IEC STANDARDS FOR VARIABLE SPEED DRIVES AND MOTOR WINDING INSULATION

Paper No. PCIC Middle-East 2014-08

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Abstract - Modern inverter-fed motors often see short risetime, high magnitude voltage surges that may lead to partial discharge. Fast risetime transients from the drive, as well as possible voltage doubling caused by transmission line impedance mismatches, can result in partial discharges (PD) in the motor stator winding even in low voltage motors. Testing for such conditions is described in IEC TS 60034-18-41 [1] which indicates that the manufacturer must prove the motor will not have PD for the expected life of the motor and sets PD inception voltage limits, based on severity of the surge environment. Medium- and high-voltage motors may also suffer from this type of inverter – specifically the stress relief coatings may age prematurely. IEC 60034-18-42 [2] provides tests that motor manufacturers can perform to ensure that such premature failure will not occur. This paper describes these two standards and comments on their effectiveness.

Index Terms — Variable speed drive, Motor qualification, partial discharge.

I. INTRODUCTION

NEMA MG-1 Part 31 was an early standard concerning variable speed drive (VSD) motors and requires low-voltage (<600 V) inverter-duty motor windings to survive a voltage impulse test with a magnitude 3.1 times the rated phase-to-phase voltage. More recently, there has been some recognition that the short-time impulse test will not always insure a satisfactory winding insulation life, at least for low-voltage VSD motors [3, 4, 5]. Part 31 also requires medium-voltage (>600 V) motors to survive an impulse test at 2.04 times the rated phase-to-phase voltage. Form-wound coils are often tested according to [6], where the requirement of the test is an applied impulse with a crest value equal to 3.5 times the peak line-to-ground voltage. Another IEC document [7] discusses motor insulation electrical stresses in detail. It provides a curve of expected impulse voltage at motor terminals and suggests applying motors within that limit. However, in all these cases, tests deal more with short term withstand rather than assuring satisfactory insulation life.

To fill this gap, IEC Technical Committee (TC) 2 on Rotating Machines initiated a working group to develop a technical specification defining insulation tests to assure design suitability for operation with a modern (fast switching 50-2000nS rise-time) VSD inverter. These standards define a collection of tests for both low- and medium-voltage motors (up to 7.5 kV). IEC 60034-18-41 covers Type I insulation systems (typically random-wound stators), while the IEC 60034-18-42 document covers Type II insulation (typically form-wound coils).

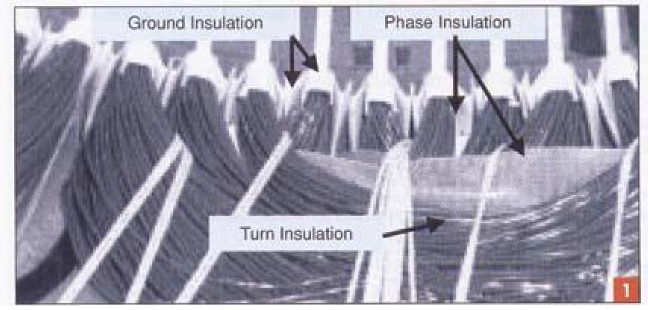
II. STRESSES ON VSD MOTOR INSULATION

Reliability of the stator insulation system is the principal concern of both VSD motor manufacturers and users. The insulation systems in question are the turn-to-turn, phase-to-ground, and phase-to-phase insulation. As these insulation systems are different for random-wound and form-wound stators, there are separate standards for each.

