Review of Stator Insulation Problems in Medium Voltage Motors Fed from Voltage Source PWM Drives

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Abstract— **In the past 10 years, motors rated 3.3 kV and above are increasingly being fed from voltage source, pulse width modulated converters to control motor speed and power output. Such converters produce short risetime voltage impulses that can accelerate the aging of the stator winding turn insulation, mainwall insulation and the surface electric stress relief coatings. This paper reviews the mechanisms that may lead to this premature aging, and outlines the status in developing IEC voltage endurance tests which enable motor manufacturers to design insulation systems that reduce the rate of deterioration by such drives. Experience with an on-line partial discharge monitoring system to detect premature stator winding insulation degradation in 45 MW natural gas compressor motors is summarized.**

Keywords: Variable Speed Drives, Stator Insulation, Impulse Aging

I. INTRODUCTION

There are several different ways to implement variable speed motors. Electronic drives, which consist of a rectifier and an inverter, can generate the AC voltage of variable fundamental frequency. Common inverter types include: load-commutated inverter (LCI), cyclo-converter, current source-pulse width modulated (CS-PWM) and the voltage source-pulse width modulated (VS-PWM). It seems that the only type of inverter drive that has a significant impact on the stator winding insulation system of the motors is the VS-PWM type.

In the early 1990s, it was noted that VS-PWM drives often caused premature failure of the insulation in conventional random-wound motor stators rated 440 to 690 V [1]. Several researchers identified the root cause to be partial discharges (PD) due to the relatively high magnitude, short risetime voltage impulses from the VS-PWM drive. As a result, IEC developed a new technical specification that required low voltage motor stator windings to be PD-free up to the highest expected impulse voltage from the drive [2].

In the past 10 years, VS-PWM drives rated 2.4 kV and above have been introduced to the market, and are becoming more popular in marine and industrial applications. It is now clear that the stator windings of these medium- and high-voltage motors can also suffer from premature insulation aging. This is in contrast with what was originally expected from such drives [3]. Again, the cause of the premature aging seems to be the voltage impulses from the drives.

Medium- and high-voltage VS-PWM drives usually consist of several cascaded lower voltage levels to produce the overall high voltage. Fig. 1 shows a schematic of the voltage output from a three level drive [3]. Drives rated up to 13.2 kV may have up to 11 levels. The typical DC bus voltage is around 1500 V (although as IGBT switching devices improve, the voltage will likely increase, and there will be fewer levels in the drive). When switched on or off, the switching device sends a short risetime voltage impulse from the drive to the motor through the power cable. Under worse case conditions, there may be voltage doubling of the impulse due to the surge impedance mismatch between the power cable and the motor winding, resulting in a 3000 V impulse [4]. The typical IGBT switching device can produce risetimes of 50 to 100 ns. However, most schemes to cascade the switching blocks to achieve the full rated voltage result in the risetime becoming significantly longer, and risetimes from 500 to 1000 ns have been measured, although shorter risetime impulses can be expected in future drive topologies [5]. The result is that a worst case 500 ns, 3000 V impulse appears at the motor terminals. The repetition rate of the impulses is typically 1 or 2 kHz, but again this is expected to increase in the future.

It seems that the voltage impulses from VS-PWM drives can lead to several different types of premature aging of the stator winding insulation system in medium- and high-voltage motors. This paper describes these processes, as they are currently understood. It also describes the development of an IEC technical specification that enables motor manufacturers to qualify their stator winding. Finally, on-line methods of detecting insulation deterioration caused by the drives is briefly presented.

II. AGING PROCESSES CAUSED BY VS-PWM DRIVES

Unlike with low-voltage random-wound stators where PD between turns was the only major factor in premature failure due to VS-PWM drives, such drives may result in four different aging processes in medium- and high-voltage stator windings [6]. Each is discussed below.

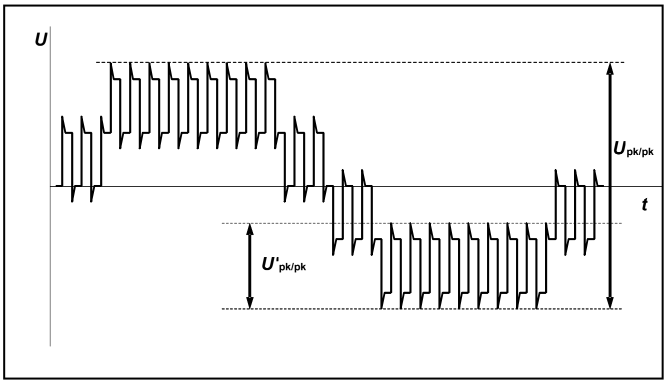

Figure 1: Stylized image of the voltage from one fundamental cycle from a 3 level VS-PWM inverter (from [4]).

