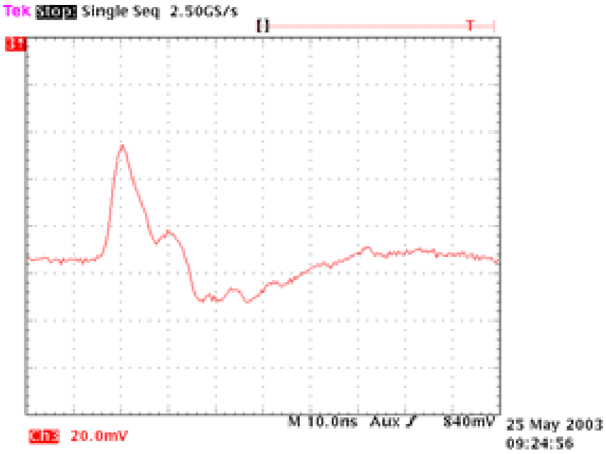

Fig. 1 Oscilloscope image of a single PD pulse measured by an 80 pF capacitive PD sensor, on an operating stator winding in air. The pulse is measured across a 50 Ω resistor. The vertical scale is 20 mV per division while the horizontal time scale is 10 ns/division.

The stator winding PD is usually displayed with respect to the 50/60 Hz ac voltage. Fig. 2 shows a typical output from an on-line PD measurement instrument where the positive and negative PD pulses are recorded [3-5, 9]. When visually inspected, the stress relief coatings of this motor were observed to be extensively deteriorated on the line end coils, due to very high PD activity [10]. The higher the PD magnitude, the greater is the size of the defect, giving a relative indication of the risk of stator winding insulation failure [3]. The higher the PD pulse repetition rate, the more defects there are in the winding. If there is a single dominant insulation aging mechanism, then the pattern of the PD with respect to the ac cycle can sometimes indicate the root cause of the PD, which will often suggest options for repair or intervention [1, 3, 9].

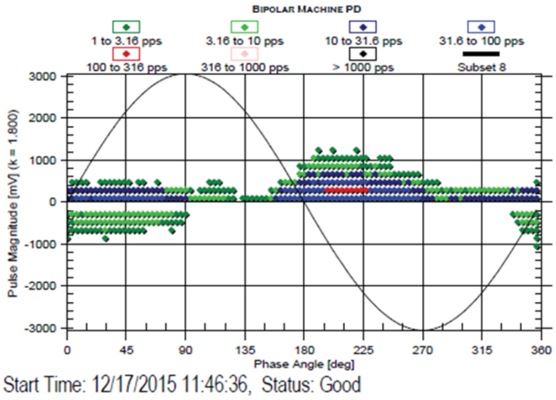

Fig. 2 Phase resolved PD (PRPD) plot of data from an operating conventional 13.8 kV, 4200 HP, 60 Hz natural gas compressor motor [10]. The vertical axis is the PD magnitude (in mV) while the horizontal axis is the phase angle of the 60 Hz ac voltage. The colour of the dots indicates the PD pulse repetition rate.

B. Difficulties in Measuring PD on VS-PWM Fed Motors

The voltage waveform from most types of inverters such as LCI and CSI drives usually do not contain significant high voltage, short risetime 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 the conventional measuring equipment [1, 11].

Fig. 3 shows the voltage waveform measured by a voltage divider on a nominal 3 kV motor fed by a VS-PWM inverter. The measuring 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. Unlike what happens with the 50/60 Hz high ac voltage, 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 (Fig. 4), which is almost 100 times the magnitude of significant PD.

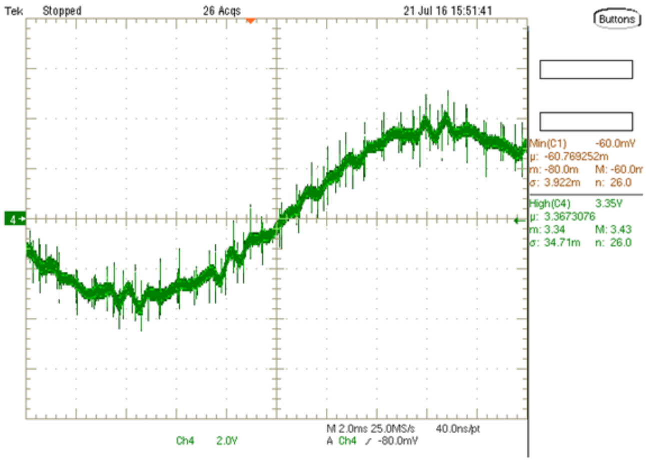

Fig. 3 Waveform of the voltage at the motor terminal of a nominal 3 kV rated motor. The fundamental voltage frequency is about 40 Hz. The voltage was measured by means of a capacitive and resistive voltage divider.

