NEW SPECS FOR ASD MOTORS

EXPLORING THE IEC 60034-18-41 AND IEC 60034-18-42 TECHNICAL SPECIFICATIONS FOR INVERTER DUTY MOTOR INSULATION

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SQUIRREL CAGE INDUCTION MOTORS WITH MODERN adjustable-speed drives (ASDs) are now pervasive for motors rated <1,000 V. Medium-voltage induction and synchronous motors with rated power-frequency voltage up to 7.2 kV are now increasingly fitted with pulse-width modulated (PWM) ASDs. As widely discussed in the literature [21-[5], applying PWM-type inverters to motors may create special problems, including:

- higher winding temperature due to reduced cooling at lower speeds or heating due to harmonic currents
- bearing damage due to induced voltages on the rotor
- stress concentration at slot exits and at junctions between stress
grading and corona pi-erection materials
- winding insulation aging due to .: 11 .' discharge and/or dielectric

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heating, often intensified between turns as well as across the mainwall of the stator coils.

This article is concerned with the last two issues.

The vast majority of motors fitted with ASDs operate reliably. Unfortunately, some premature failures have occurred due to the extra stresses that an ASD may impose on the motor. To ensure that a motor can withstand the extra stresses associated with these applications, standards organizations such as National Electrical Manufacturer's Association (NEMA) and International Electro-Technical Commission (IEC) are developing technical specifications to ensure that motors will operate satisfactorily in ASD applications.

Some of the first standards concerned with ASD motors were NEMA MG 1 Parts 30 and 31 [1]. In particular. Part 31 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 (Vrated). Recently, there has been some recognition that the short-time impulse test at 3.1 x Vrated '""ay not always insure a satisfactory winding insulation life, at least for low-voltage ASD motors [5], [7], [8]. Part 31 also requires medium-voltage (>600 V) motors to survive an impulse test at 2.04xVrated.

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 (2.9 x Vrated). Another IEC document [10] 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, as with [I], motor testing is not sufficiently defined to assure satisfactory insulation life. It is important to note that while these specifications provide methods for determining short-term withstand test limits, they do not consider the high-cycle fatigue conditions experienced by the stator winding under ASD operation.

In 2002, the IEC Technical Committee (TC) 2 on Rotating Machines initiated a working group to develop a technical specification defining insulation rests to assure design suitability for operation with a modern ASD inverter. Over the past four years, the working group has developed a collection of tests for low- and medium-voltage motors. The technical specifications describe the qualification and acceptance tests proposed for both low- and medium-voltage (up to 7.2 kV) motor windings intended for ASD operation.

During 2005, the technical specification was separated into two parts: IEC 60034-18-41 covers Type I insulation systems, while the IEC 60034-18-42 document covers Type II insulation. This article was originally presented at the 2005 Petroleum and Chemical Industry Conference, 12-14 September 2005, Denver, Colorado.

The technical specifications have since undergone changes. IEC 60034-18-41 has been approved by national committee ballot, and its publication is expected in 2007. IEC 60034-18-42 is a draft document and the current focus of the working group.

Challenges for ASD Motor Insulation

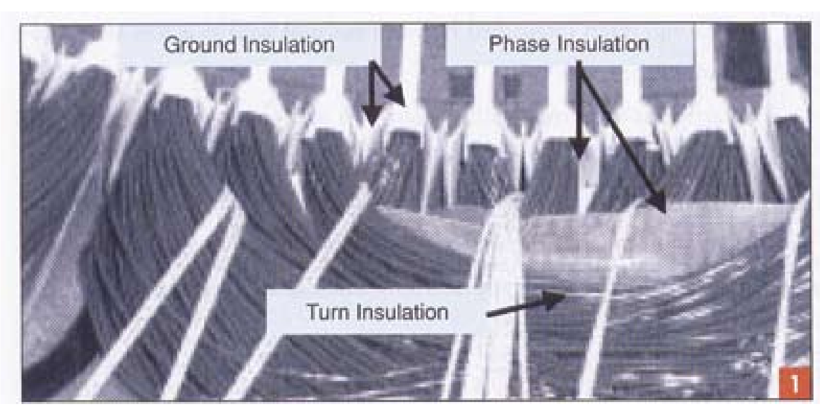
The principal concern of" both ASD motor manufacturers and users is reliability of the ASD system [9]. Of special concern is the stator winding insulation system, which consists of turn-to-turn, phase-to-ground, and phase-to-phase insulation. Experience shows that the mechanism of insulation failure due to voltage impulses from pulse-width modulated (PWM) inverters is likely to be different for random-wound and form-wound stators [2], [4]. Thus, the aging processes involved are addressed separately.

