IEEE 1349-2021 - ELECTRIC MACHINES IN HAZARDOUS LOCATIONS - WORLDWIDE APPLICATIONS

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Abstract – IEEE Std 1349-2021™ [1] "Guide for the Application of Electric Machines in Zone 2 and Class I, Division 2 Hazardous (Classified) Locations," the third edition, has been updated for the 2020 National Electrical Code, *NEC* [2] and guidance has been added for the 2021 Canadian Electrical Code, CE Code [3]. The Guide has been expanded to harmonize internationally and updated for IEEE Std 841 [4] for TEFC motors and IEEE P303 [5] for auxiliary devices. Some elements from the IEC – International Electrotechnical Commission - Increased Safety standard was included. Precautions against excessive surface temperatures and sparking are covered. To mitigate hot surface temperatures and sparking, this document provides guidance for selecting, operating, and maintaining motors where flammable gases and vapors may occasionally be present.

This paper provides an overview with highlights of key elements, discusses worldwide applications, includes new space heater tests and applications, and describes a new test method to determine the permanent magnet (PM) motor rotor temperature. It also details machine temperature test information along with adjustable speed drive (ASD) test configurations and provides an overview of discharge energy calculations due to common-mode voltage (CMV) for ASD applications with a link to the new IEEE 1349 Discharge Energy Calculator [6].

Index Terms — Adjustable Speed Drive, Common-mode Voltage, Generator, Hazardous Locations, IEEE 1349 Discharge Energy Calculator, Motor, Surface Temperature, Rotor, Sparking, Space Heater.

I. INTRODUCTION

A. Background and Scope

This Guide was originally published in 2001 and revised in 2011. Overviews are provided in papers [7] and [8] for the first and second editions, respectively. In 2018 the Working Group scope expanded and the Working Group name changed from motors to machines. This 2021 edition was revised by about 40 members of the Machines in Hazardous Locations Working Group Committee of the IEEE Petroleum and Chemical Industry Committee.

IEEE has several categories of documents denoted as "standards:" 1) *Guides* suggest good practices but no clear-cut recommendations are made, 2) *Recommended Practices* have preferred positions and procedures, and 3) *Standards* provide mandatory requirements.

Developed as a Guide, IEEE 1349 [1] assists individuals, organizations, and suppliers with the application of machines in Zone 2 and Class I, Division 2 locations, where flammable gases and vapors may occasionally be present as shown in Fig. 1. Primary emphasis is on the use of open or nonexplosionproof enclosed or nonflameproof enclosed machines and precautions against excessive surface temperatures and sparking of rotor bars and enclosure joints. IEEE 1349 [1] provides guidance for selecting, operating, and maintaining machines in Zone 2 and Class I, Division 2 locations to help mitigate hot surface temperatures and sparking.

Key advancements of the Guide include new space heater temperature test procedures and a new rotor temperature test method for PM motors. Machine rotor and stator surface temperature data tables were expanded for sine wave and ASD applications with new test configuration figures for ASD tests. IEEE 1349 [1] significantly expanded the information for sparking and discharge energy determination due to CMV for ASD applications, and the Guide includes a free download of the new IEEE 1349 Discharge Energy Calculator [6].

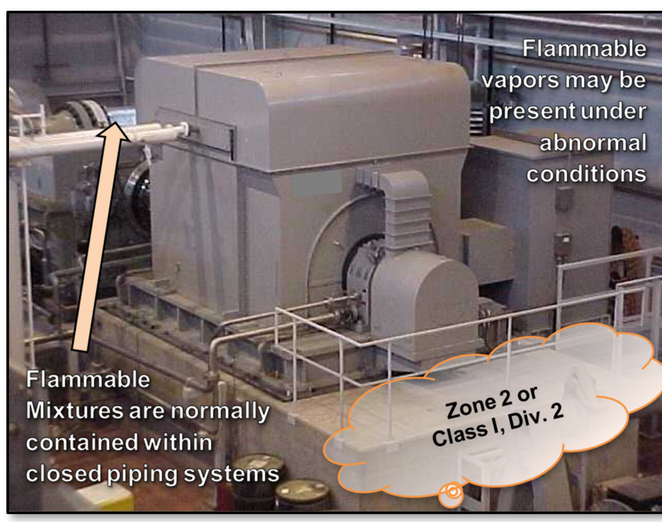


Fig. 1 Hazardous (classified) location, Zone 2 or Class I, Div. 2

B. Third edition impact

This edition of the Guide updated information throughout the document to include the latest technologies. The scope expanded to include the CE Code [3], generators, and PM motors.

The Guide includes the space heater temperature test method in Clause 8 [1] described below in III. Manufacturers conducted independent machine and ASD temperature tests and confidentially shared their data with the Working Group, which was captured in Annex H [1]. Machine temperature test data was expanded for fixed speed and ASD applications along with new companion ASD Test Configuration drawings. The maximum recommended exposed surface temperatures were updated and expanded to include PM motors in Table 1 [1] with an excerpt in Table A-I in Appendix A herein.

For ASD applications, a CMV is caused by the switching strategy of the ASD and creates a shaft voltage that can discharge, which may have a discharge energy that is incendive or nonincendive. The procedure for determining discharge energy due to CMV was significantly expanded in Annex G.3 [1] and an IEEE 1349 Discharge Energy Calculator [6] spreadsheet was made available for free download and use.

C. Key Elements - Event Mitigation and Motor Protection

The petrochemical industry has experienced an excellent history utilizing open-type and TEFC motors in Zone 2 and Class I, Div. 2 hazardous locations. Starting in the 2001 edition up through the 2021 edition, nine events have been documented in Annex J [1]. Six of the events involved gas compressor applications, where the flammable gas source was transferred via a common bearing lubricating oil system from the compressor to the motor. This flammable material accumulated inside the motor enclosure and then various ignition sources caused the events. Mitigation techniques include separating high-pressure gas compressor lubricating oil systems from the motor lube oil system, continuously degassing the lubricating oil and transferring gas into a closed piping system, or using pedestal bearings for the machine, which are described in 5.6.3 [1] and IEEE Std 3004.8 [9].

The motor should be selected to avoid overload conditions. Refer to Fig. 2 showing rotor operating temperatures of induction motors that are rated for 1.0 Service Factor (SF) with a Class B stator temperature rise which are tested at 1.15 SF load (overload condition). The overload protection requirements are in the 2020 *NEC* [2], Sections 430.32 (Continuous-Duty Motors), 430.124 and 430.126 (Adjustable Speed Drive systems overload and overtemperature protection, respectively) and 430.225(B) (motors over 1000 V nominal). In some locations, similar requirements with some variations may be stipulated by the authority having jurisdiction. Refer to IEEE Std 3004.8™-2016 [9] for information on overload types and selection.

Sound engineering judgment should be used for setting overload devices considering the motor rating, load, autoignition temperature (AIT) of the flammable vapors, and operation. For sine wave applications, overload device settings should be 115% or less of motor nameplate rated current for 1.0 and 1.15 SF motors. For ASD applications, current limit setting should be 100% of motor nameplate rated current and overload device settings should be 115% or less of motor nameplate rated current.