A. Random-Wound Motor Stators

Fig. 1 shows the components of the winding insulation system in a random-wound stator, which usually apply to motors rated <1,000 V (Type I machines). Pulse Width Modulation (PWM) inverters using insulated gate bipolar transistors (IGBTs) or similar switching devices create relatively high magnitude, short-rise-time voltage impulses that travel to the motor terminals. Many factors such as cable length, cable grounding, and the relative surge impedance of the cable and the stator winding affect the magnitude of the impulse voltages impinging on the motor winding. In some circumstances, these surges can be as much as three or four times the rated, rms phase-to-ground voltage, with a risetime as short as 50 ns [5, 8]. These fast risetime surges result in a non-uniform distribution of the impulse voltage across the winding components [7 to 10] with the turns in the first coil seeing much higher stress than the rest of the winding. The severity of the VSD impulses increases as either the magnitude increases or the risetime decreases. In random-wound stators, there are often small air gaps between turns, between turn and ground, and between phases. The high voltage impulses, although brief, can cause the electrical stress in the normally occurring small air gaps between turns, between turns and ground, and between phases. If this stress exceeds the dielectric breakdown strength of air (about 3 kV/mm for uniform fields) a partial discharge (PD) - or small electric spark will occur. Over time, repetitive PD will erode the insulation film on the magnet wire, or even the ground and phase insulation barriers eventually failing the motor.

Machine designers recognizing this issue have developed many ways to prevent the occurrence of PD in random-wound stator windings. These include increasing the insulation thickness of the magnet wire and/or the ground and phase insulation; improved varnish impregnation methods such as trickle impregnation, vacuum pressure impregnation (VPI); and other processes to reduce the number and size of voids. The intent of the IEC standard is to specify test methods that assure a given stator insulation design can prevent formation of PD in new windings and continue to suppress PD throughout the life of the motor (Type I insulation).



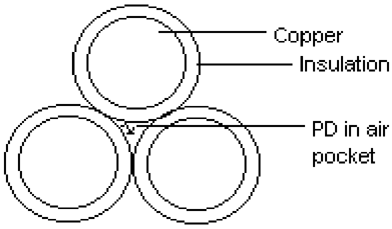


Fig. 1 Magnet wire at high stress in air voids

B. Form-Wound Motor Stators

Unlike random-wound systems, in form-wound coils the turns always occupy a defined location within the coil. These machines generally operate at higher rated voltages (>690 V) and, because they may experience PD within their lifetime, are defined by IEC 60034-18-42 as Type II. The principal characteristic of Type II insulation systems is the use of inorganic filler [11] and micaceous materials treated with VPI and/or resin-rich pressing operations to minimize voids and resist degradation by PD. Fig. 2 shows an example of a form-wound coil cross section. The most significant factors associated with aging of such insulation in VSD machines are PD imposed by voltage overshoots on each applied impulse, dielectric heating of phase-to-ground insulation, and heating of the corona protection materials caused by the higher frequencies. If the risetime of the repetitive voltage impulse appearing at the motor terminals is <500 ns, the turn insulation may be affected by the PD fatigue mechanism.

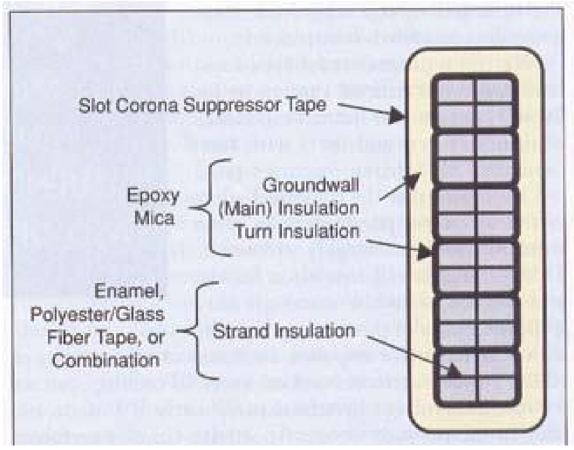


Fig. 2 Example of slot exit insulation system cross-section

C. Aging Mechanisms

As described above, Type I systems should experience no PD during their service lifetime. In these systems, the aging mechanism is thermo-mechanical rather than electrical. For this reason, test objects constructed to represent the insulation system are subjected to aging by heat, agitation, and humidity, followed by a PD test [12, 13]. Type II systems as expected to experience PD during normal service thus their principal aging mechanism is considered to be electrical in nature. They are normally form-wound, employing micaceous insulation to combat the long-term effects of PD. Form-wound systems rated >3 kV will also generally include semiconductive materials for in-slot partial discharge suppression and may have high-voltage endwinding stress grading.