Random-Wound Motor Stators (Normally Type I)

Figure 1 shows the components of the winding insulation system in a random-wound stator. Random-wound motors are usually rated < 1,000 V. PWM inverters using insulated gate bipolar transistors (IGBTs) or similar switching devices create relatively high-magnitude, short-rise-time voltage impulses that strike the motor terminals. Depending on the cable length, cable grounding, and the relative surge impedance of the cable and the stator winding, the impulse voltages may be as much as three or four times the rated, rms phase-to-ground voltage, with a rise time as short as 50 ns [2], [31, [8]. Impulses with such short rise times create harmonic frequencies as nigh as 5 MHz. This high frequency results in a nonuniform distribution of the impulse voltage across the winding components [2]—[4}, [10]. Specifically, the voltage between turns in the first coil may be a very high percentage of the applied impulse voltage. The shorter the impulse rise time, the greater the nonuniformity and, thus, the higher the turn-to-turn voltage stress. The severity of the ASD impulses increases as either the magnitude increases or the rise time 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 these small air gaps to exceed the dielectric breakdown strength of air (about 3 kV/mm for uniform fields). The result is a partial discharge (PD)—a small electric spark. Repetitive PD will eventually erode organic insulation, such as the insulation film on the magnet wire, or even the ground and phase insulation barriers. If PD occurs as a result of impulses from an ASD in a stator winding not designed to withstand such discharges, the insulation will eventually fail [2], [3], [5], [7], [8].

Motor designers 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. In addition, improved varnish impregnation methods such as trickle impregnation, vacuum pressure impregnation (VPI), and other processes reduce the number and size of voids.



Random-wound motor stator, showing the insulation system components.

The intent of the new IEC documents 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). Some motor manufacturers are working on the design qualification of Type I random-wound motors [5], [7].

Random-Wound Motor Stators (Normally Type II)

Form-wound coils have conductors organized in distinct turn packages consisting of a number of stranded conductors. Unlike random-wound systems, the turns in form wound coils 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 [12] and micaceous materials treated with VPI and/or resin-rich pressing operations to minimize voids and resist degradation by PD. Figure 2 shows an example of a form-wound coil cross section, and Figure 3 is an example of form-wound coils existing in the slot in the endwinding region.

The most significant factors associated with aging of Type II insulation in ASD 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. These are caused by voltage impulses with short rise time and high repetition frequency from the ASD waveform. If the rise time of the repetitive voltage impulse appearing at the motor terminals is <500 ns, the turn insulation may be affected by the PD fatigue mechanism as the number of repetitive cycles increases.

Key Definitions

Type *I and Type II* Systems

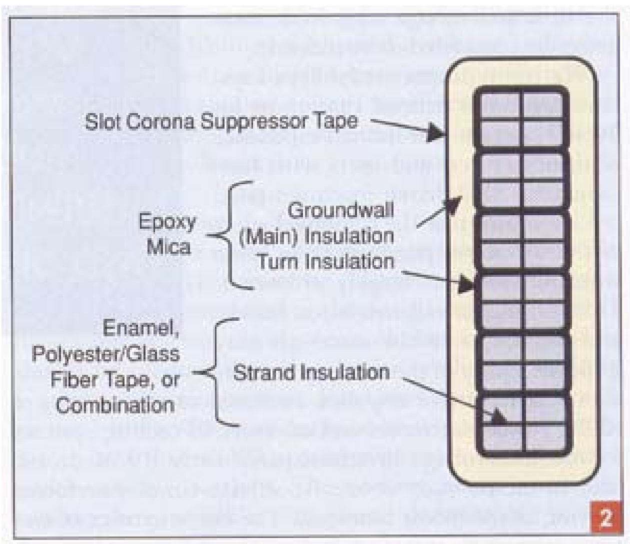
Type I systems should experience no PD during their service lifetime. These are normally random windings. In these systems, the aging mechanism is thermo-mechanical rather than electrical. For this reason, test objects constructed to represent the insulation system are subjected to aging by heat, agitation, and humidity, followed by a PD test [13], [15].

Type II systems will probably experience PD during service; their principal aging mechanism is considered to be electrical. They are normally form wound, employing micaceous turn-to-turn and/or phase-to-ground insulation to combat the long-term effects of PD, Form-wound systems rated >3 kV will generally include semiconductive materials for in-slot partial discharge suppression and may have high-voltage endwinding stress grading.