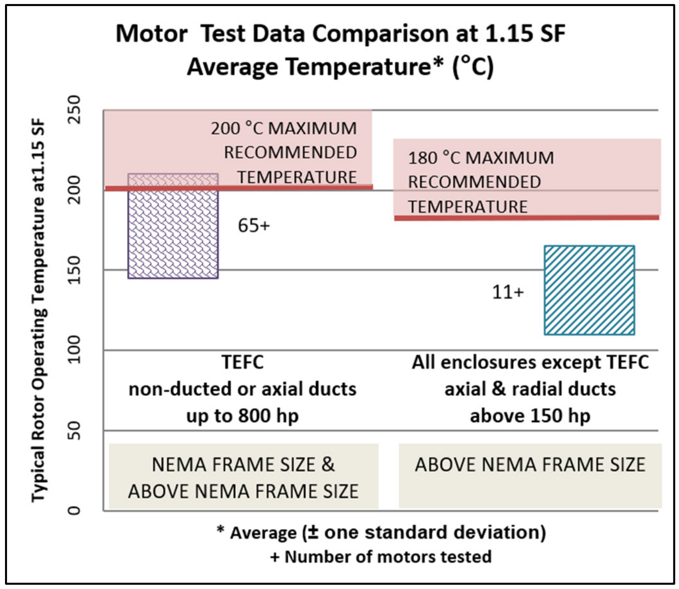


Fig. 2 Induction Motors Rated 1.0 SF, Class B Rise, Tested at 1.15 SF, Showing Rotor Operating Temperature.

II. WORLDWIDE APPLICATIONS

A. NEC and CE Code Harmonization

There have been on-going efforts to harmonize the *NEC* and the CE Code. Machines designed for the Division system as defined in *NEC* Article 501 [2] are equally accepted in the IEC based Zone system as defined in *NEC* Article 505 [2] and vice-versa. Within the USA, Division system installations are the predominant system following the original path taken by the *NEC* [2]. The Zone system installation requirements were introduced to the *NEC* [2] in 1996. The CE Code [3] for Canada mandates the IEC based Zone system as specified in Section 18 of the CE Code, although it allows Division based machines as specified in the Annex J18 of the CE Code [3]. The *NEC* [2] and CE Code [3] allow machines suitable for unclassified locations to be installed in Zone 2 or Division 2 classified location as long as they do not spark or have hot surfaces exceeding the AIT of gas or vapor in normal operating conditions. Normal operating condition is the condition when a machine is operating at its steady state load condition. Starting or accelerating of a machine is not considered a normal operating condition for the machine design when it's installed in a Division 2 or Zone 2 area. Space heaters, if supplied with machines, must follow the *NEC* [2] and CE Code [3] to limit the maximum surface temperatures as discussed later in this paper.

Recognized as an application guide for many international locations, IEEE 1349 [1] is referenced in the "Note" of Appendix B of the CE Code [3] Rule 150 (2) (e) when machines are designed for Class I, Division 2 or Zone 2 areas.

The *NEC* [2] also refers to IEEE 1349 [1] in the informational notes of Sections 501.125 (B) and 505.20(C) as the Guide to follow for machines installed in Division 2 or Zone 2 areas, respectively. In addition, the Guide specifically addresses space heaters and determining if the discharge energy is incendive or nonincendive for applications of shaft bonding brushes in ASD applications.

B. IEEE Harmonization

IEEE P303 [5] is presently being revised and harmonized to include all accessories being used or provided in machines designed for Zone 2 or Class I, Division 2 locations. Primary areas of harmonization with IEEE 1349 [1] are space heaters and shaft bonding brushes.

IEEE Std 841 [4] covers TEFC, severe-duty, induction motors up to 370 kW (500 hp) suitable for unclassified locations; and, these motors have all features as explained in the Common Applications of IEEE 1349 [1]. Therefore, these motors can equally be installed in Zone 2 or Division 2 locations as specified in the *NEC* [2] and the CE Code [3]. The “Common Application” sine wave power and “Common ASD Application” categories in IEEE 1349 [1] require machines not to exceed 200 °C surface temperature based on 40 °C ambient air temperature. In addition, these categories are harmonized with IEEE 841 [4] for stator temperature rise of 80 °C for sine wave power and 95 °C for ASD power for variable torque loads. Motors designed to meet IEEE 841 [4] do not require specific Nationally Recognized Testing Laboratory (NRTL) in USA or Certifying Body (CB) certification in Canada for Zone 2 or Division 2 locations.

C. IEC Global Influence

The United States and Canada have adopted the IEC-based Zone area classification systems; however, the IEC equipment standards have been accepted with US and Canadian national differences. Although the numerical designations of the IEC standards are kept the same, the US and Canadian versions are prefixed with “UL” and “CSA C22.2 No.,” because those organizations have revised the IEC standards with in-country differences. A quick reference comparison is in PCIC paper [10]. For 2021, an updated Table D.2 in IEEE 1349 [1] summarizes the Zone Type of Protection suitable for installation in Zone 2.

The application and technical requirements for electric machines installed in a Zone 2 area classification have evolved differently for those installations covered by the *NEC* [2] and those covered by other jurisdictions. The *NEC* [2] jurisdictions (along with the CE Code) have dominantly been based upon the successful experiences over many decades of using conventional induction motors without any additional special requirements, except for a temperature assessment and the use of only non-sparking accessories. The IEC has historically taken a different approach, being prescriptive in its requirements intended to make the equipment suitable for the application. Note the following definition for “equipment protective level (EPL) Gc” from IEC 60079-0 [11], which governs the general category of electrical equipment for application in a Zone 2 area classification: “EPL Gc is equipment for explosive gas atmospheres, having an “enhanced” Level of Protection, which is not a source of ignition in normal operation and which may have some additional protection to ensure that it remains inactive as an ignition source in the case of regular expected occurrences (for example failure of a lamp)” [11].

An increased safety Ex “ec” machine, per IEC 60079-7 [12], would be appropriate for installation as EPL Gc equipment, for example. “Normal service” for Level of Protection “ec” electric motors (of duty types S1, S2, S6 or S9 per IEC 60034-1[13]) has excluded starting, consistent with the *NEC* [2] and CE Code [3] approach for Division 2 and Zone 2 installations.

It is helpful to go back in history several years, as the IEC standards have evolved. In 2005, there were efforts by those experienced with the *NEC* to moderate the IEC requirements for motors intended to be applied in a Zone 2 area classification, because industrial-type motors – without significant special requirements – had been used successfully since the 1940s. Prior to 2015, the IEC standard applicable for electric motors commonly installed in a Zone 2 area was non-sparking, type “nA”, governed by IEC 60079-15 [14], which had minimal additional requirements. The conditional exclusion of motor starting from normal service was introduced. Beginning with IEC 60079-7, Ed 5 (2015) [12], the requirements for the type “nA” motor were migrated to this standard as Level of Protection “ec”. This standard also includes more stringent requirements for Level of Protection “eb” for equipment installations principally in Zone 1, although occasionally specific country jurisdictions may require Level of Protection “eb” for Zone 2 installations. Equipment protection by increased safety is infrequently used in jurisdictions enforcing the *NEC* [2], but is becoming more common in jurisdictions enforcing the CE Code [3].

IEEE 1349 [1] has also added considerable information to the initial content on shaft voltage and discharge energy, harmonized with Annex H of IEC 60079-0, Ed 7 (2017) [11], which is described below in section V.

Consistent with the technical content of the latest editions of IEC 60079-0 [11] and IEC 60079-7[12], IEEE 1349 [1] has added two new definitions: prestart ventilation and comparable converter, where a converter is the same as an ASD.

1) *Prestart Ventilation:* “Prestart ventilation” is not the same as the purged and pressurized enclosure requirements of the NFPA, UL, or CSA standards mentioned above, and this has been clarified with the new IEEE 1349 [1] definition and in the IEC draft standard revisions that are in process. Additionally, a note in Section 6.12.1 on Pressurization, Purging, or Ventilation adds an important aspect to be considered, where prestart ventilation is described as the process of applying purging, but not the pressurization aspects of NFPA 496 [15] or UL 60079-2 [16] or CSA 60079-2 [17], prior to starting a motor to reduce the concentration of any flammable gas or vapor that may initially be present [1]. Also note, if the application conditions are so unusual that pressurization, prestart purging, or prestart ventilation is deemed necessary to reduce ignition risk, consideration should be given to the designation of the electrical area classification.

