Partial-Discharge-Inception Testing on Low-Voltage Motors

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***Abstract*—This is a review of one manufacturer's efforts toward testing National Electrical Manufacturers Association (NEMA) low-voltage motor insulation for compatibility with adjustable-speed drives (ASDs). Partial-discharge-inception-voltage (PDIV) measurements were selected as a tool to evaluate the future performance of the stator insulation system to resist deterioration by the drives. PDIV measurement is explained in terms of procedure and accuracy. Data are presented from tests made on motors from several prominent manufacturers.**

***Index Terms*—MG1 Part 31, motor insulation, partial-discharge-inception voltage (PDIV).**

I. Introduction

Motors operated on sine-wave power long before the advent of modern adjustable-speed drives (ASDs). Stator insulation systems and standards evolved over time to be well suited for sine-wave power. ASDs (both dc and ac) challenged motor manufacturers to design insulation systems capable of withstanding repeated voltage impulses. Modern pulsewidth-modulation (PWM) low-voltage drives are recognized as one of the most demanding applications for a motor. National Electrical Manufacturers Association (NEMA) MG1 parts 30 and 31 [1] were developed to provide a standard for motor insulation systems capable of operating in the PWM environment. Partial-discharge-inception-voltage (PDIV) testing has gained popularity as a method to measure insulation-system capability to withstand voltage impulses. There are no standards for the application of PDIV testing on low-voltage motors. This paper documents the steps one manufacturer has taken to assure that motors meet and exceed the NEMA MG1 part 31 standard for voltage withstand.

II. History

MG1 part 30 was issued in 1993 as: "application considerations for constant speed motors used on sinusoidal bus with harmonic content and general purpose motors used with variable-voltage or variable-frequency controls or both." This was the first time NEMA made any mention of the use of ac motors on drives. Part 30 is a glossary of terms and a tutorial covering derating of motors as a result of cooling inefficiency.

In NEMA MG1 part 31—1998, the voltage withstand was set to 3.1 times the line voltage in par 31.4.4.2, and remains the same today in MG1—2003. This withstand is calculated for motors with base rating voltages $V_{\text{rated}} \leq 600$ V as

$$V_{\text{peak}} \leq 1.1 * 2 * \sqrt{2} * V_{\text{rated}} = 3.1 * V_{\text{rated}} \qquad (1)$$

where

1.1	10% overvoltage;
2	2× voltage on the reflected wave;
$\sqrt{2}$	converts rms to peak volts;
V_{peak}	single-amplitude zero-to-peak line-to-line voltage;

and the rise time is 0.10 μs.

These limits are echoed in [2, paragraph 5.2.9.5].

Motor manufacturers have complied with this standard. Motors are designed with robust insulation systems and put in operation. As failures occur, lessons are swiftly (and sometimes painfully) learned. Long service in environments that approach the limits of MG1 part 31 indicates compliance with the standard.

The International Electrotechnical Commission (IEC) is developing a standard "Evaluation and qualification of electrical insulation systems used in rotating electrical machines when fed from voltage converters," IEC 60034-18-41. The committee draft is November 2005 [3]. This proposed standard contains definitions and a tutorial covering insulation damage due to inverter operation. When it is finished, it will document complementary test methods. The draft suggests two winding types, the first of which will be subject to impulse voltage but the winding will not be exposed to partial discharge (PD) over its expected life (type I). The second will be subject to repeated impulse voltages where PD may occur in operation (type II). It goes on to define three "duty levels" for motor insulation systems, A (benign), B (medium), and C (severe). Finally, each "duty level" has a description of voltage-withstand requirements and a description of acceptance criteria. Table I describes the requirements for type-II insulation systems. The draft is changing, but it appears type II-C insulation systems will be very similar to MG1 part 31.

