EXPERIENCE WITH ON-LINE PARTIAL DISCHARGE MEASUREMENT IN HIGH VOLTAGE INVERTER FED MOTORS

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Abstract – Partial discharge (PD) testing has long been 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 drive used today is the voltage-source, pulse width modulation (VS-PWM) type. VS-PWM drives rated up to 13.8 kV are becoming more common in natural gas processing plants, as well as in other petrochemical facilities. Such drives generate high voltage impulses in the kV range with risetimes in the sub-microsecond range. These impulses are a form of severe electrical interference that can make the on-line detection of partial discharge (with magnitudes 1000 times smaller) difficult due to the overlapping frequency content in PD and in the impulses. Thus, PD detection on medium voltage VS-PWM systems has been a challenge in spite of the serious stator winding insulation aging that such drives may cause to these motors. This paper discusses the stator winding failure mechanisms which produce PD, including the insulation problems that VS-PWM drives can accelerate. A research project that lasted several years is reviewed. It culminated in a prototype on-line PD monitoring system suitable for motors fed by VS-PWM drives.

Index Terms — Variable Speed Drives, Stator Winding Insulation Failure, Partial Discharge.

I. INTRODUCTION

Variable speed drives (VSD), also called variable frequency drives, are becoming more and more common. They enable efficiency improvements in some processes [1, 2] and enable a soft start of the motor which reduces the stress on the windings caused by inrush currents. In these drives, the 50/60 Hz power frequency voltage is rectified to dc and then power electronics creates an output voltage and current of variable frequency (the fundamental frequency). The speed of a squirrel cage induction motor is directly proportional to the fundamental frequency. There are several types of drives. The most popular type at the present time is the voltage-source, pulse width modulation (VS-PWM) drive, since this type tends to have a smaller footprint and is usually less expensive. The VS-PWM drive uses fast switching devices to chop the positive and negative dc voltages to provide the desired fundamental frequency (Fig. 1). The rectangular voltage pulses of specific widths that are produced by this type of drive result in a current of the desired frequency. Such drives produce hundreds, and possibly thousands, of transient voltage impulses per second. These voltage impulses travel along the power cable that connects the drive to the motor. The stator winding insulation system may be affected by these high voltage impulses [3].

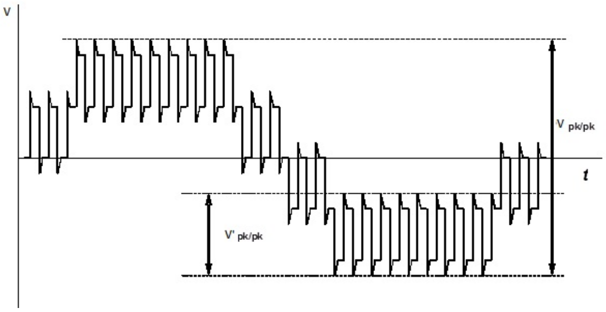


Fig. 1 Idealized waveform of one complete cycle of the phase-to-phase voltage at the terminals of a machine fed from a 3-level VS-PWM inverter (from reference [3]).

In conventional 50 or 60 Hz motors, it is common to monitor the partial discharge (PD) activity in the stator winding insulation system in critical motors rated 6 kV and above [4-7]. PD are small electrical sparks that occur within the stator winding as a symptom, or as a cause, of several aging processes (see below). Excessive and/or increasing PD activity over time is an indication that the motor stator winding insulation has weakened and may eventually fail, and thus maintenance intervention would be prudent.

Each partial discharge creates a current pulse that can be detected at the machine terminals [4, 5, 7]. When measuring PD during normal operation of the motor, the PD pulses can often be obscured by similar current pulses from other sources such as power system corona, power tool operation, electrostatic precipitators and/or power system PD sources. An important aspect of on-line PD detection is separating this electrical interference from the stator PD, in order to reduce the risk of false indications of stator insulation problems [4, 5, 7].