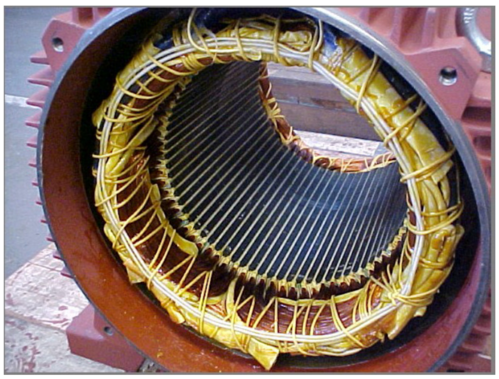
2) *Comparable Converter:* The “comparable converter” concept is important from a motor surface temperature perspective, because harmonic currents and voltages can affect the losses within a motor and influence the application considerations, particularly if the motor is installed in an environment where a low AIT material is handled. A “comparable converter” is defined as a converter where the losses in the motor supplied by the converter are not higher than the losses that would have occurred if the motor were used with the specific converter that was used during the type test [1]. Also note this converter is similar with respect to the output voltage, output current, and switching frequency specifications so the machine limiting temperatures, for maximum surface temperature and material thermal stability, are not exceeded [1]. There is work in progress on the draft of the future Edition 6 of IEC 60079-7 [12], which will give guidance on the selection of comparable converters as applied to increased safety electric machines.

III. SPACE HEATERS

A. Space Heater Example

To prevent moisture condensation when a motor is not in operation, space heaters can be installed to maintain the internal temperature of the motor approximately 5 °C above the ambient temperature. The Guide illustrates various types of space heaters provided in motor enclosures depending upon types of motor construction/enclosure.

Flexible strip heaters as shown in Fig. 3 are applied directly on the motor winding. When required to limit surface temperature, thermostatically controlled type heaters are used, typically in an enclosure. The CE Code [3] does not allow thermostatically controlled heaters in Zone 2 areas unless heaters and controls are approved for the location. Refer to Appendix A, Table A-II for additional information on space heater applications.



NOTE—Silicone insulated heater fastened onto the motor end-turns (white color in photograph).

Fig. 3 Example of a wrap around flexible space heater installed on a motor (Fig. 5 [1])

B. Test Procedures

The space heater test method is based on the temperature rise method. The machine is operated at its nameplate hp or kW until thermal equilibrium has been attained. After thermal equilibrium is observed on all the monitored temperature channels, the machine is shut down and immediately power is applied to the space heater at circuit rated nameplate voltage. The power applied to the space heaters and temperature monitoring of all the heating elements needs to remain active until all temperatures are no longer increasing and have stabilized or show a decreasing trend. The highest temperatures seen during the test are taken as reference temperatures to determine the suitable temperature nameplate in accordance with the *NEC* [2] or the CE Code [3]. The 40 °C standard reference ambient is then added to the calculated temperature rise delta to obtain the final maximum operating surface temperature. For ambient temperatures higher than the standard reference ambient, the maximum operating surface temperature should be adjusted.

C. Space Heater Temperature Limits

Various temperature limits are based on the *NEC* [2] and CE Code [3] for the Division and Zone systems. Those limits are summarized in Table A-II in Appendix A.

Heaters on machines, when assessed for the specified maximum surface temperatures as discussed above, require a dedicated nameplate for the space heaters to determine suitability for the area classification and AIT. The nameplate includes heater circuit voltage, maximum total space heater watts, and the maximum measured surface temperature (based on 40 °C ambient) as determined above. Alternatively, the suitable temperature class (T Code), per the *NEC* [2] and CE Code [3], can be listed.

IV. TEMPERATURE TESTS

High stator and rotor temperatures are possible sources of ignition; therefore, significant data has been accumulated over the years on machine temperatures. The original data has been supplemented by new data collected since the previous edition of the Guide was published.

In most applications, the rotor has the higher loaded temperature rise. The rotor temperature is more difficult and expensive to measure, particularly while the motor is running. Various methods have been used to determine rotor temperature, where these test methods are described in IEEE 1349 Clause 8 and Appendix I [1]. Below are discussions for the new PM motor temperature test, general machine temperature overview and observations, sine wave power machine temperature test results, and ASD test configurations with ASD fed motor temperature test results.

A. New Permanent Magnet (PM) Motor Test Method

One type of machine that is new to the Guide is the PM motor where the rotors do not carry any fundamental or slip frequency current, causing different temperature distributions. A new unique rotor temperature test method, “Open circuit voltage for PM motors,” was introduced in the Guide test method section that enables determination of the PM temperature. This method relies on the fact that a PM’s flux density decreases with its temperature. For typical rare earth magnets, the flux density decreases by about 0.1% per °C, however exact data should be obtained from the magnetic material supplier. If a motor rotates without the stator being connected to a supply, i.e., on coast-down, it will act as a generator and the no load terminal voltage at a particular speed will be dependent on the flux density and therefore the PM temperature.

To do the test, the known ambient temperature motor should be accelerated to some speed on ASD power, then allowed to coast down while open circuited. Simultaneously, the output voltage and frequency are measured. The motor is then run on load until the stator temperature is stabilized and the open circuit coast down voltage and frequency again measured. The change in output voltage at a particular frequency can then be determined while using the known flux density versus temperature relationship; therefore, the change in rotor temperature can be determined. The rotor temperatures listed were obtained by adding 5 °C to allow for “Hot Spot” differences. Many of the traditional methods such as thermocouples, heat sensitive paint and sensitive stickers can still be used, but this method does not require later dismantling of the motor.

Note that at a particular temperature, often below 200 °C, the PM material loses its magnetism and does not return to its pre-heating levels; therefore, overloading should be avoided.

B. General Machine Temperature Overview and Observations

The Guide provides general discussions on causes of temperature rises in various designs and provides some AIT data of flammable gases commonly encountered in the petrochemical industry. In a hazardous (classified) location, the machine's exposed surface temperature should not exceed the AIT of the potential flammable gas. There are now 29 tables of temperature data for hundreds of motors and generators from fractional hp to 66 000 hp included in Appendix H [1]. Tables are broken down into power rating, synchronous or induction or PM motor, enclosure type, loading, cooling method, and fixed or adjustable speed application.

As a reminder, engineers and operators should be aware of the 2001 observation, during the Working Group laboratory tests, when operating motors did not ignite a flammable mixture, but when the motors were shut off with a low AIT gas present, the heat rise and loss of circulating air immediately caused an ignition in some motors where the rotor operating temperature was significantly greater than the published AIT of the gas. Each application involves engineering judgment as noted in Annex H.3 [1], "Temperature Test Observations." Motors should be shutdown in a programmed and controlled manner to minimize the introduction of unknown effects on the surrounding environment. However, it is recognized there are times when quickly shutting motor-driven systems down when a gas release occurs may be preferred over a slower controlled shutdown [8].

C. Sine Wave Test Results – Motors and Generators

Most of the 13 tables of fixed speed data are at rated voltage with results of machines tested at 1.0 SF load summarized in Fig. A-1 with a graph showing the average of maximum measured rotor temperature with ± one standard deviation of the motors tested. These test results were used to develop the motor operating temperature for Common Application conditions, Table 1 [1] with excerpts shown in Table A-I herein that identifies the maximum recommended exposed surface temperature limits of 200 °C or 180 °C.

Most of the tables correlated extremely well with previous data in earlier editions of the Guide. For WP II enclosures, above 300 kW (400 hp) with axial duct or non-ducted rotor cooling, significant differences were identified between induction and synchronous machines and the table was split into Table 13a [1], induction, and Table 13b [1], synchronous. The WP II induction motors had an average rotor temperature of 160 °C; while, the WP II synchronous motors had an average rotor temperature of 100 °C. See Fig. A-1 for motor test data comparisons.

Results of motors tested at 1.15 SF load are shown in Fig. 2, illustrating that the rotor temperature in some cases may exceed the maximum recommended surface temperature. Table H.17 [1] is for TEFC motors tested at 90% voltage where the stator and rotor temperatures increase +5% to +15% from rated voltage.