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TABLE I
SURGE VOLTAGE AT MOTOR TERMINALS AND ACROSS STATOR-WINDING INSULATION COMPONENTS [3]

Type of voltage	Maximum voltage at the motor input terminals (V_{peak})					
	Phase to ground (frame)	Phase to phase	Turn to turn	Example for V_{line}=400 V_{rms}		
				Phase to ground	Phase to phase	Turn to turn
Sinusoidal voltage, V_{line} (V_{rms})	$\sqrt{2}\ V_{line}/\sqrt{3}$	$\sqrt{2}$ Vline	($\sqrt{2}$ Vline/$\sqrt{3}$)/N	± 327	± 566	± 327/N
Converter directly connected to the machine (or through a short cable)	± ½ $Vbus_{dc}$	± $Vbus_{dc}$	Uneven	± 270	± 540	Uneven
Converter connected to the machine through a long cable	± $^3/_2$ $Vbus_{dc}$	± 2 $Vbus_{dc}$	Uneven	± 810	± 1080	Uneven
Converter connected to the machine through a long cable while the machine is regenerative braking	≥ $^3/_2$ $Vbus_{dc}$	≥ 2 $Vbus_{dc}$	Uneven	≥ 810	≥ 1620	Uneven

Where: N = number of turns per phase,
$Vbus_{dc}$ = DC bus voltage

There is a diversity of definitions used in existing literature. For the purpose of this paper, we will use the following.

1) Peak voltage refers to peak-to-peak voltage rather than zero-to-peak voltage. It is possible to have adjacent zero-to-peak positive and a zero-to-peak negative peaks. These can only be properly evaluated as peak to peak. Ultimately, the motor must be capable of withstanding the peak-to-peak voltage applied.
2) Per-unit base voltage is the peak line-to-neutral voltage. Essentially, rms line-to-neutral (line-to-line/1.73) multiplied by the square root of 2 for peak.

The MG1 definition does not allow for transients in the opposite polarity. Section IV describes several transients that are best measured peak to peak.

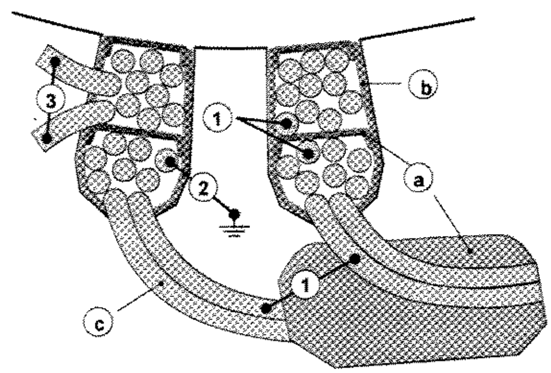
III. WINDING CONFIGURATION

Most low-voltage motors are random wound. Individual coils are made up of insulated copper wire, inserted into the stator and finished by connecting together with leads. Fig. 1 shows a typical section of a stator winding.

Turn-to-turn voltage is typically limited to 100 Vrms. Since these machines are random wound, coils of different phases are often adjacent, and it is necessary to separate them by additional insulation. Wire to wire contact in the motor is limited to about 300 Vrms.

Magnet wire is typically round copper coated with multiple coats of insulating film. The wire insulation consists of a base coat for dielectric strength, a second coat with an inorganic filler, which is PD resistant, and a top coat for mechanical toughness. The total build of enamel is 0.0015 to 0.0025 in, depending on wire diameter. These wires have demonstrated longer life in the presence of PD [4].

The wire standard for PD-resistant wire is NEMA MW 1000, class MW35C [5]. The standard uses the same mechanical properties as the normal magnet wire, including the temperature rating (200 °C or higher), the resistance to abrasion, and crack resistance. There are several different acceptable manufacturing processes under the standard. Each manufacturer is responsible



a phase insulation / overhang insulation
b ground insulation
c turn insulation
1 phase to phase
2 phase to ground
3 turn to turn

Fig. 1. Section of stator winding [3].

for application and satisfactory results in a particular motor design.

Stator slots are lined with ground insulation. The ground insulation has a short time dielectric breakdown on the order of 20 kV. Coils are designed to be inserted into the stator either in lap winding form or concentric winding form. In the end-turn region, different phases are separated by glass cloth with a short time dielectric breakdown of 8 kV. The ground wall insulation level and phase insulation levels are based on material and manufacturing constraints that cause them to have plenty of voltage margin. Rarely do we see failures caused by drive application in these parts of the machine.