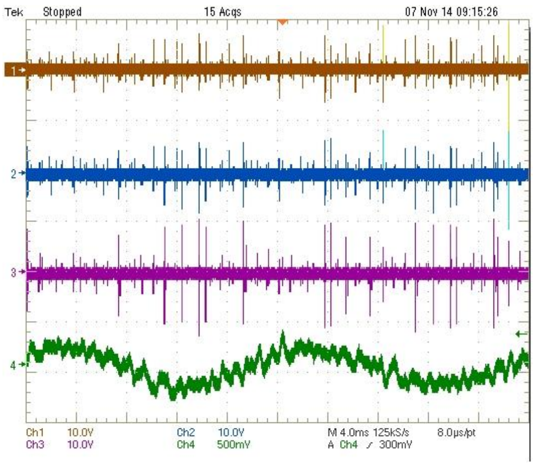

Fig. 4 Oscilloscope traces of the output of 80 pF PD sensor feeding 50 Ω (top three traces, one per phase) vs. the ac fundamental voltage (bottom trace) in the 12.5 MW motor. Phase 3 is indicating nearly 15 V pulses (0 to peak) on the output of the PD sensor.

In addition to better means of suppressing the switching noise detected by the PD sensors, there are two other issues with detecting and measuring PD on VS-PWM drives. As indicated in Fig. 2, it is traditional to display the stator PD activity with respect to the 50 or 60 Hz ac cycle. In other words, the electronics needs to be able to synchronize the PD to frequencies other than 50 and 60 Hz for IFM driven motors. Modifications were needed to allow the test instrument to operate over a desired fundamental frequency range of say 20 to 100 Hz. An additional problem is detecting the start of each fundamental ac cycle. Traditionally, 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 Fig. 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.

C. Practical On-Line PD Measurement System for VS-PWM Drives

The above challenges for on-line detection of PD in motors fed by VS-PWM drives resulted in the development of the following system. 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 IFMs are situated. Their use also permits the employment of PD severity tables compiled for conventional motors 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 many years of comparing PD levels with the observed condition of the stator winding as determined by visual inspection.

Two basic methods are used to strongly suppress the 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 shorter than 20 ns, become more popular, these filters may need further adjustment. In addition, the instrumentation employs the same algorithm as has been used for 20 years to separate PD from noise based on the shape of the pulse [5]. For example, the risetime of each input pulse is measured by electronic hardware, and if the t_r is < 6 ns, the pulse is classed as PD, whereas if the t_r > 6 ns, it is digitally classed as noise [2, 5].

Efforts to use the 80 pF PD sensor as a reliable indicator of the fundamental frequency were not successful due to the presence of many zero voltage crossings in each cycle, which are caused by switching transients. Instead, it was found necessary to use a separate voltage divider to provide the fundamental frequency synchronization signal. One divider is needed per motor. 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.

Fig. 5 shows the block diagram of the on-line PD measurement system applied to VS-PWM drives. Fig. 6 shows a photo of an installation on an inverter fed motor.

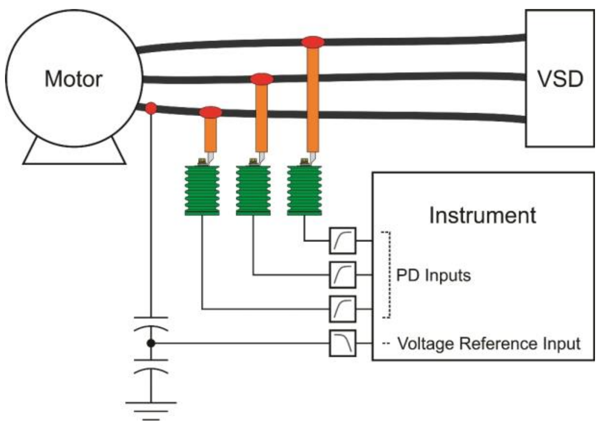

Fig. 5 Schematic of the PD measuring system for motors rated 3 kV and above.