D. ASD Tests – Configurations and Results

Understanding test configurations for ASD fed motor tests is paramount to interpreting the test data results. Annex H includes eight new ASD test configuration illustrations showing various motor/ASD test setups developed to align with the motor/ASD test data provided in Annex H [1] for real world applications. Refer to Fig. A-2 in Appendix A for the test configuration ASD-LV-1 which was typically used for low-voltage (LV), pulse-width-modulated (PWM) applications without filters. The dynamometer simulates the load. Refer to Fig. 4 for the test configuration ASD-MV-E [18], an illustration of a "back to back" test for large MV machines with two ASDs and two motors where one operates as a motor and the other as a generator.

Most LV and MV systems can generally be tested directly with a dynamometer such as Fig. A-2. However, for larger motors, it is usually preferred to keep utility energy costs low by recovering as much of the energy as possible. Therefore, in these situations some form of "back to back" test is performed, such as Fig. 4. Load testing of large ASD fed machines generally requires them to operate at full load from either the "on site" or the "comparable" ASD, typically at the specified or designed speed range. The Guide includes schematics of various loading arrangements including that shown in Fig. 4 [18] used on a 23 MW system where the plant power system only had to supply the losses.

Most of the data presented in the tables was obtained using the "on site" ASDs. One requirement that has recently been introduced for testing of motors on ASDs is for the "comparable converter" discussed in II.C.1) herein when the "on site" ASD is not used for testing.

There are nine data tables of temperature readings supplied for ASD fed motors from 2 hp to 31 400 hp operated at various speeds and loads. For ASD fed TEFC motors up to 370 kW (500 hp), the stator temperature rise was within 95 °C when operated at rated speed and 1 per unit torque, except one 450 hp motor had a 101 °C stator temperature rise. There are spreads in the data with typically only one or two machines of similar ratings in any particular group, but it does appear that a motor on an ASD does have slightly higher temperatures than on a sine wave power at the same load and speed.

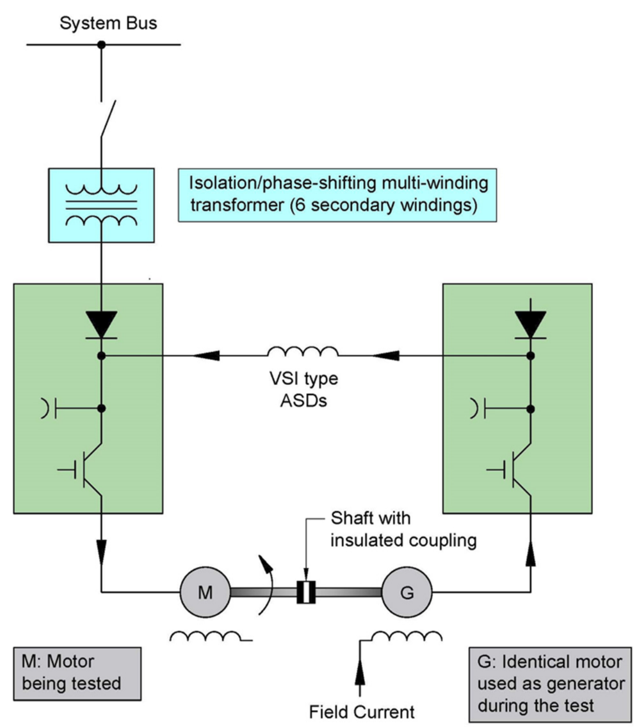


Fig. 4 Test configuration ASD-MV-E [18]
Back to back with two ASDs and two motors where one operates as a motor and the other as a generator (Fig. H.11 [1])

Motors driving "constant torque" loads, such as positive placement pumps, at reduced speed do have higher temperatures at the reduced speed. ASD tests typically establish the minimum speed for "constant torque" loads where the cooling from the fan becomes inadequate.

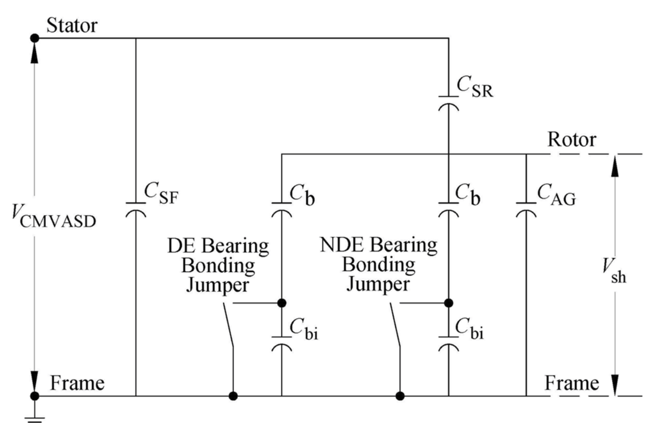
V. DISCHARGE ENERGY DUE TO CMV

A. Overview of Common-Mode Voltage (CMV)

The ASD output operates with a switching mode, dc to ac, therefore motors fed by ASDs have a CMV appearing between the neutral and ground. The magnitude of the CMV depends on the system voltage, the ASD topology, remediation measures such as filters, the cable type, and cable length. The CMV develops a shaft voltage that can discharge in bearing causing electric discharge machining (EDM). IEEE 1349 [1] recommends that the insulation and bonding should be discussed with the motor manufacturer and maintained to prevent damage to bearings. To prevent EDM, shaft bonding devices may be used without explosionproof enclosures provided it's determined that this discharge energy is nonincendive for the flammable vapor that may be present as noted in *NEC* 501.125(B)(5) [2].

Various calculation and measurement methods are used to determine the capacitive discharge energy. Table G.1 [1] is included in IEEE 1349 to give a comparison of the available calculation and measurement methods as well as their suitability for various applications. There are multiple capacitances internal to a motor as shown in Fig. 5. Because of capacitive coupling, there is a voltage induced between the rotor-shaft assembly and the frame which charges the capacitance and stores energy. This energy may be discharged as capacitive discharge energy through a spark.

The Guide gives an example of the calculation methods to determine the available energy in the charged-up rotor to frame total capacitance, C. The calculation requires construction details of the motor such as rotor, stator and air gap dimensions, number of stator slots, coil ground wall insulation, bearing data and magnitude of expected or measured CMV of the ASD.



NOTE—For C_{SF}, this capacitance bypasses some of the CMV energy away from the rotor to frame capacitance. C_{SF} can be measured or calculated; however, it is generally not considered, which is a more conservative energy calculation.

Fig. 5 Motor voltage schematic, general (Fig. G.6 [1])

In Fig. 5,

- C_b is the capacitance between the shaft and the bearing at each end, with lubricant as the dielectric (farads)
- C_{bi} is the capacitance of the bearing to frame insulation (if any) (farads) (This capacitance is often bypassed at one or both ends by a bonding jumper.)
- C_{AG} is the capacitance across the air gap between the rotor and the stator laminations. (farads)
- C_{SR} is the capacitance between the stator winding and the rotor (farads)
- C_{SF} is the three-phase capacitance between the stator winding and the frame (farads)
- V_{sh} is the peak shaft voltage (volts)
- V_{CMVASD} is the CMV of the ASD output (volts).

The discharge energy (spark energy) can be calculated using Equation (1).

$$E = \tfrac{1}{2} C V_{sh}^2 \tag{1}$$

where

E	is the discharge energy (joules)
C	is the total capacitance, sum of all capacitances of the rotor to the frame including the bearings across which the voltage, V_{sh}, appears (farads)
V_{sh}	is the peak shaft voltage (volts)

An example of a four- lobe sleeve bearing illustration included in the Guide is shown in Fig. 6 describing the data used to determine C_{bi}. In the design phase all three cases - none, one, or both of the bearings with a bonding jumper - can be analyzed to aid motor construction decisions.