The introduction of medium voltage VS-PWM variable speed drives to the petrochemical industry has created a special challenge for on-line PD measurement. The switching impulse risetime in modern VS-PWM drives tends to be in the range of 500 – 1000 ns, with magnitudes of 1 - 2 kV (Fig. 2). This causes an additional type of "interference" with magnitudes that can be a thousand times higher than those of the PD pulses. The signal to noise ratio (-60 dB) is two orders of magnitude worse than that experienced by conventional 50/60 Hz motors in PD testing. This paper discusses the development of an on-line PD measurement system that is reasonably effective in suppressing the effect of switching impulses from the drive. First, the causes of deterioration in the stator winding, and especially in windings supplied by variable speed drives, are briefly presented.

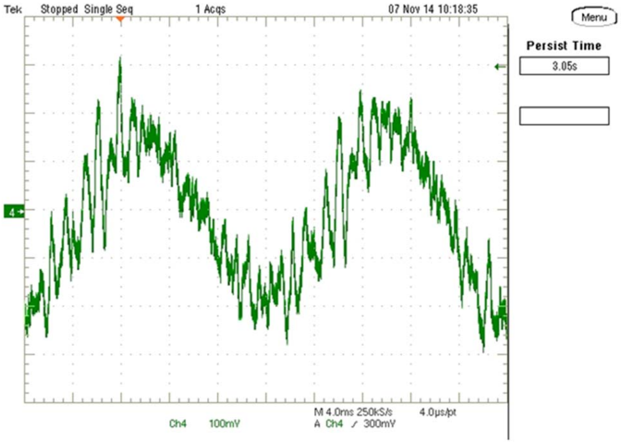


Fig. 2 Waveform of two ac voltage cycles measured at the motor terminals via a 20,000 to 1 voltage divider and filter. The fundamental frequency at the time of the measurement was about 20 Hz. The motor is rated 12.5 MW, 3 kV.

II. CAUSES OF PD IN STATOR WINDINGS

Experience over the past 20 years has indicated that PD is a symptom of several processes that gradually age and fail the stator winding insulation in conventional motors rated 6 kV and above [4, 5, 7]. In addition, certain defects in the design and manufacture of stator windings can cause significant PD to occur and may eventually break down the insulation [8]. PD will occur whenever there is a small air gap between the copper conductor in a high voltage coil and either the stator core at ground potential or coils of different potentials in the endwinding [5, 7].

Aging mechanisms that can produce an air gap and eventually lead to PD, include [7]:

1) Long term operation at temperatures above about 120°C in a Class F insulation system. After many years at such temperatures, the epoxy binding material in the groundwall loses its ability to glue the layers of mica paper tape together, leading to delamination and air-filled voids within the insulation. In high voltage coils, a sufficiently large voltage may develop across the air gap, resulting in breakdown of the air – i.e. a partial discharge.
2) Contamination of the stator endwinding by a partly conductive coating can lead to electrical tracking on the coil insulation surface. Partly conductive contamination (resistance in the megaohm range) is present when bearing oil or moisture mixes with dust (for example from cement or a chemical plant by-product), which then allows tiny currents to flow over the insulation surface. Discharges occur where the contamination has a very high resistance or gaps, leading to carbonization of the epoxy insulation.
3) Most modern motors are made using the global vacuum pressure impregnation (GVPI) process, i.e., the coils are all impregnated with epoxy after being installed in the stator core. For motors not made with this process (often large, old motors or large, rewound stators), the insulation and wedges will shrink with age, leading to coil vibration in the slot due to the 100/120 Hz electromagnetic forces. This vibration abrades the insulation as it rubs against the stator core. The air space between the coil and the stator core in line-end coils breaks down – again causing PD.

Some design and/or manufacturing problems can also lead to PD and eventual failure, including [7, 8]:

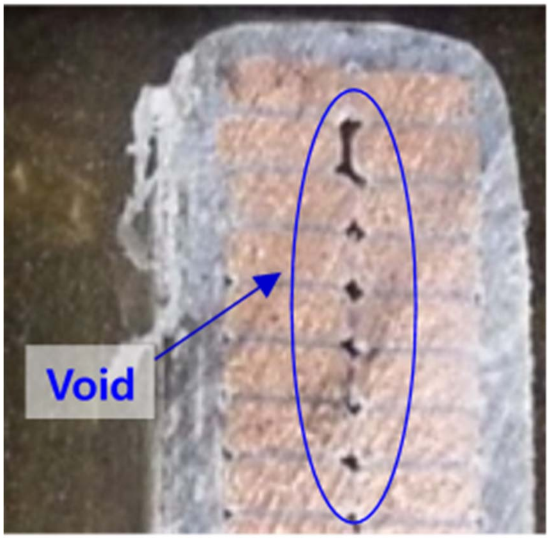
1) Insufficient space between line-end coils in the endwinding, between line-end circuit rings, or between the high voltage leads to the motor terminal box. For a 13.2 kV motor, if the air space is less than about 5 mm, PD is likely to occur in the space. After many years, the PD will bore a hole through the insulation, resulting in a ground fault or phase-to-phase fault.
2) Conventional motors rated 6 kV and above, usually have surface coatings on the coil to prevent PD between the surface of the coil and the stator core [3, 7]. The coating in the slot area is a graphite-loaded tape or paint. On the coil surface, just outside of the slot, is a paint or tape that is loaded with silicon carbide to produce a linear voltage distribution over the length of the coating in 50/60 Hz motors. If these coatings are missing, or poorly applied, surface PD (and ozone) will result. The ozone leads to nitric acid which chemically attacks virtually every material within the motor, including the bearing oil, water-cooled heat exchangers, rotor short circuit rings, and stainless steel retaining rings (if present).
3) If the epoxy resin impregnation of the coil insulation was insufficient, voids may be left between the insulation and the copper turns. In line-end coils these voids will have PD, eventually leading to winding failure.

It has become apparent with the early application of the VS-PWM drives in motors rated 3 kV and above that such drives may accelerate some of the failure processes described above. In a VS-PWM drive, the ratio of the peak voltage (V pk/pk in Fig. 1) to rms voltage is usually higher than that in a conventional motor [2, 3]. This is caused by travelling wave phenomena that result in as much as a voltage doubling due to short risetime switching transients from the drive. It is also aggravated if a reduced number of levels are used in the drive (and the trend is to use fewer levels as the switching devices become capable of handling higher voltages). Since the breakdown of an air gap is dependent on the peak voltage (not the rms voltage), the higher peak voltages from the drive make PD within any air voids more likely. Thus, groundwall voids due to poor impregnation and thermal aging will experience increased PD activity and more rapid aging, all other things being equal.

Some motors fed by VS-PWM drives have experienced turn-to-turn insulation failure due to voids within the copper conductor stack (Fig. 3a). Each short risetime voltage impulse from the drive (Vᑊ pk/pk in Fig. 1) creates a relatively high voltage across the turn insulation in the coils connected to the motor terminals [3, 7]. What is believed to have occurred to the motor in Fig. 3 is that the voltage was high enough to initiate PD in the voids that probably were created during manufacturing (such voids within the copper stack are harmless in conventional motors). The PD created by each drive impulse eventually eroded the turn insulation, leading to an inter-turn fault which rapidly progressed to a ground fault (Fig. 3b).

The most serious impact of VS-PWM drives on the stator winding seems to be the more rapid aging of the PD suppression coatings [7, 9-11]. The pulse repetition rate from the drives is up to 2000 impulses per second – a frequency 33 times higher than 60 Hz power frequency and 40 times higher than 50 Hz power frequency. In addition, the risetime of the switching transient in medium voltage drives is in the 500 - 1000 ns range. This short risetime creates Fourier frequency components in the 1 MHz range. These high frequency voltages increase the capacitive currents flowing from the copper conductor to the stress relief coatings. These significantly higher currents then flow through the resistance of the PD suppression coatings, and raise the surface temperature above normal operating conditions by as much as 40°C [9-11]. This can lead to rapid deterioration of the coatings and consequent elevated surface PD, as well as accelerate the thermal aging of the groundwall insulation. It is important to note that manufacturers can alter the PD suppression coating design so that the windings are less susceptible to this problem, if they know the motor is to be fed from a VS-PWM drive.

In all the mechanisms discussed above, PD is a symptom, and sometimes a cause, of stator winding failure. This has driven the desire for on-line PD monitoring of VSD motors, to anticipate the need for stator winding maintenance or a rewind, before motor failure occurs.