A. PD Between Turns

In low-voltage motors, a 100 ns risetime voltage impulse will have high frequency components that cause most of the applied voltage at the motor terminals to be applied across the first few turns in the line end coils [7]. This results in a high electric field between these turns that results in PD between turns if there are voids adjacent to the turn insulation. In medium- and high-voltage drives, the step change in the voltage is about the same as for low-voltage drives, however, the risetime is significantly longer (500 – 1000 ns). This results in lower frequency components and thus a lower percentage of the terminal impulse voltage will occur across the turns in the line end coils. This reduces the risk of PD. However, even in the event PD does occur, most motor manufacturers will use a PD resistant mica paper turn insulation if they are aware that the motor will be used in a VS-PWM application.

B. PD Within the Mainwall Insulation

The peak-to-peak phase-to-ground voltage ($U_{pk/pk}$ in Fig. 1) is usually much higher than the peak-to-peak voltage from a 50/60 Hz voltage. Since PD is initiated by the peak voltage (not the rms voltage), the higher peak voltage is likely to stimulate more PD pulses of higher magnitude in the mainwall insulation than in an equivalent conventional (sinusoidal voltage) motor. If there are significant voids within the groundwall, then this may result in earlier failure from VS-PWM drives, especially with drives that have fewer levels.

C. Dielectric Heating of the Mainwall Insulation

It is well known that as the AC frequency increases, most solid dielectrics will exhibit higher dielectric loss. Since the switching frequency is 1-2 kHz, this is a 20-40 times increase in frequency. The associated dielectric loss will be in addition to the dielectric loss at the fundamental frequency. The result is that all other things being equal, the stator winding will operate at a higher temperature due to the additional dielectric losses from the voltage impulses from the drive. This increase in temperature may accelerate the thermal aging of the mainwall insulation if the stator winding is designed to operate at above 120°C when supplied from a fixed frequency power source.

D. Stress Relief Coating Degradation due to High Temperature

Most conventional motors rated 6 kV and above have a graphite coating on the surface of the coils in the slot area, and a silicon carbide semiconductive coating extending beyond the slot by 10 – 15 cm or so (Fig. 2). The purpose is to suppress PD between the surface of the coil and the ends of the stator slots. Several studies [8, 9] have shown that, with a pulsed power supply, the stress relief coatings outside of the slot have a tendency to overheat, presumably due to the higher capacitive currents that must flow through the stress relief coatings (Fig. 2). The temperature at the surface has been measured as raising the temperature at the coil surface by as much as 50°C [9]. This temperature rise, on top of the temperature rise due to I^2R losses in the conductors, may yield hotspot temperatures in excess of 150°C. This will rapidly thermally age the stress relief coatings as well as the adjacent mainwall insulation.

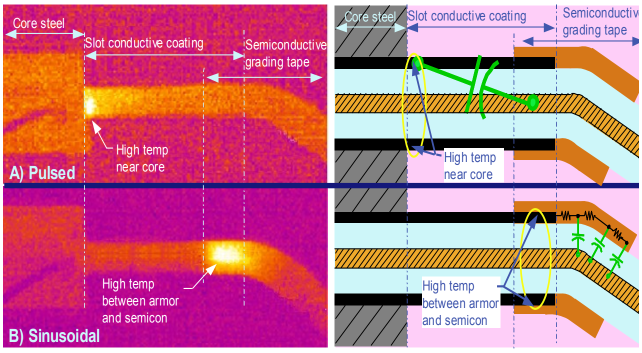

Figure 2: Thermal image of endwinding stress grading under A) pulsed, and B) sinusoidal conditions with accompanying electrical equivalent circuit on the right. The left thermal images are from [8]. Under sinusoidal conditions the current flows through the capacitance of the mainwall insulation and then through the resistance of the semiconductive grading tape and then onto ground via the slot coating. Under impulse conditions, the lower impedance path is directly through the mainwall capacitance to the slot conductive coating.

Experience shows that the stress relief coating can quickly degrade and fail to suppress the surface PD. This results in ozone (in air-cooled machines) that further exacerbates the situation.

III. IEC TS 60034-18-42

Anecdotal evidence from operating medium-voltage motors fed by VS-PWM drives suggests that unless the winding insulation system has been adequately designed, premature insulation system failure occurs. One way of addressing the issue is to design an insulation system for motors fed by VS-PWM drives as if it is operating at one voltage class higher. For example, a motor with a nominal voltage rating of 6.6 kV could have an 11 kV insulation system. This may be effective, but it may be wasteful, resulting in unnecessarily thick mainwall insulation and excessive endwinding clearances between coils and to ground.

Alternatively, the insulation system could be specifically designed for inverter duty operation using aging tests to ensure that the turn insulation, mainwall insulation and the stress relief coating system will survive the impulse voltages expected. To this end, a working group of the IEC has developed a series of voltage endurance tests that can be performed to qualify the insulation system components [4]. When developing the technical specification it became clear that a single accelerated aging test would not easily duplicate the four aging processes described above, since a very expensive impulse power supply would be needed. Instead, three separate voltage endurance tests were developed:

- A turn insulation test where either impulse or sinusoidal overvoltages are applied to a model of the turn insulation system. Usually three different test voltages are used to create a life line.
- The mainwall insulation of a model coil, similar to a formette, is subject to sinusoidal or impulse voltages. Usually three different test voltages are used to create a life line.
- A model coil with the prospective stress relief system is subject to impulse voltages (usually three different levels).