At first glance, the capacitance across the air gap between the rotor and the stator laminations C_{AG} should be simple, however for salient-pole rotors, the proportion of the rotor circumference where there is actually a non-continuous air gap is used for the calculations as shown in Fig. 7.

Historically, the shaft voltage (V_{sh}) induced from the CMV of the stator has been taken as 10% of the CMV of the ASD, assuming it is similar at the motor terminals, which is often conservative, especially with larger machines.

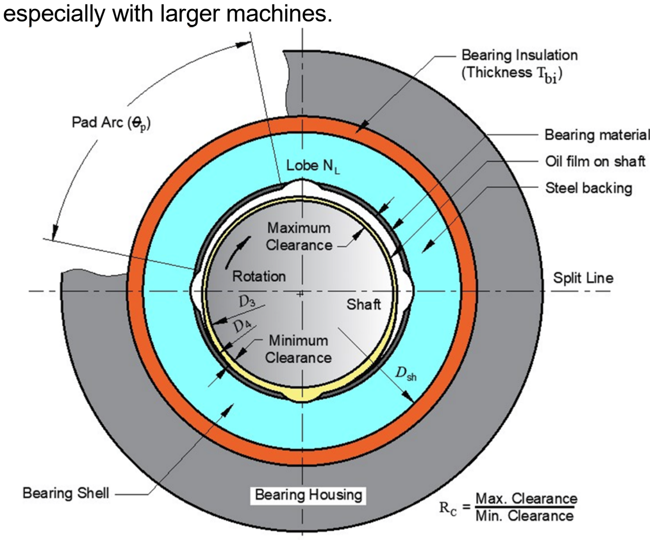


Fig. 6 Example of four-lobe sleeve bearing (Fig. G.4 [1]).

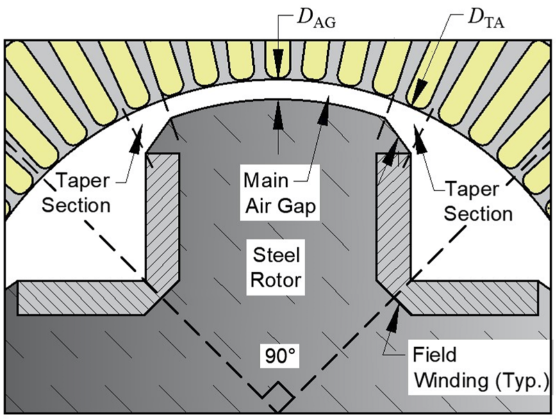


Fig. 7 Salient-pole rotor; proportion of the rotor circumference where there is actually a non-continuous air gap, Ps (Fig. G.5 [1]).

B. Overview of IEEE 1349 Discharge Energy Calculator

The Guide and the IEEE 1349 Discharge Energy Calculator [6] spreadsheet includes induction motors, salient pole and cylindrical rotor synchronous machines with hydrodynamic bearings, and also gives information on NEMA Frame machines with antifriction bearings. Examples in the Guide are the data used in the Discharge Energy Calculator spreadsheet which is freely available from IEEE. The spreadsheet uses the same formulas as the calculation method. Where it has been possible to compare calculated values with measured ones, the predicted and measured figures are similar.

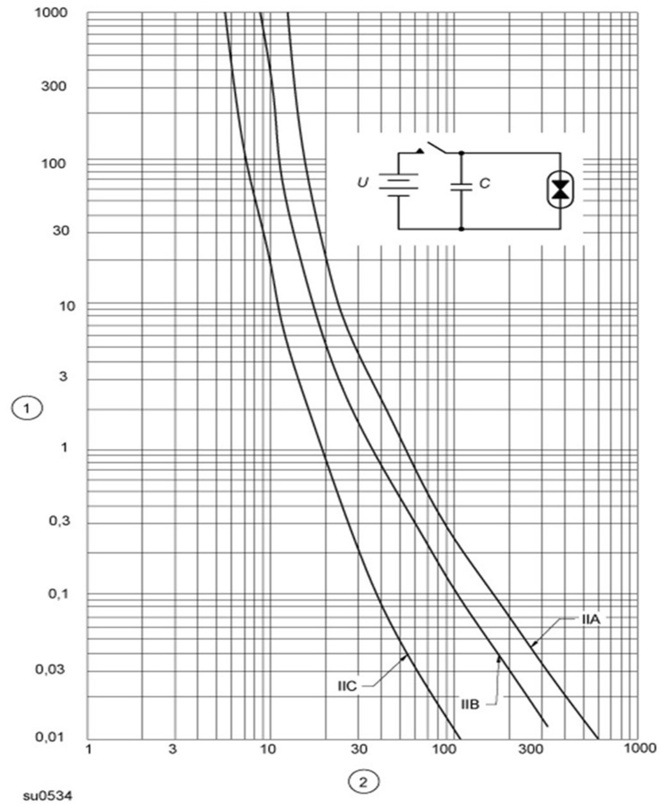
Although both the supplied formulas and the spreadsheet give useful data on discharge energy based on supplied machine and predicted data, it is also possible to enter measured data on capacitances and CMV levels into the calculations. Adjustment factors are included in the equations and spreadsheet for use as needed. Files are available in the IEEE 1349-2021 directory located at: https://standards.ieee.org/downloads.html [6].

C. Compare Discharge Energy to Minimum Ignition Energy (MIE) Method or Alternative Graph/Table Method

To perform an evaluation of CMV, compare the capacitive discharge energy to the MIE of the potential flammable gas, "comparison method." The Guide includes the NFPA 497 [19] listed MIE of more common flammable gases, e.g., the MIE of ethylene is 70 microjoules and methane is 280 microjoules. The calculated discharge energy can be determined using the equations in Annex G.3 [1], IEEE 1349 Discharge Energy Calculator [6] spreadsheet, or actual measurements of "C" and "V_{sh}". "Measurement methods" are described in Annex G.3.4 [1].

IEEE 1349 [1] also provides an "alternative graph/table method" shown in Fig. 8, a graphical plot of shaft voltage, V_{sh}, versus total capacitance, C, to determine which applications for the gas group are nonincendive, when data plots on the left-side of the applicable curve. With permission, IEEE 1349 [1] uses the IEC Capacitive Ignition Curves [11], Fig. 8.

Tests and analysis methods described in IEEE 1349 [1] indicate that sparking caused by ASDs typically should not cause problems; however, analysis should be done on applications involving gases such as acetylene and hydrogen with low MIEs, 17 microjoules and 19 microjoules, respectively.



Legend: 1 is total capacitance, C (μfarad); 2 is shaft voltage V_{sh} (volts).
Fig. 8 Capacitive Ignition Curves
IEC 60079-0 ed.7.0 [11] © 2017 IEC Geneva, Switzerland. www.iec.ch

VI. CONCLUSIONS

IEEE 1349-2021 is the premier Guide for the application of electric machines in hazardous (classified) locations as referenced in the *NEC* [2] and CE Code [3]. The techniques provide proven methods to prevent overtemperature and sparking in locations where flammable gases may be present.

The Guide provides a significant update of surface temperature measurements that were conducted on many types and sizes of fixed speed and ASD fed motors. The influence of applicable global IEC standards has also been incorporated in the text of the Guide. A space heater temperature test method was added to provide nameplate data used to prevent overtemperature. A new PM motor rotor temperature test provides vital information for this new technology.

A major expansion, over 20 pages, added details for determining discharge energy due to CMV to analyze if the energy is nonincendive. The informative Annex presents several methods, including a free download IEEE 1349 Discharge Energy Calculator [6] spreadsheet and measurement techniques, to determine discharge energy. These form the basis for future investigative work to validate the calculations.

VII. ACKNOWLEDGEMENTS

It is our honor to present this paper on behalf of the dedicated Working Group members, experts, contributors, and balloters that shared their time and expertise to provide the latest technologies. Thank you to our reviewers for providing valuable feedback.