D. Stress Categories for VSDs

There are any number of different types and designs of VSD systems which will continue to evolve with power electronic developments. The wave shape from the inverter can be described by three principal parameters: impulse repetition frequency, peak impulse voltage, and impulse risetime. In the Standards, for Type I systems, the risetime and magnitude are classified into four categories: *benign, moderate, severe, or extreme.* The Type I stress category severity increases with voltage impulse magnitude as the risetime of the wave front of each impulse decreases. The individual and combined effects of varying each of these factors are extremely difficult to define, particularly when the myriad of coil designs and material combinations available are considered. For this reason, the Type I risetime and voltage magnitude categories are considered independently.

For Type II systems, the limited experience of manufacturers and users with fast-switching VSD-driven machines rated >6 kV means that the combined effect of the waveform parameters on these windings remains largely unknown. Increased switching rates of IGBT power electronics and advances in cooling systems for medium-voltage inverters, particularly

PWM drives, lead to increasingly severe (short-rise-time) waveforms arriving at the motor terminals. The characteristics of system aging under these conditions are not fully understood and thus the waveform applied to Type II insulation systems cannot be assigned a specific stress category as they are in Type 1. The technical specification encourages open communication between the purchaser of the drive system, the inverter designer, and the motor designer to permit definition of appropriate qualification and acceptance tests.

III. TESTING

For the purpose of IEC 60034-18-41 and IEC 60034-18-42, the term "impulse" refers to a voltage transient from a VSD or a special high-voltage "surge" tester. PD in a winding creates low-voltage pulses in response to the applied "impulse." For these technical specifications, a term called the repetitive partial discharge inception voltage (RPDIV) is defined as the lowest impulse voltage at which PD can be detected on most impulses when the voltage is raised gradually from zero. The RPDIV is measured according to the procedures described in another IEC document, IEC 61934 TS [16]. Testing for both Type I and Type II systems consists of qualification and acceptance rests. Qualification tests are used to prove a given combination of insulating materials and processing technique. Acceptance tests are performed for completed motors or coil sees on a per-design basis.

A. Type I Tests

1) *Qualification Test:* The premise for Type I insulation systems is that PD will not occur at any time during the expected life of the stator winding. If PD does occur, the expectation is that deterioration and failure will be relatively rapid. Thus, each design first needs to be evaluated to determine its RPDIV when new and after simulated aging. To determine if PD due to VSD transients would occur during the expected life of a motor, IEC 60034-18-41 requires that the RPDIV be measured during an accelerated aging test. It also recommends the accelerated aging test method be the same as those described in [12] (for random-wound machines) or [14] (for form-wound machines). The aging consists of exposing special test coils (in motorettes or formettes) to repetitive cycles of heating, vibration, and humidity, followed by a short voltage withstand test. For qualification as a Type I insulation system for an inverter duty application, the RPDIV measured after each aging cycle must remain above the levels shown in Table 1 plus a 30% safety factor for the aging cycle required for the thermal class. Detection of PD at any point during the qualification test of a Type I insulation system constitutes failure. Phase-to-phase and phase-to-ground insulation can be tested separately. In the first case, the voltage is applied between pairs of phases, with the neutral ends floating. In the phase-to-ground test (which also serves as a turn insulation test), the impulse is applied to one phase with the neutral grounded.

2) *Acceptance Test:* To ensure that a stator winding is manufactured according to design, at least one stator from a production lot must have an RPDIV that exceeds the level for the stress category indicated in Table 1 plus a 30% safety factor. Table 2 shows these rest voltages for a 460 V motor. This test must be done using impulse voltages from a surge generator.