When sinusoidal voltages are used, correction has to be made between the frequency of the AC and the repetition rate of the impulses expected in-service using the inverse frequency relationship [7]. The voltage is increased enough to result in failure in a few hundred to a few thousand hours. The voltage endurance test in IEC TS 60034-18-42 is a comparison test. Thus, the life line from any prospective design is compared against the life line from a "proven" system. This is the weakness in comparison approach, since some believe there is insufficient experience with existing insulation systems for VS-PWM drives to know if they are service-proven.

IV. In-Service Detection of Stator Insulation Problems

Two of the four mechanisms described above are the direct result of PD occurring within the mainwall insulation or between the turns. The other two mechanisms: increased dielectric loss and overheating of the stress relief coatings; lead to more rapid thermal aging and the production of voids within the insulation or destruction of stress relief coatings, and hence to PD. As a result, PD testing should detect the degradation caused by the drive. There are three methods to detect the PD:

- Ozone monitoring
- Off-line PD testing
- On-line PD monitoring.

On-line ozone gas monitoring can detect the surface PD that is associated with deterioration of the stress relief coatings. Electronic ozone detectors are now economical and relatively easily installed [7]. Unfortunately, they cannot detect PD occurring in the turn insulation or within the mainwall insulation.

Conventional off-line PD testing according to IEC 60034-27 can detect three of the aging mechanisms. However, since conventional testing uses a 50/60 Hz power supply, PD between the turns will not be detectable since there will be insufficient turn-to-turn voltage. Although in principle a 500 – 1000 ns risetime voltage impulse can be applied to the winding, detecting the PD in the presence of the high frequency components from the impulse supply may be difficult.

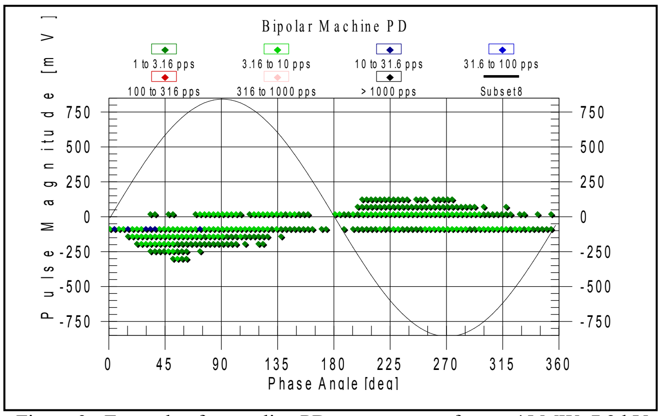

Figure 3: Example of an on-line PD measurement from a 45 MW, 7.2 kV motor fed by a VS-PWM drive

On-line PD testing, when the motor is connected to the drive, would detect the PD from all four types of aging mechanisms. However, the detection of the PD is more complicated than with 50/60 Hz sinusoidal on-line PD testing due to the presence of the high frequency components of the several thousand volt 500-1000 ns risetime voltage impulses. These impulses will generate large voltages up to 1 MHz or so, and can easily dominate the relatively small PD pulse magnitudes. Over the past several years, a practical on-line PD measuring system for VS-PWM drives rated 2.4 to 13.8 kV has been developed. It is based on a well-established PD test that works in the very high frequency (30-300 MHz) range using 80 pF PD detection capacitors on the phase terminals of the motor [10]. Two modifications were found to be necessary [5]. One was the addition of a multi-pole high pass filter with a 10 MHz lower cutoff to the PD sensors, to strongly suppress the residual of the drive voltage impulses. In addition, a capacitive voltage divider was needed to obtain a fundamental frequency AC voltage reference, required to place the PD with respect to the AC cycle. The divider was necessary since the distortion from the drive was so high, the normal AC cycle phase reference from the PD sensor was not able to trigger reliably. Fig. 3 shows the PD detected on a 45 MW, 7.2 kV motor fed by a VS –PWM drive. The PD has the typical characteristics of PD, and the residual from the drive impulses has been successfully reduced. Using experience from conventional motors, the peak magnitude of the PD (about 300 mV on this motor phase), is moderate [10].

V. Conclusion

VS-PWM drives in the medium- and high-voltage ranges can cause more rapid deterioration of the stator insulation than would be expected from similarly rated 50/60 Hz conventional motors. It seems that the most aggressive of the new deterioration processes resulting from the drive voltage impulses is the accelerated aging of the stress relief coatings. One way for motor designers to reduce the risk of premature failure is to use an insulation system that is rated for a higher voltage. Alternatively, the motor designer can design each insulation component and perform voltage endurance tests on the components to ensure long life. This is the intent of IEC 60034-18-42. Users can detect if any of the new failure processes is occurring using modified on-line PD testing.

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