VIII. REFERENCES

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[3] CAN/CSA C22.1-2021, Canadian Electrical Code® (CE Code®) Safety Standard for Electrical Installations.

[4] IEEE Std 841™, IEEE Standard for Petroleum and Chemical Industry—Premium-Efficiency, Severe Duty, Totally Enclosed Fan-Cooled (TEFC) Squirrel Cage Induction Motors—Up to and Including 370 kW (500 hp).

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IX. VITAE

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APPENDIX A
MOTOR SURFACE TEMPERATURE AND SPACE HEATERS

TABLE A-I
MOTOR OPERATING TEMPERATURE FOR COMMON APPLICATION CONDITIONS [a] (Table 1 [1])

Size	Enclosure types	Rotor cooling Type [b]	Typical rotor operating temperatures at full load [c] (°C)	Maximum recommended exposed surface temperature at full load (°C)
Three phase—NEMA frame sizes – Induction				
Up to 335 kW (450 hp)	ODP	Nonducted ventilation	115–150 [e]	200
Up to 300 kW (400 hp)	TEFC	Nonducted or axial duct ventilation	105–160	200
Three phase—above NEMA frame sizes – Induction				
100 kW to 300 kW (125 hp to 400 hp)	TEFC	Nonducted or axial duct ventilation	120–175	200
Above 300 kW (400 hp)			120–195	200
Above 300 kW (400 hp)	WPII	Nonducted or axial duct ventilation	115–205	200
Three phase—above NEMA frame sizes – Synchronous				
Above 300 kW (400 hp)	WPII & ODP	Nonducted or axial duct ventilation	90–110	180
Above 300 kW (400 hp)	TEFV & TEWAC	Nonducted or axial duct ventilation	85–115	180
Three phase—above NEMA frame sizes – Induction & Synchronous				
Above 110 kW (150 hp)	All [f]	Axial duct and radial duct ventilation	90–135	180
Three phase—above NEMA frame sizes – Permanent Magnet				
Up to 100 kW (125 hp)	TEFC	Nonducted or axial duct ventilation	110–160	180

[a] Table A-I is based on a small sampling of motors. Engineering judgment should be used and users should confer with the motor manufacturer. Temperatures are based on Class B rise at 1.0 SF, low-slip induction motors and synchronous motors, with a 40 °C ambient, rated voltage, and rated frequency.
[b] See H.1.2 [1] for a discussion of the rotor cooling types. See also Figure 2 [1], which shows axial and radial ventilation ducts in the rotor.
[c] Average rotor temperature of tested and calculated values within 1 standard deviation (rounded up to the nearest 5°). (In the Guide [1], see Table H.8, Table H.9, Table H.10, Table H.11, Table 13a, Table 13b, Table H.14, Table H.15, Table H.16, and Table H.18.)
[d] (not included in excerpt)
[e] Typical range is primarily based on motor manufacturer's calculated rotor temperatures on NEMA Design B motors. (Refer to Table H.8 [1].)
[f] Radial rotor ventilation is currently not used for NEMA frame-sized TEFC enclosures and is rare for above NEMA frame-sized TEFC enclosures.

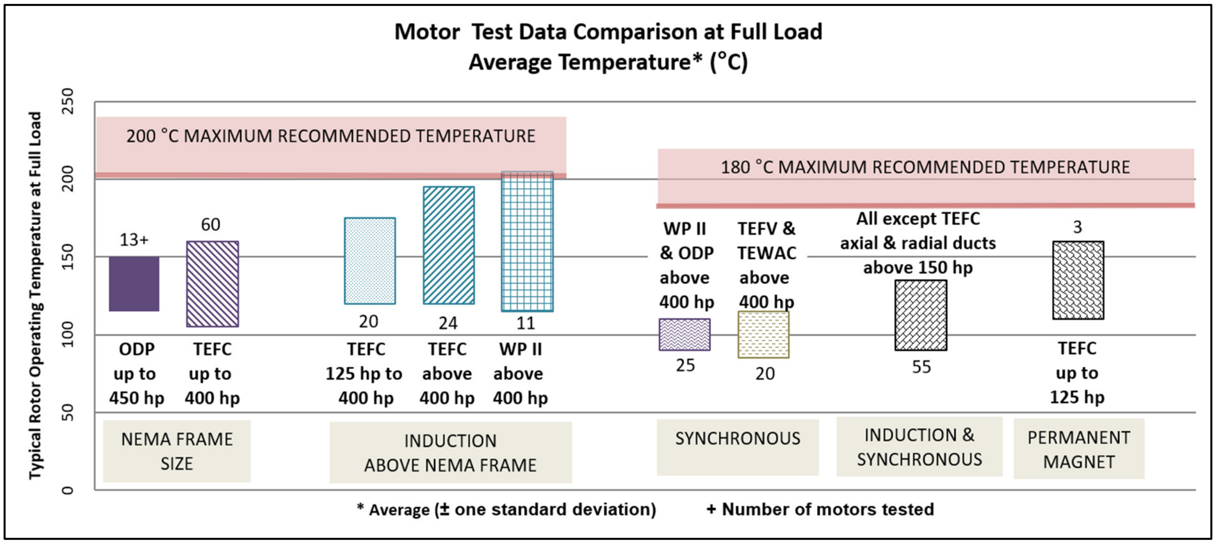

Fig. A-1 Motor Test Data Comparison at Full Load – Fixed Speed – Rotor Operating Temperature

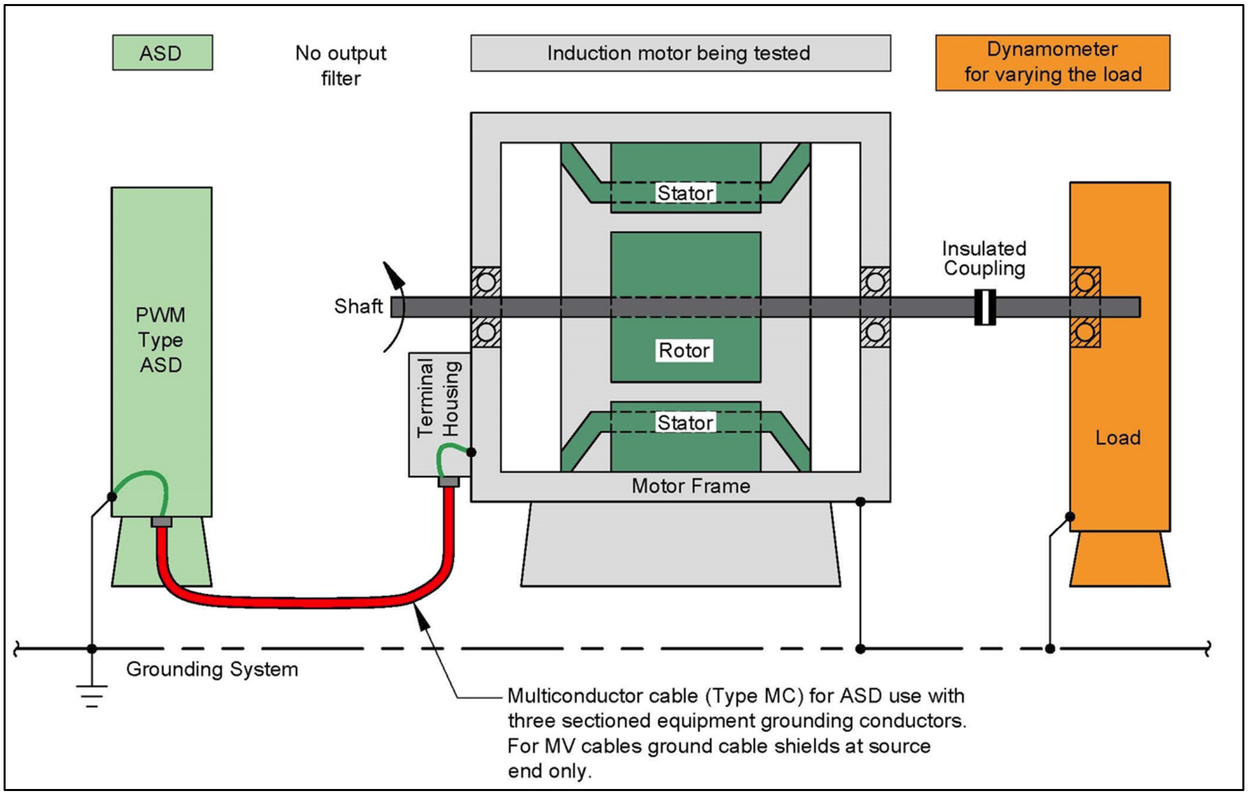

Fig. A-2 Test Configuration ASD-LV-1, PWM type ASD, no filters (Fig. H.6 [1])