Once the coils are inserted into the stator, the connections are made up. This is accomplished using cold crimp connectors or brazing.

After the winding is installed into the stator laminations, it is sealed with varnish. The varnish provides resistance to environmental damage, mechanical stability, transfers heat, and fills air gaps to reduce corona. It is believed that varnished coils

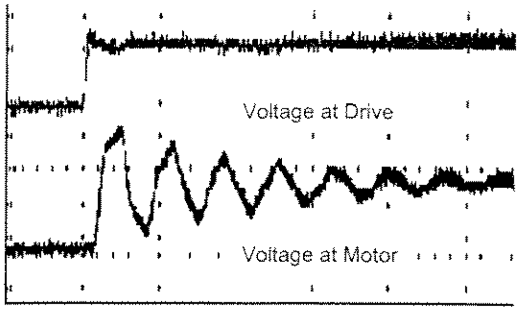


Fig. 2. Voltage at drive and motor measured phase–ground.

with voids within the varnish, which encapsulate either air or vacuum, can lower the PDIV [6].

IV. Electrical Environment

Over the years, many different methods have been developed to rectify the power system voltage and convert fixed frequency sine-wave ac to an ac voltage with selectable frequency [7]. Almost all drives convert incoming ac to a dc voltage (bus) then switch the dc bus to construct a variable-frequency variable-voltage ac output voltage. The present generation of drives are based on power transistors and PWM technology. The positive and negative dc is switched thousands of times per second to create an ac current waveform of the desired frequency and voltage. The drive generates short-rise-time rectangular pulses of fixed amplitude voltage, which have varying duration and frequency. The voltage of the pulses at the output of the converter is about the same as the dc-bus voltage. Early switching transistors were bipolar junction transistors (BJTs) and had relatively slow turn-on times, on the order of microseconds. Such relatively long-rise-time pulses cause high drive-power loss and do not construct a good sine wave. Poor sine-wave construction causes excessive heating in motors.

Virtually all modern drives for low-voltage motors use IGBTs (insulated gate BJTs) as the switching devices. The IGBTs are commonly configured using PWM technology. The dc-bus voltage depends on the rectified 60-Hz voltage or regenerative braking voltage level (Table I). The rise time of the pulse from a PWM-IGBT drive is usually on the order of 50–100 ns, with a voltage that equals the dc-bus voltage (Fig. 2).

However, if it takes longer for the pulse to travel along the power cable connecting the drive to the motor than the rise time of the pulse, then a reflection will occur at the motor terminals, which can (for a very short time) cause superposition, and thus, a higher voltage than the dc-bus voltage [8]. In most power cables, the velocity of pulse propagation is about 0.15 m/ns. Thus, the travel time along a 30-m-long cable between the drive and the motor will take about 200 ns. Consequently, the drive/cable/motor system behaves like a transmission line and reflections will occur. If the drive is integrated into the motor, the pulse travel time is 0, and no reflections occur (and thus, no voltage transient higher than the dc-bus voltage is present).

The amount of overvoltage depends on the surge impedance of the power cable (typically 30 Ω) and surge impedance of

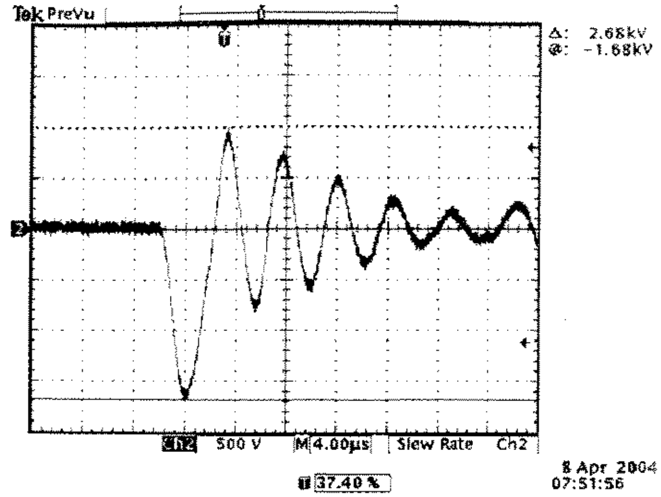


Fig. 3. Short-pulse phenomena.

the motor (depends on the winding capacitance and number of stator-winding parallels per phase)—typically higher than 100 Ω for a random-wound stator. From transmission-line theory, the higher the surge impedance of the motor, the greater the overvoltage will be, up to a maximum of twice the dc-bus voltage [9].