(a)

(b)

Fig. 3 (a) Voids between the turns in a coil in a motor rated 3.1 MW, 3 kV fed by a VS-PWM drive. The coil has 4 turns per coil. Fig. 3(b) shows the melted copper in the coil removed after the turn fault.

III. CHALLENGES WITH PD MEASUREMENT ON MOTORS FED BY A VS-PWM DRIVE

Three significant difficulties were experienced when research began to develop the prototype on-line PD monitoring system in 2005 [12]:

- Separating stator winding PD from the very severe switching noise produced by the drive;
- Obtaining a reliable fundamental frequency voltage waveform that can be used to synchronize the PD with the ac voltage, as it is common to display PD on a phase resolved pulse distribution graph [5];
- Changing the instrumentation to recognize ac frequencies besides 50 or 60 Hz, as the motor may be running at a wide range of speeds depending on the load at any time.

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The following discusses how each of these challenges was addressed.

A. PD Separation from Switching Transients

In most conventional motors, the PD is measured by means of capacitors connected at the motor stator winding terminals. Such PD sensors have a very high impedance to 50/60 Hz voltages, and thus attenuate the high voltage at low frequencies passing through the capacitor. In contrast, PD has a risetime of a few nanoseconds, and thus contains Fourier frequency components up to a few hundred MHz [4, 5]. A PD pulse passes through the capacitor with little modification at this high frequency. Essentially the PD capacitor, in combination with a 50 Ω load resistor is a high pass filter. For the most common PD sensor capacitance of 80 pF – frequencies below 40 MHz are attenuated with a 20 dB per decade of frequency roll-off.

Unlike conventional power frequency sources, VS-PWM drives produce large voltages at high frequencies. Fig. 2 shows the actual waveform of the voltage at the motor terminals on one phase, for a motor fed by a VS-PWM drive. As expected, there are many voltage transients on the waveform. The switching transients have a risetime of 500 to 1000 ns, and can reach 1500 – 2000 V in amplitude due to travelling wave reflections along the power cable between the motor and the drive. Thus, on the output of the capacitive PD sensors, the switching transients can result in impulses of many tens of volts, since the 1 MHz components of the transients are not suppressed as much by the high pass filter effect compared to 50/60 Hz frequencies. Fig. 4 shows the PD sensor output for a 12.5 MW motor. Many switching transients are observable on all three phases, even after the 40 MHz high pass filter. Phase 3 (3rd trace from the top in purple) indicates 15 V pulses (0 to peak) on the output of the PD sensor. This is about 30 times higher than significant PD activity. Clearly, these residual switching transients need to be strongly suppressed before on-line PD measurement can be made with confidence.

As discussed in [4], there are several possibilities to suppress noise and disturbance:

- Time-of-pulse-flight using a pair of sensors per phase,
- Filtering,
- Pulse shape analysis.

Initial investigation concentrated on employing the time-of-flight approach using two PD sensors per phase to determine if a pulse came from the drive or from the motor [4, 5]. This approach has been used successfully on more than 8000 generators to suppress false indications from PD and noise pulses that originate from other electrical equipment, such as transformers and the isolated phase bus-bars. However, since the risetime of the switching transients from a VS-PWM drive is in fact very complex, possibly due to the operation of multiple switching devices when a transition occurs, it is actually difficult to determine the precise time of “arrival” of the pulses, therefore, resulting in misclassification. This separation method was abandoned for this application.

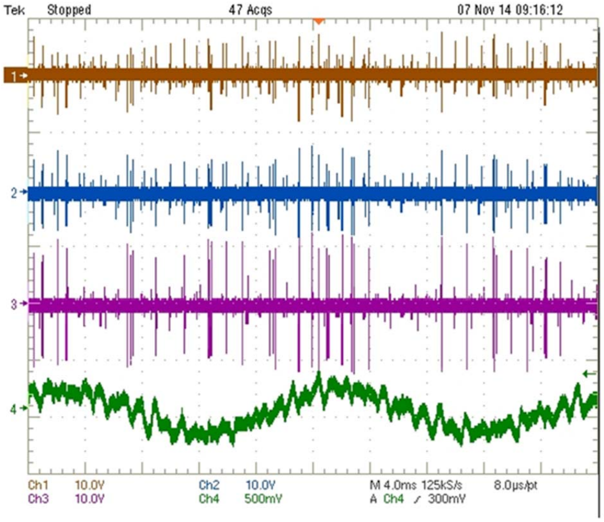

Fig. 4 Oscilloscope traces of the output of 80 pF PD sensors (top three traces, one per phase) vs. the ac fundamental voltage (bottom trace) in the 12.5 MW motor. Phase 3 is indicating 15 V pulses (0 to peak) on the output of the PD sensor.