TABLE A-II
SPACE HEATER TEMPERATURE UNDER NORMAL OPERATING CONDITIONS (Table 2 [1])

Zone 2 & Division 2		
Space heater tested and labeled with a T Code **Space heater tested and labeled with a maximum temperature based on the ambient**		
Applicable Code	Ambient [c]	Space Heater Temperature Limit
Zone 2 2021 CE Code Subrule 18-150 3) and Temperature Rule 18-054 [b]	40 °C	T Code temperature does not exceed the AIT
	40 °C	Maximum surface temperature [a] does not exceed the AIT
Division 2 2021 CE Code Subrule J18-150 3) and Temperature Rule J18-054 [b]	40 °C	T Code temperature does not exceed the AIT
	40 °C	Maximum surface temperature [a] does not exceed the AIT
Zone 2		
Space heater tested and labeled with a T Code		
Applicable Code	Ambient [c]	Space Heater Temperature Limit
2020 *NEC* Section 505.20 (C)	40 °C	T Code temperature does not exceed the AIT
Division 2		
Space heater marked with a maximum temperature based on the ambient		
Applicable Code	Ambient [c]	Space Heater Temperature Limit
2020 *NEC* Section 501.125 (B)	40 °C	Maximum surface temperature [a] does not exceed 80% of the AIT
Space heater identified for Class I, Division 2 (for example tested and labeled with a T Code)		
Applicable Code	Ambient [c]	Space Heater Temperature Limit
2020 *NEC* Section 501.125 (B)	40 °C	T Code temperature does not exceed the AIT

[a] See 8.3.2 [1] for space heater temperature test method.
[b] For the CE Code [3], space heaters (anti-condensation heaters) shall not have any arcing devices in general-purpose enclosures. The CE Code [3] does not permit the use of temperature-limiting controls to limit the maximum surface temperature of the heater (in case of failure of the limiter). See Figure 6 [1].
[c] For higher ambient temperatures, adjust the maximum surface temperature of the space heater. See 8.3.2 [1].

IEEE 1349-2021 - ELECTRIC MACHINES IN HAZARDOUS LOCATIONS - WORLDWIDE APPLICATIONS

Paper No. PCIC-

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Abstract – IEEE Std 1349-2021™ [1] "Guide for the Application of Electric Machines in Zone 2 and Class I, Division 2 Hazardous (Classified) Locations," the third edition, has been updated for the 2020 National Electrical Code, *NEC* [2] and guidance has been added for the 2021 Canadian Electrical Code, CE Code [3]. The Guide has been expanded to harmonize internationally and updated for IEEE Std 841 [4] for TEFC motors and IEEE P303 [5] for auxiliary devices. Some elements from the IEC – International Electrotechnical Commission - Increased Safety standard was included. Precautions against excessive surface temperatures and sparking are covered. To mitigate hot surface temperatures and sparking, this document provides guidance for selecting, operating, and maintaining motors where flammable gases and vapors may occasionally be present.

This paper provides an overview with highlights of key elements, discusses worldwide applications, includes new space heater tests and applications, and describes a new test method to determine the permanent magnet (PM) motor rotor temperature. It also details machine temperature test information along with adjustable speed drive (ASD) test configurations and provides an overview of discharge energy calculations due to common-mode voltage (CMV) for ASD applications with a link to the new IEEE 1349 Discharge Energy Calculator [6].

Index Terms — Adjustable Speed Drive, Common-mode Voltage, Generator, Hazardous Locations, IEEE 1349 Discharge Energy Calculator, Motor, Surface Temperature, Rotor, Sparking, Space Heater.

I. INTRODUCTION

A. Background and Scope

This Guide was originally published in 2001 and revised in 2011. Overviews are provided in papers [7] and [8] for the first and second editions, respectively. In 2018 the Working Group scope expanded and the Working Group name changed from motors to machines. This 2021 edition was revised by about 40 members of the Machines in Hazardous Locations Working Group Committee of the IEEE Petroleum and Chemical Industry Committee.

IEEE has several categories of documents denoted as "standards:" 1) *Guides* suggest good practices but no clear-cut recommendations are made, 2) *Recommended Practices* have preferred positions and procedures, and 3) *Standards* provide mandatory requirements.

Developed as a Guide, IEEE 1349 [1] assists individuals, organizations, and suppliers with the application of machines in Zone 2 and Class I, Division 2 locations, where flammable gases and vapors may occasionally be present as shown in Fig. 1. Primary emphasis is on the use of open or nonexplosionproof enclosed or nonflameproof enclosed machines and precautions against excessive surface temperatures and sparking of rotor bars and enclosure joints. IEEE 1349 [1] provides guidance for selecting, operating, and maintaining machines in Zone 2 and Class I, Division 2 locations to help mitigate hot surface temperatures and sparking.

Key advancements of the Guide include new space heater temperature test procedures and a new rotor temperature test method for PM motors. Machine rotor and stator surface temperature data tables were expanded for sine wave and ASD applications with new test configuration figures for ASD tests. IEEE 1349 [1] significantly expanded the information for sparking and discharge energy determination due to CMV for ASD applications, and the Guide includes a free download of the new IEEE 1349 Discharge Energy Calculator [6].

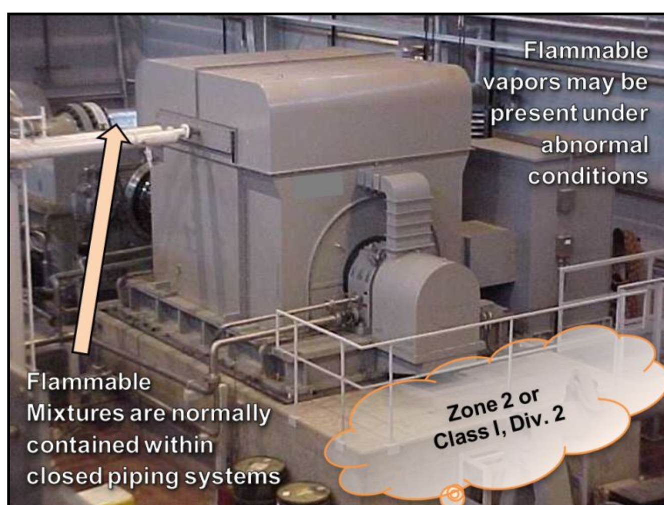


Fig. 1 Hazardous (classified) location, Zone 2 or Class I, Div. 2

B. Third edition impact

This edition of the Guide updated information throughout the document to include the latest technologies. The scope expanded to include the CE Code [3], generators, and PM motors.

The Guide includes the space heater temperature test method in Clause 8 [1] described below in III. Manufacturers conducted independent machine and ASD temperature tests and confidentially shared their data with the Working Group, which was captured in Annex H [1]. Machine temperature test data was expanded for fixed speed and ASD applications along with new companion ASD Test Configuration drawings. The maximum recommended exposed surface temperatures were updated and expanded to include PM motors in Table 1 [1] with an excerpt in Table A-I in Appendix A herein.