The rise time at the motor terminals depends on the cable grounding system, various design aspects of the cable, the motor surge impedance, and the presence of any filters that slow the pulse rise time.

Oscilloscope traces of voltage surges from a typical inverter drive are given in Fig. 2. The top trace shows the pulse as measured phase to ground at the drive on the same phase as at the motor in the second trace. The vertical scale is 500 V per division and the horizontal scale 10 μs per division. The waveform at the motor has a much higher peak voltage than the drive due to the "ring" from reflections.

Very short pulses can produce voltages above two times the dc-bus voltage. Fig. 3 shows the effect of a short pulse. The short pulse allows a significant ring to occur when it is turned OFF. The peak voltage is 2680 V. Fig. 3 also shows the need for peak-to-peak measurements rather than only zero to peak.

Voltages above two times the dc-bus voltage can also be produced by drive double transition caused by a converter-fed drive algorithm that does not allow a minimum time between successive pulses. Double transition occurs when an IGBT in one phase switches from minus to plus dc-bus voltage at the same instant that an IGBT in another phase switches from plus to minus. Fig. 4 is a case where phase C (trace 3) shows the resulting transient when a negative switching event is immediately followed by a positive switching event. Such events may generate two times the dc-bus voltage wave, which travels to the motor and can then build to greater than two times the dc-bus overvoltage when reflected at the motor terminals.

Due to the different IGBT-drive switching times, practical experience shows there are a range of surge-voltage magnitudes and rise times that any particular inverter-fed motor will see. Fig. 5 shows a three-dimensional (3-D) plot of surge rise time (in nanoseconds) versus surge magnitude (in terms of pu, where

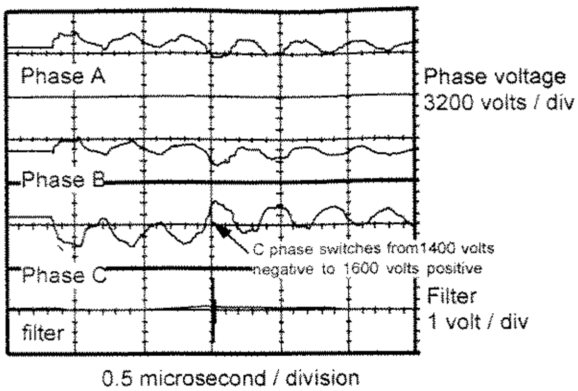


Fig. 4. Double transition.

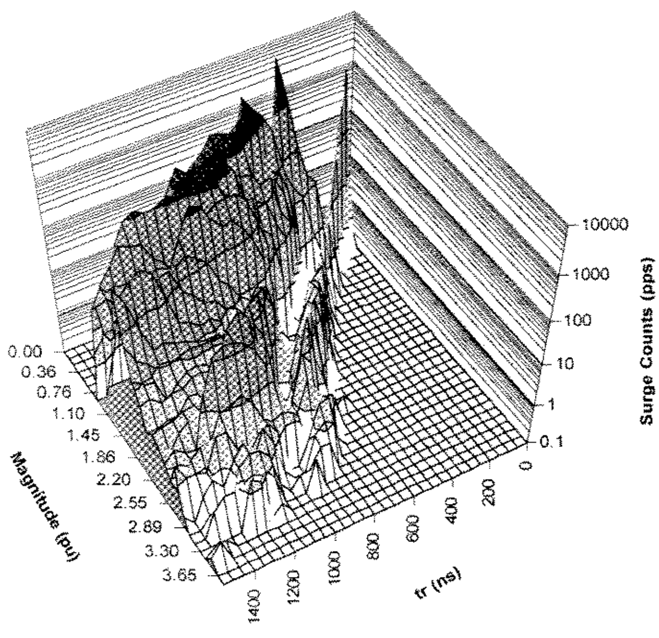


Fig. 5. Surge environment, phase A.