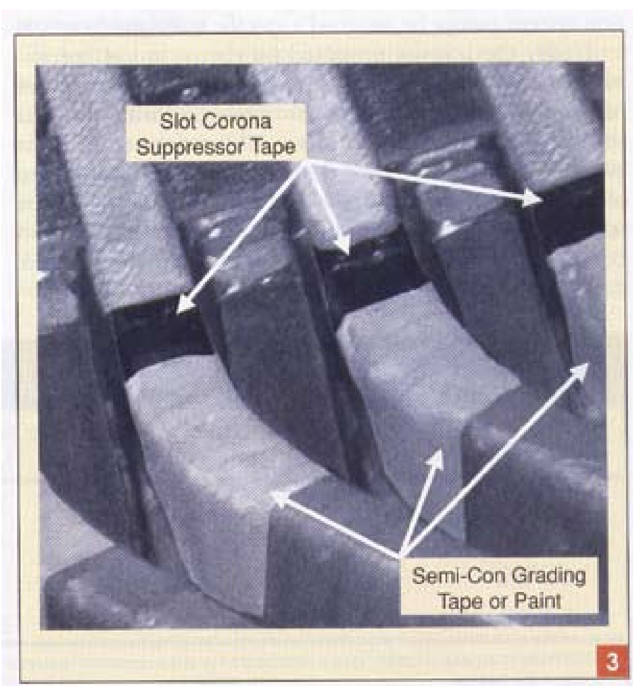
Stress Categories

Many different types of ASD system configurations exist. Listing all the possible permutations would make the technical specifications terribly complex. To complicate matters further, inverter configurations and components will continue to evolve. The technical specifications emphasize the importance of the inverter designer's role in defining the characteristics of the output wave shape as it appears at the motor terminals.

The wave shape is described completely by three principal parameters: impulse repetition frequency, peak impulse voltage, and impulse rise time. In turn, for Type I systems, the rise time and magnitude are classified into four categories: *benign, moderate, severe, or extreme.* The Type I stress category severity increases with voltage impulse magnitude and as the rise time of the wave front of each impulse decreases. Impulse magnitude is expressed as the overshoot factor Vp/Vdc, where Vp is the magnitude of the voltage at the motor terminals and Vdc is the bus voltage of the ASD. It is recognized that the repetition rate (carrier frequency) is not a critical factor for Type I systems.



Example of the slot exit area of a form-wound stator.



Example of the coil section of a form-wound stator.

Problems are encountered when defining overall stress categories for ASD machine insulation. For example, in some applications, an impulse voltage magnitude that is considered severe may have a moderate rise time. In others, the voltage arriving at the motor terminals may not be onerous, but the race of rise could be very steep. 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 rise time and voltage magnitude categories are considered independently.

Waveform parameters for Type I systems are better defined than those for Type II systems. The limited experience of manufacturers and users with fast-switching ASD-driven machines rated >6 kV means that the combined effect of the waveform parameters on these windings remains largely unknown. Thinner groundwall insulation builds, and the nature to the materials may limit the ability to the winding to operate under repetitive impulses. 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-rime) waveforms arriving at the motor terminals. The characteristics of system aging under these conditions are not fully understood. For this reason, the waveform applied to a Type II insulation system cannot be assigned a specific stress category.

Under the scheme proposed by the technical specifications, the inverter designer shall determine the nature of the waveform profile at the motor terminals at the start of the system design phase. This information must be shared with the motor designer to permit definition of appropriate qualification and acceptance tests. The technical specification encourages open communication between the purchaser of the drive system, the inverter designer, and the motor designer.

Partial Discharge Inception Voltage

For these technical specifications, the conventional definition of PD inception voltage (PDIV) does not strictly apply if the applied voltage consists of impulses rather than sinusoidal 50/60 Hz ac. A slightly modified term called the repetitive PDIV (RPDIV) is defined as the lowest impulse voltage at which PD can be detected on most impulses when die voltage is raised gradually from zero. The RPDIV is measured according to the procedures described in another new IEC document, TEC 61934 TS [181.

Impulse

For the purpose of IEC 60034-18-41 and IEC 60034-18-42, the term "impulse" refers to a voltage transient from an ASD or a special high-voltage "surge" tester. PD in a winding creates low-voltage pulses in response to the applied "impulse."

Type I Tests

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.