The techniques that were more reliable for the separation of PD and switching transients were additional filtering and pulse shape analysis. The very high frequency (VHF) PD measurement method uses the frequency band 40 MHz to 350 MHz, with a 20 dB/decade roll-off below 40 MHz for noise separation [5]. Additional filtering was inserted into the PD signal with a multi-pole roll-off at selectable cut-off frequency from 500 kHz to 20 MHz. The higher cut-off frequency reduces the PD magnitude, and thus must be corrected for during interpretation of the PD results.

As described in [4], pulse shape analysis was also used to further suppress the effect of the switching noise. Pulses with a risetime longer than about 6 ns were classified as “invalid” pulse shapes, since stator PD measured at the motor terminals has a risetime shorter than 6 ns [4, 5].

B. Fundamental Frequency Voltage Reference

It is common in conventional on-line PD measurement to display PD activity with respect to the 50 or 60 Hz ac cycle. The pulse pattern gives greater assurance that the signals measured are PD (rather than noise), and can sometimes help in diagnosing the aging mechanisms. In most on-line PD measuring systems using capacitors as sensors, the ac voltage reference can be extracted from the PD sensor because a small amount of 50/60 Hz current does come through the capacitor. However, in the prototype installations involving VSDs, it was clear that a reliable fundamental frequency voltage could not be extracted from the PD sensor due to the switching transients (Fig. 2).

After several attempts, it was decided to use a capacitive voltage divider to provide the fundamental frequency reference. A capacitive voltage divider produces a fixed ratio output independent of frequency, unlike a capacitor into a 50 Ω load. Thus, high frequency transients do not dominate fundamental frequency detection. The high voltage capacitor of the divider is the conventional 80 pF capacitor that is regularly used for PD detection. A low voltage, high capacitance capacitor is connected in series to the bottom end of the high voltage capacitor to provide the required low voltage output to the test instrument. In early tests, the divider had to be installed at the drive to obtain a reliable synchronizing signal. Further refinements seem to permit the installation of the divider at the motor terminals. In the case studies below, all motors were equipped with the voltage divider.

Fig. 5 shows the schematic of the PD sensors plus capacitive voltage divider installed on a drive system.

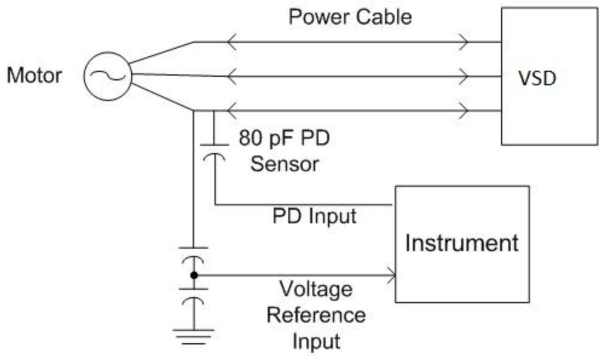

Fig. 5 Schematic of the PD monitoring system intended for drives.

C. Synchronizing to a Variable Fundamental Frequency

Variable speed drives produce an output voltage and current that is variable over a wide range of frequencies. Conventional PD instrumentation uses narrow band pass filters at 50 and 60 Hz to eliminate the power frequency harmonics, combined with a voltage zero crossing detector to synchronize the PD to the ac cycle. This conventional circuitry was modified with a wider band pass frequency range so that it could align the PD with respect to the ac waveform over a fundamental frequency range of 25 Hz to 100 Hz.