1 pu is the peak line–ground rated power-frequency voltage) and number of surges per second measured at the motor terminals [7]. The figure clearly shows that a single magnitude with a single rise time is not practically encountered.

Failures related to these pulses have been well documented. Usually, the failure is in the first turn or two of a coil. Fig. 6 shows a representative failure. Often, little damage occurs due to the fast turn-OFF time of the IGBTs. The voltage transient is extremely fast and decays rapidly in the coils due to inductance. Typically, the first coil can have between 30% and 80% of the pulse voltage across it [10].

V. OFFLINE MEASURING OF PDIV

Winding failures seen on motors in drive applications have generally occurred in the first coil of a pole connected to a power lead. Depending on the motor/drive setup, sometimes the failure may extend between phases. It has been a standard practice to add extra phase insulation between coils within a pole. Unfortunately, standard test procedures did not test the effectiveness of this practice, leaving the real test to the field.

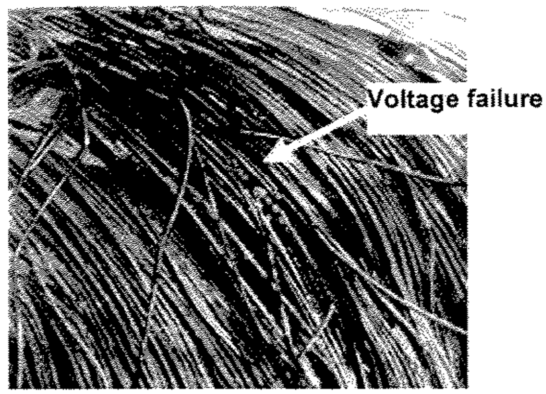


Fig. 6. Winding failure due to voltage spike.

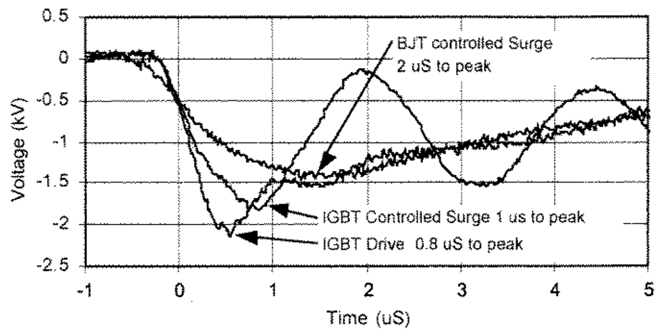


Fig. 7. Surge and drive waveforms.

Presently, a test method has been developed to measure the voltage at which PD occurs. The development of the test method produced several lessons.

A variable voltage source producing a rise time similar to that of an IGBT drive has only recently become commercially available. Fig. 7 is a graph showing an IGBT-drive voltage pulse measured at the terminals of a 40-hp motor. The graph also shows the output of an IGBT-controlled surge unit applied to the same 40-hp motor, and a BJT-controlled surge unit applied to the same 40-hp motor. The rise time of the surge unit is slightly faster than that of an IGBT drive, and the rise time of the BJT surge unit is considerably slower than the IGBT units. Early attempts to measure PD with units that had slower rise times (a BJT-controlled surge unit) yielded inception voltages that were higher than when measured with an IGBT-controlled surge unit.

PD was first measured by using a surge unit to test one winding with the other windings grounded while measuring the current in a grounded lead. Unfortunately, the frequency response of most current probes is not high enough to capture currents in the frequency range of PD ($>$ 100 MHz). Ultimately, a PD detection equipment using high-pass filtering techniques was chosen. Surges are applied to windings and a high-pass filter returns small high-frequency voltage drops that occur when PD is produced. This method measures PDIV line to line and line to ground as only one winding is surged while the other two are grounded. All the measurements described are voltage line to line.