TABLE 1
RPDIV MEASURED WITH A SURGE TESTER FOR A 480 V RATED MOTOR STATOR FED FROM A TWO-LEVEL INVERTER

Stress Category	Peak V/DC Bus	RPDIV ($V_{p\text{-}p}$)		
		Phase-Phase	Phase-Ground	Turn-Turn
Benign	1.1	1853	1297	1297
Moderate	1.5	2527	1769	1769
Severe	2.0	3370	2359	2359
Extreme	2.5	4212	2948	2948

TABLE 2
EXAMPLE OF MINIMUM IMPULSE RPDIV FOR A 460 v RATED MOTOR FED BY A TWO-LEVEL CONVERTER

Voltage Category	Overshoot Factor (V_p/V_{ac})	Phase-Phase (V)*	Phase-Ground or Turn-Turn (V)*
Benign	1.1	1771	1240
Moderate	1.5	2416	1691
Severe	2.0	3221	2255
Extreme	2.5	4027	2818

*These voltages are measured from zero to peak with a conventional surge generator which converts a fast risetime and slow decay time impulse.

B. Type II Tests

1) *Qualification Test:* Qualification tests described by the proposed 60034-18-42 Technical Specification ensure a sufficiently robust insulation system design for the requirements of its specified waveform. The expected waveform is defined by the inverter designer. The test qualifies the materials and processes used to build the insulation system and provides a relationship between service stresses and insulation life for that particular configuration. The test endpoint is defined by the elapsed time to electrical breakdown of the insulation under the specified waveform conditions. Stress to each component of the insulation is separately tested. Thus, each of the insulation system components (turn-to-turn, phase-to-ground, and stress grading materials) must withstand a voltage endurance test. The mainwall insulation tests require only a sinusoidal 50/60-Hz applied voltage waveform. Under most circumstances, the grading material and turn insulation require aging under impulse conditions.

2) *Turn-to-Turn Insulation:* Test samples are made solely to represent the insulation between turns. They must be constructed from the same materials and dimensions as those used for the machine's insulation system. Aging tests of the turn insulation are conducted under impulse conditions and compared to a proven system.

3) *Mainwall Insulation:* For voltage ratings where stress grading is not required by design, the test purpose is to obtain a life curve for the mainwall insulation using elevated voltage. In effect, this amounts to a simple room or elevated temperature voltage endurance test, usually under sinusoidal 50/60

Hz. A curve is constructed from test points for life at three different voltages at a given frequency. The inverse frequency rule [15] is applied by multiplying the ratio of frequencies to the lifetime obtained at a power frequency for a given voltage. In a form-wound coil insulation system, the main insulation, stress grading, and corona protection materials interact under the applied stress. Samples must represent the design features of production coils and are fitted into fixtures representing slots and subjected to aging tests under impulse voltage conditions. The specific combination of stress grading and corona suppression materials must survive a minimum lifetime under the specified conditions, both at room temperature and at their thermal class limit minus 30°C. This takes into account the local temperature elevation associated with dielectric thermal losses at the stress grading which is common in VSD applications.

4) *Acceptance Test:* Windings must meet a minimum lifetime requirement on voltage endurance. The applied waveform is sinusoidal 50/60 Hz, with voltage magnitude equal to 2.5 times the rated peak-to-peak voltage at the motor terminals under the specified inverter operating conditions. Any single failure within a given test set occurring before the minimum time constitutes failure of the entire sample set.

IV. CONCLUSIONS

Currently, there is no internationally accepted means by which to define inverter duty insulation systems. The desire for energy economy means that more and more industrial and utility applications call for the use of very advanced power supply devices such as PWMs. Technical Specifications IEC 60034-18-41 and IEC 60034-18-42 are the first complete documents to define criteria for evaluating rotating machine insulation for use with inverters. The state to the art is constantly changing. Inverter drive designers are employing higher voltages and faster switching devices with steeper wave fronts. Technical information exchange between the inverter drive designers and the motor insulation designer will continue to be important. Further technical development may be necessary to facilitate online PD measurements on VSD fed motors. As insulation systems evolve, some of the category options may not be applicable.

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