IV. PRACTICAL REALIZATION

The first on-line PD measurement system on a VS-PWM type of drive was installed at a Liquefied Natural Gas (LNG) compressor plant in the Middle East in 2007. Since then, similar but improved systems have been installed on dozens of LNG compressor motors in the Middle East and Australia, as well as petrochemical plant motors in the USA and Singapore. Fig. 6 shows the installation of the sensors plus divider in the terminal box of a 4000 HP motor fed by a VS-PWM drive.

A purpose-built portable instrument was developed to measure the pulses, separate the PD from the switching transients as described above, determine the fundamental frequency from the voltage divider and display the resulting pulses with respect to the ac voltage. The data is then stored on a laptop computer like any ordinary PD test data.

Early results showed that the separation of PD from the switching transients was not perfect. Thus, to date, a continuous on-line PD monitor does not seem practical because there would be too high a risk of false indications of high stator PD, when in reality the recorded signals may be interference from the drive. Furthermore, many aborted measurements may be recorded when the continuous monitor cannot synchronize to a fluctuating ac reference voltage during speed changing. Work is continuing in this area.

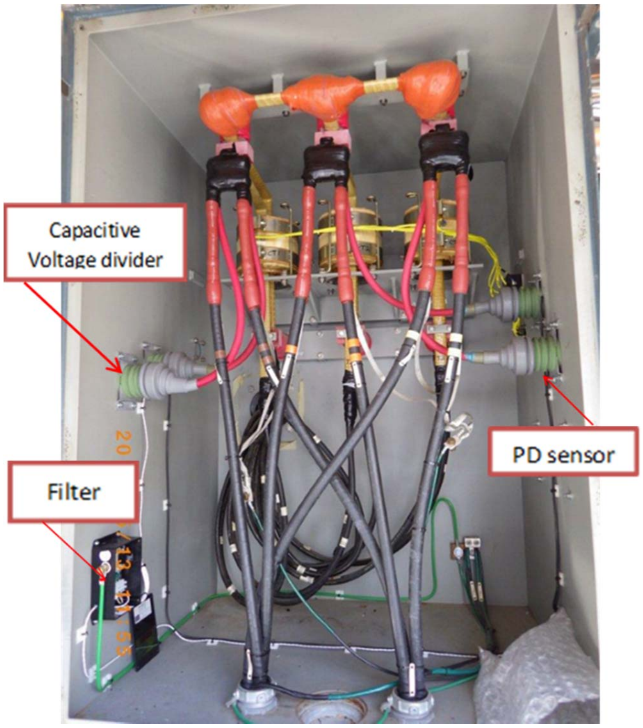

Fig. 6 Photograph of the installation of the three PD sensors (one per phase) and a capacitive voltage divider (all rated 6.9 kV) that provides a fundamental frequency voltage reference. The sensors are installed in the motor terminal box of a 4000 HP, 4.1 kV motor fed by a VS-PWM VSD.

V. PD RESULTS

Data has been collected from many VS-PWM motors with the new PD measurement system. An example of the successful collection of stator winding PD data is shown in Fig. 7. This plot shows a classic PD pattern with respect to the ac cycle, that is, the positive PD occurs in the 180° to 270° quadrant of the ac cycle, and negative PD is occurring in the 0° to 90° quadrant of the ac cycle. In this case, the positive PD pulses are both higher and more numerous than the negative PD. Such a pattern is typical of PD at the stress relief coatings on the surface of coils operating at high voltage [13]. As described above, this problem is more likely with VS-PWM drive motors. The higher the PD, generally, the more aged the insulation [5], and thus the greater need for maintenance. In comparison to a PD database using 80 pF PD sensors in conventional air-cooled machines, the peak PD magnitude measured on this machine is about 250 mV, which is well below the Alert level of 350 mV established for conventional motors rated at 6-9 kV [4].

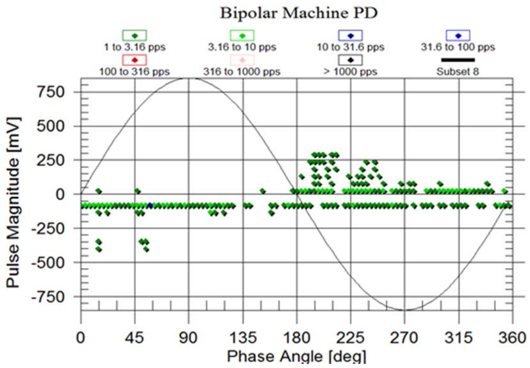

Fig. 7 PD pattern from one phase of a 45 MW, 7.2 kV motor fed by a VS-PWM drive. The vertical scale is the positive and negative PD magnitude. The horizontal scale is the ac phase position of the fundamental frequency voltage. The color of the dots indicates the number of PD pulses per second.