Fig. 8 shows the test circuit for PDIV measurement. The surge generator surges each lead individually while the other

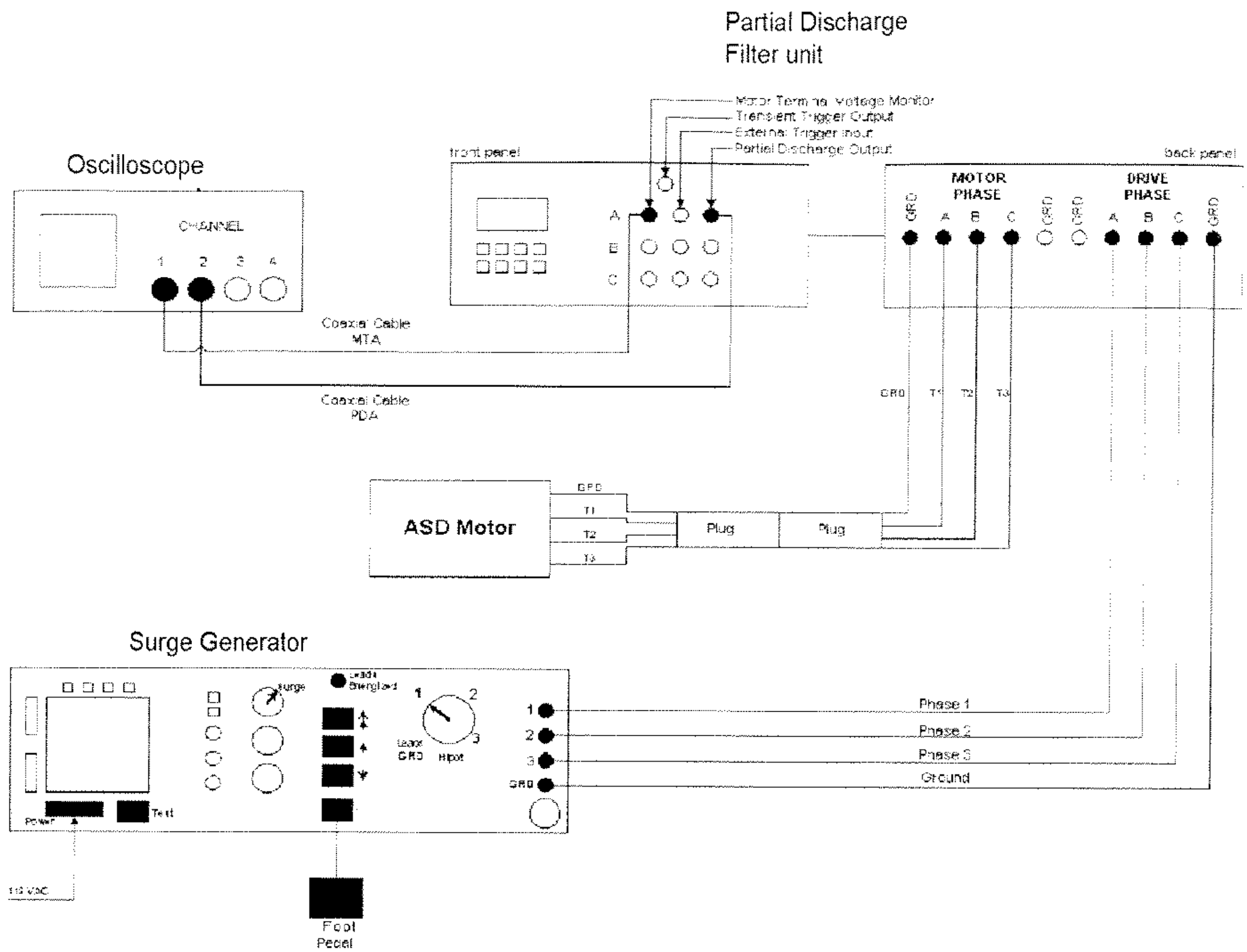


Fig. 8. PDIV measurement test setup.

two leads are grounded. The voltage is slowly increased from 0 V while motor terminal voltage and PD output is monitored on the oscilloscope. Once the peak PD output exceeds 100 mV, the voltage is no longer increased, and the PDIV recorded.