Qualification Test

The premise of the qualification test 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 ASD transients would occur during

TABLE 1. PHASE-TO-GROUND STRESS CATEGORIES FOR TYPE I INSULATION SYSTEMS [11].		
Stress Category	Overshoot Factor V_p/V_{dc}	Impulse risetime, t_r (μs)
A - Benign	≤1.1	≥1
B - Moderate	≤1.5	≥0.3
C - Severe	≤2.0	≥0.1
D - Extreme	<2.5	≥0.05

Note: Where V_p = peak value of impulse voltage arriving at the motor terminals and V_{dc} = dc bus voltage in the inverter.

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 [13] (for random-wound machines) or [14] (for form-wound machines). These are essentially the same aging tests as those described in [15] and [l6], which are used to determine the thermal classification of the insulation system. 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. Under the terms of IEC 6034-18-41, detection of PD at any point during the qualification test of a Type I insulation system constitutes failure.

The applied voltage used to measure the discharge inception voltage may either be sinusoidal 50/60 Hz ac where PDIV is measured or an impulse from a suitable short-rise-time surge tester where RPDIV is measured. Testing with a sinusoidal applied voltage is acceptable only for special test objects where the turn insulation stress is simulated by having two parallel magnet wires, one of which is grounded and the other energized from the ac rest set. Impulse testing with a suitable impulse voltage is required to ensure a turn-turn voltage stress occurs. The test object is a conventional coil or winding.

Table 2 shows the minimum RPDIV voltages for a stator rated 460 Vrms fed by a two-level inverter for each of the four stress categories. For this example, the dc bus voltage of the two-level inverter is 621 V. The table only shows the RPDIV when a normal stator is tested with a short-rise-time impulse with a slow decay time (as for most commercial surge generators used for motor testing). The severity of the impulse voltage used depends on its rise time (from Table 1).

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.

Since the phase-to-phase RPDIV may stress the phase-to-ground and turn-turn insulation in a manner not representative of the true aging mechanism, a "rescue" procedure is provided to distinguish which insulation component is causing the PD. IEC 60034-18-41 describes the derivation of these test levels in detail.

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.

Type II Tests

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 envelope is defined by the applicable waveform supplied 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 rime to electrical breakdown of the insulation under the specified waveform conditions.

Since varying aging mechanisms make simultaneous testing of all form-wound coil insulation components impossible, the technical specification addresses each component separately. 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.

Turn-to-Turn Insulation

These 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 should be conducted under impulse conditions, whereby a proposed system of turn insulation is compared to a proven system. The tests may not be required if it can be determined that no PD activity will occur between turns under service conditions. The working group is still discussing the acceptable voltage and duration of the turn insulation voltage endurance test.

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

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_{dc}	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

Note * These voltages are measured from zero to peak with a conventional surge generator that creates a fast rise time and slow decay time impulse.

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 [17] is applied by multiplying the ratio of frequencies to the lifetime obtained at a power frequency for a given voltage. The result is a curve providing a mean time to breakdown that must be equal to or better than that of a proven system.

Stress Grading and Corona Protection

In a form-wound coil insulation system, the main insulation, stress grading, and corona protection materials interact under the applied stress. Therefore, these must be combined for qualification tests on coil designs where all three materials will be used. Samples must represent the design features of production coils and are fitted into fixtures representing slots.

The sample must be 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. The dual-temperature condition is imposed to take into account the local temperature elevation associated with dielectric thermal losses at the stress grading.

Qualification criteria are met when each of the samples reaches 100 hours without failure and without showing visible deterioration of the surface of the materials.

Acceptance Test

In the current draft, sample windings must meet a minimum lifetime requirement on voltage endurance of 250 hours. The applied waveform is sinusoidal 50/60 Hz, with voltage magnitude equal to. 2.5r 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.

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. Technical Specification IEC 60034-18-41 for Type I systems has been approved and should be published in 2007 For Type II form-wound systems, the IEC 60034-18-42 draft is still under development.

The state to the art is constantly changing. Inverter drive designers are employing higher voltages and faster switching devices with steeper wave fronts. As insulation systems evolve, some of the category options may not be applicable. ASD standards will also evolve, and these changes will need to be recognized. Thus, the draft will receive further definition concerning the specific test methods and requirements.

The working group is still considering technical and commercial questions. Further experimental work is recommended concerning the equivalence of voltage and frequency to the mainwall insulation life curve and the establishment of a qualification scheme suitable for a variety of different inverter system designs. The definition of "service-proven systems" and the question of obtaining data describing waveforms at the motor terminals for custom-built medium-voltage machines will require further discussion.

Acknowledgment

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