Fig. 8 shows an example from a new motor that seems to have little PD activity. Both positive and negative pulses are scattered across the ac cycle, with a peak magnitude of 150 mV or so. The Alert level for a 3 kV motor is about 240 mV, so the stator winding of this motor seems to be well-made and is not yet suffering aging.

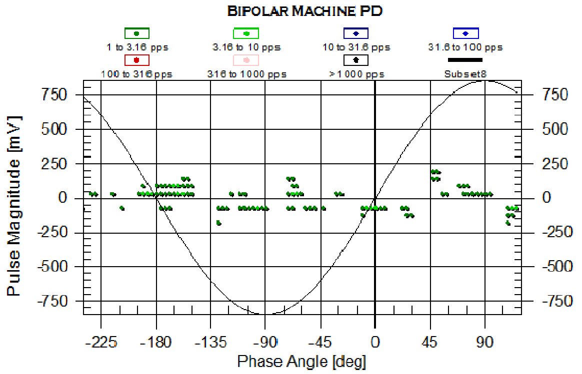

Fig. 8 PD pattern on one phase of a 12.5 MW, 3 kV motor. Very little PD is detected on this new winding.

Fig. 9 shows recent data from a 4.1 kV motor fed by a VS-PWM drive. The pattern is extremely complex. Initially it does not appear to be PD due to the unusual polarity and phase relationships with respect to the fundamental frequency. However, it is possible that this pattern could be associated with PD in air gaps between the turns – although this has not been verified.

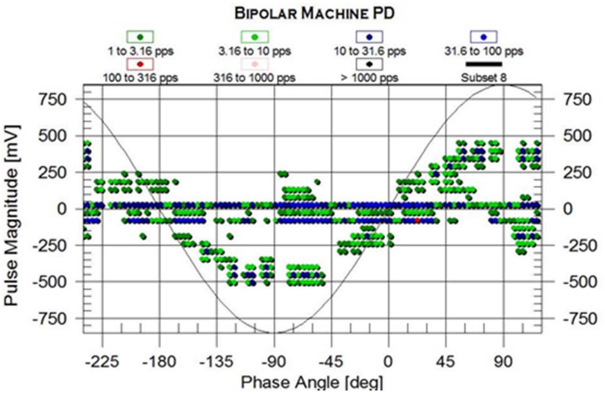

Fig. 9 PD pattern from a 4000 HP, 4.1 kV motor (the measurement system is shown in Fig. 6). The pattern is complex and does not show the typical PD pattern.

As mentioned in Section II, short risetime switching impulses can produce relatively high voltages between the turns, depending on the impulse risetime and the coil design. The high inter-turn voltages from the drive may cause any voids between turns to break down, creating inter-turn PD. The PD can occur both on the rising and falling edges of the switching transients, creating both positive and negative PD in the same half cycle. Such PD could occur across the ac cycle, since the PWM drive is switching over the entire ac cycle (Fig. 1). If the pulses in Fig. 9 are PD, the signal magnitudes are high compared to the Alert level of 240 mV for a 4.1 kV machine. Alternatively, the pulses may be residue from the switching transients that were not effectively suppressed. Unfortunately, the source of the pulses cannot be identified until either a turn fault occurs on this stator, or a dissection of the line-end coils can be performed. This motor is not likely to be available for examination for a long time.

VI. CONCLUSIONS

A method has been demonstrated to measure the stator winding PD during normal operation of medium voltage motors fed from voltage-source, pulse-width-modulated variable-speed drives. This ability to measure PD on-line is useful to detect not only the normal aging processes in stator windings, but also to detect some aging processes that can be accelerated in such variable speed applications.

VII. ACKNOWLEDGMENTS

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IX. VITAE

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