Fig. 9 shows an example of the PDIV measurement. Channel 1 is the motor terminal voltage. Channel 2 is the PD output. The zero to peak of the PD output is considerably greater than 100 mV, as mentioned above. That is typical of most of the motors tested. With just a small change in voltage, the PD occurs suddenly, and may be much greater than 100 mV at the inception. The PDIV measurement for this motor phase is 3620 V. The vertical scale on the top trace is 1000 V per division.

All testing is done on wound cores with the rotor removed. Several tests were run with rotors installed. In general, higher PDIV readings resulted, but the variation was excessive.

Preliminary testing of varnished stators indicated low PDIVs compared to those required to meet NEMA MG1 part 31 voltages. PDIV levels needed to be improved. Based on analysis of failures, most problems occur in the end turns. This is consistent with service experience where slot failures with motors on IGBT drives are extremely rare.

End-turn phase paper placement and how it overlapped with slot separators was reviewed. Materials were not changed. Separately, end-turn forming was reviewed. Process improvements were instituted, but materials were not changed. After these changes, the average PDIV increased from 2300 V, with a standard deviation of 350 V, to an improved average of 3000 V,

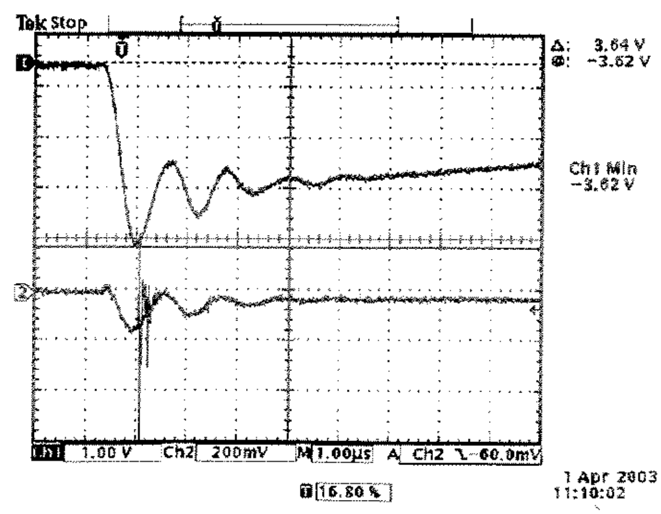


Fig. 9. PDIV is achieved.

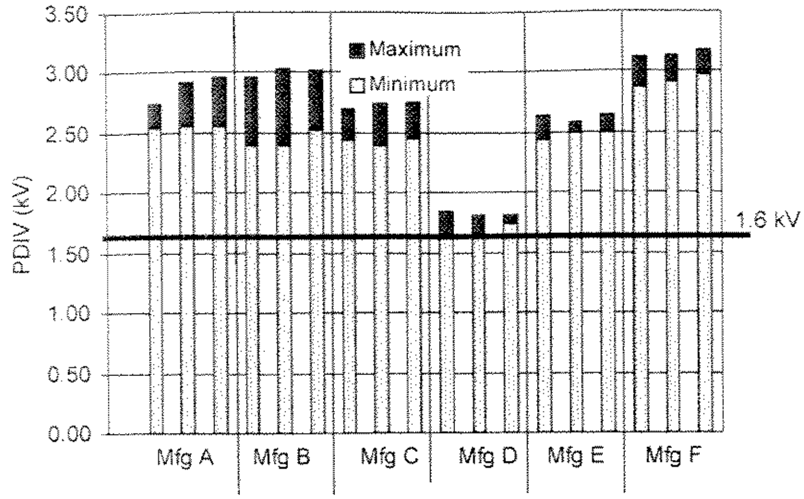


Fig. 10. PDIV For 10-hp, 4-pole, 460-V motors from six different manufacturers.

TABLE II
MANUFACTURING TEST RESULTS

Partial Discharge Inception Voltage (kV)				
frame	2 Pole	4 Pole	6 Pole	8 Pole
320	3.27	3.13	3.2	2.95
360	3.21	3.69	3.05	3.23
400	3.14	3.13	3.04	3.43
440	3.11	3.11	3.19	3.16

with a standard deviation of 250 V. Considering that NEMA MG1 part 31 requires a 600-V motor to be able to handle a pulse of 1860 V, the present process has a 4.5 sigma capability to NEMA.