Fig. 6 Installation of 3 PD sensors (behind the power cables) and a voltage divider (in the foreground) in the terminal box of an IFM.

II. PRACTICAL EXPERIENCE

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

A. 45 MW, 7.2 kV Compressor Motor

Fig. 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. This motor shows a classic PRPD pattern for a winding that is suffering from 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 (Qm as defined in IEC 60034-27-2 and IEEE 1434) above 336 mV using an 80 pF PD sensor are considered significant for a 7.2 kV rated voltage fed from 50/60 Hz [5].

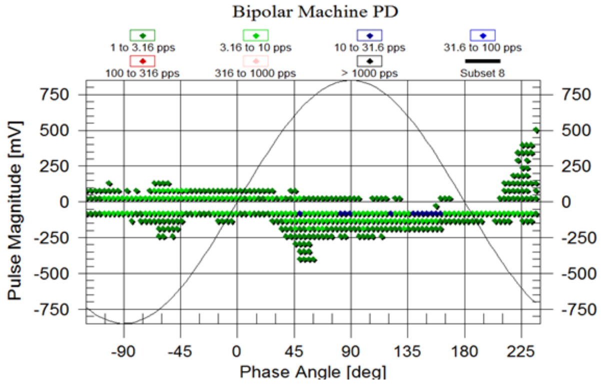

Fig. 7 PRPD plot showing classic surface PD in a 45 MW, 7.2 kV motor operating at 100 Hz.

B. 4000 HP, 4.1 kV Oil Pump Motor

Fig. 8 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, that is negative PD between 0 and 90° of the ac cycle and positive PD between 180° and 270° of the ac cycle. Significant PD activity on a sinusoidal 4.1 kV motor would have a Qm value greater than 214 mV [5]. 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. However, we will not be certain until the motor fails and a coil dissection is possible.

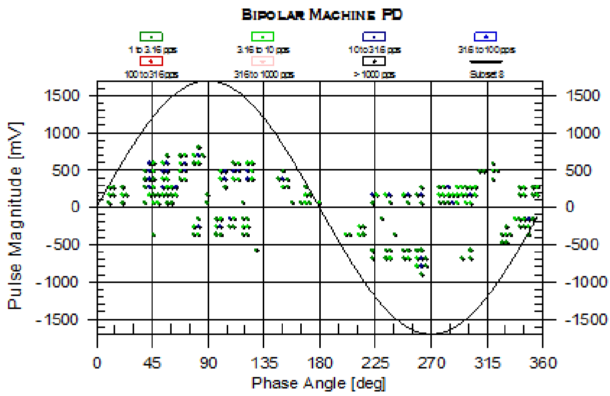

Fig. 8 PRPD plot of measured activity in a 4000 HP, 4.1 kV motor fed by a VS-PWM drive.

C. 3.1 MW, 3 kV Fan Motor

Fig. 9 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.

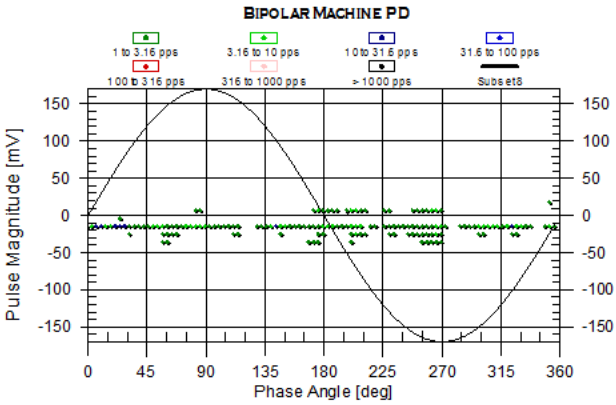

Fig. 9 PRPD pattern from an operating 3.1 MW, 3 kV motor fed by a VS-PWM drive. No discernable PD is occurring.

III. CONCLUSIONS

On-line PD detection has long been used 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 and 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 risetime 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. This challenge will only increase as switching devices work at higher voltages and have shorter risetimes. 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, but pattern verification will require winding dissections after failure.

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IV. VITA

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