VI. Offline PDIV-Testing Motors

Eighteen motors were tested to compare insulation systems across the industry. These motors all had the following characteristics: 10 hp, four poles, 460 V, severe duty, and energy efficient. They represent a sampling of prominent NEMA manufacturers. Fig. 10 displays results from the PDIV tests.

Reviewing the details, the most important is the minimum PDIV level. All the manufacturers tested above the MG1 part 31 requirement of 1426 V (3.1 × 460 V). In fact, all except manufacturer #4 passed 2.0 kV. These tests were made on wound cores, left in the frame, with rotors removed.

It is interesting to note the range of the readings on a per-manufacturer basis. The range is indicative of both the test variation and the motor variation. The test variation is relatively the same for all motors as the same procedure and equipment was used. The small deviation between motors, per manufacturer and between phases of the same motor, demonstrates there is significant differences overall between the motors.

Table II shows results obtained from factory production testing covering 2088 machines. Production testing is done at room temperature on the factory floor. Repeatable results are being obtained from the PDIV test. The PDIV is relatively frame and speed independent. These results were obtained after the manufacturing and testing processes were consistent.

VII. Life Test

A life test was run to verify that motors would maintain PDIV over time. Motors were operated on a drive at the insulation class temperature. Every 500 h, the PDIV was measured.

Ten motors were operated no load on an IGBT PWM inverter with long cable lengths in order to achieve peak motor voltages approximately 10%–25% above NEMA MG1-31 limits. For a 600-V insulation system, the max NEMA MG1-31 voltage would be 1860 V. Peak voltages from the drive system are all in the 1600–2700 V range. Fans were removed to increase the motor winding temperature to class F limits of 145 °C. The motor winding temperature was measured using thermocouples.

Table III shows motor temperatures and PDIV measurements on the ten test motors as a function of time. The peak voltages measured at the motors are within the desired range and the winding temperature is operating very close to 145 °C. The PDIV for each of the motors remains very constant over time. During the life test, PDIV was measure on motors both at room temperature and at insulation class temperature (~ 145 °C). Testing indicates there is no difference in PDIV between a hot motor and a cold motor.

VIII. Conclusion

NEMA standards address insulation level in motors used on drives. The method for testing that insulation level is not yet accepted in a standard. IEC is currently working on a standard for motor insulation, including test methods and levels.

One manufacturer's test method is discussed. Repeatable results are currently being obtained. In order to produce acceptable results, several manufacturing-process changes were required while the materials were not changed.

Limited testing indicates there are differences in insulation systems between motor manufacturers. It is expected that manufacturing procedures from all manufacturers will improve as testing becomes more common.

TABLE III
MOTOR PDIV AND TEMPERATURE OVER TIME

Motor	Average PDIV @ 250 hours (kV)	Average PDIV @ 500 hours (kV)	Average PDIV @ 1000 hours (kV)	Average PDIV @ 2000 hours (kV)	Average PDIV @ 2500 hours (kV)	Average PDIV @ 3000 hours (kV)	Average Peak Voltage at motor terminals (kV)	Average winding temperature by T/C ©
1	3.8	3.6	3.6	3.6	3.7	3.6	2.10	138
2	3.6	3.6	3.5	3.5	3.5	3.5	2.00	140
3	3.7	3.6	3.5	3.5	3.6	3.5	2.02	136
4	3.5	3.3	3.4	3.4	3.5	3.4	2.06	144
5	3.5	3.2	3.2	3.2	3.2	3.2	2.02	150
6	3.5	3.2	3.2	3.4	3.3	3.3	2.04	139
7	3.4	3.2	3.3	3.3	3.3	3.3	2.14	138
8	3.5	3.3	3.4	3.3	3.2	3.3	2.12	138
9	3.5	3.3	3.5	3.4	3.4	3.3	2.12	140
10	3.4	3.3	3.3	3.3	3.4	3.5	2.16	133

Aging tests on several stators driven by inverters indicate that motors with high-discharge inception voltages exhibit a long life in the PWM drive environment. The data show no degradation in PDIV when PD is not suspected.

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