For ASD applications, a CMV is caused by the switching strategy of the ASD and creates a shaft voltage that can discharge, which may have a discharge energy that is incendive or nonincendive. The procedure for determining discharge energy due to CMV was significantly expanded in Annex G.3 [1] and an IEEE 1349 Discharge Energy Calculator [6] spreadsheet was made available for free download and use.

C. Key Elements - Event Mitigation and Motor Protection

The petrochemical industry has experienced an excellent history utilizing open-type and TEFC motors in Zone 2 and Class I, Div. 2 hazardous locations. Starting in the 2001 edition up through the 2021 edition, nine events have been documented in Annex J [1]. Six of the events involved gas compressor applications, where the flammable gas source was transferred via a common bearing lubricating oil system from the compressor to the motor. This flammable material accumulated inside the motor enclosure and then various ignition sources caused the events. Mitigation techniques include separating high-pressure gas compressor lubricating oil systems from the motor lube oil system, continuously degassing the lubricating oil and transferring gas into a closed piping system, or using pedestal bearings for the machine, which are described in 5.6.3 [1] and IEEE Std 3004.8 [9].

The motor should be selected to avoid overload conditions. Refer to Fig. 2 showing rotor operating temperatures of induction motors that are rated for 1.0 Service Factor (SF) with a Class B stator temperature rise which are tested at 1.15 SF load (overload condition). The overload protection requirements are in the 2020 *NEC* [2], Sections 430.32 (Continuous-Duty Motors), 430.124 and 430.126 (Adjustable Speed Drive systems overload and overtemperature protection, respectively) and 430.225(B) (motors over 1000 V nominal). In some locations, similar requirements with some variations may be stipulated by the authority having jurisdiction. Refer to IEEE Std 3004.8™-2016 [9] for information on overload types and selection.

Sound engineering judgment should be used for setting overload devices considering the motor rating, load, autoignition temperature (AIT) of the flammable vapors, and operation. For sine wave applications, overload device settings should be 115% or less of motor nameplate rated current for 1.0 and 1.15 SF motors. For ASD applications, current limit setting should be 100% of motor nameplate rated current and overload device settings should be 115% or less of motor nameplate rated current.

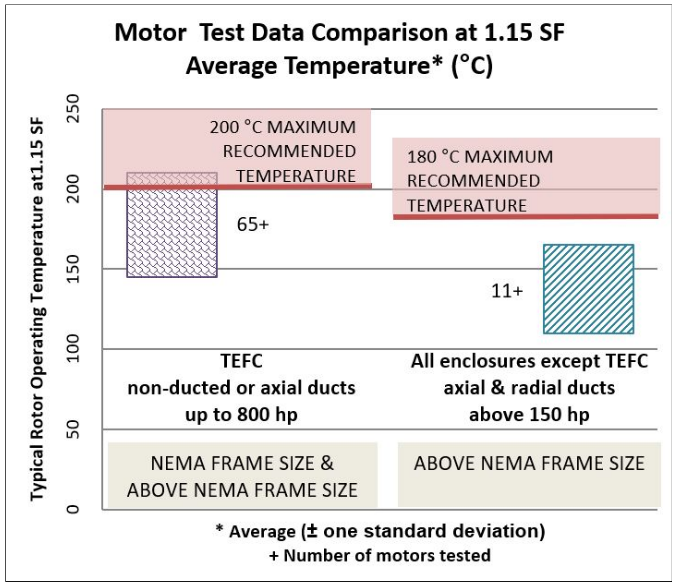


Fig. 2 Induction Motors Rated 1.0 SF, Class B Rise, Tested at 1.15 SF, Showing Rotor Operating Temperature.

II. WORLDWIDE APPLICATIONS

A. NEC and CE Code Harmonization

There have been on-going efforts to harmonize the *NEC* and the CE Code. Machines designed for the Division system as defined in *NEC* Article 501 [2] are equally accepted in the IEC based Zone system as defined in *NEC* Article 505 [2] and vice-versa. Within the USA, Division system installations are the predominant system following the original path taken by the *NEC* [2]. The Zone system installation requirements were introduced to the *NEC* [2] in 1996. The CE Code [3] for Canada mandates the IEC based Zone system as specified in Section 18 of the CE Code, although it allows Division based machines as specified in the Annex J18 of the CE Code [3]. The *NEC* [2] and CE Code [3] allow machines suitable for unclassified locations to be installed in Zone 2 or Division 2 classified location as long as they do not spark or have hot surfaces exceeding the AIT of gas or vapor in normal operating conditions. Normal operating condition is the condition when a machine is operating at its steady state load condition. Starting or accelerating of a machine is not considered a normal operating condition for the machine design when it's installed in a Division 2 or Zone 2 area. Space heaters, if supplied with machines, must follow the *NEC* [2] and CE Code [3] to limit the maximum surface temperatures as discussed later in this paper.

Recognized as an application guide for many international locations, IEEE 1349 [1] is referenced in the "Note" of Appendix B of the CE Code [3] Rule 150 (2) (e) when machines are designed for Class I, Division 2 or Zone 2 areas.

The *NEC* [2] also refers to IEEE 1349 [1] in the informational notes of Sections 501.125 (B) and 505.20(C) as the Guide to follow for machines installed in Division 2 or Zone 2 areas, respectively. In addition, the Guide specifically addresses space heaters and determining if the discharge energy is incendive or nonincendive for applications of shaft bonding brushes in ASD applications.

B. IEEE Harmonization

IEEE P303 [5] is presently being revised and harmonized to include all accessories being used or provided in machines designed for Zone 2 or Class I, Division 2 locations. Primary areas of harmonization with IEEE 1349 [1] are space heaters and shaft bonding brushes.

IEEE Std 841 [4] covers TEFC, severe-duty, induction motors up to 370 kW (500 hp) suitable for unclassified locations; and, these motors have all features as explained in the Common Applications of IEEE 1349 [1]. Therefore, these motors can equally be installed in Zone 2 or Division 2 locations as specified in the *NEC* [2] and the CE Code [3]. The "Common Application" sine wave power and "Common ASD Application" categories in IEEE 1349 [1] require machines not to exceed 200 °C surface temperature based on 40 °C ambient air temperature. In addition, these categories are harmonized with IEEE 841 [4] for stator temperature rise of 80 °C for sine wave power and 95 °C for ASD power for variable torque loads. Motors designed to meet IEEE 841 [4] do not require specific Nationally Recognized Testing Laboratory (NRTL) in USA or Certifying Body (CB) certification in Canada for Zone 2 or Division 2 locations.

C. IEC Global Influence

The United States and Canada have adopted the IEC-based Zone area classification systems; however, the IEC equipment standards have been accepted with US and Canadian national differences. Although the numerical designations of the IEC standards are kept the same, the US and Canadian versions are prefixed with "UL" and "CSA C22.2 No.," because those organizations have revised the IEC standards with in-country differences. A quick reference comparison is in PCIC paper [10]. For 2021, an updated Table D.2 in IEEE 1349 [1] summarizes the Zone Type of Protection suitable for installation in Zone 2.

The application and technical requirements for electric machines installed in a Zone 2 area classification have evolved differently for those installations covered by the *NEC* [2] and those covered by other jurisdictions. The *NEC* [2] jurisdictions (along with the CE Code) have dominantly been based upon the successful experiences over many decades of using conventional induction motors without any additional special requirements, except for a temperature assessment and the use of only non-sparking accessories. The IEC has historically taken a different approach, being prescriptive in its requirements intended to make the equipment suitable for the application. Note the following definition for "equipment protective level (EPL) Gc" from IEC 60079-0 [11], which governs the general category of electrical equipment for application in a Zone 2 area classification: "EPL Gc is equipment for explosive gas atmospheres, having an "enhanced" Level of Protection, which is not a source of ignition in normal operation and which may have some additional protection to ensure that it remains inactive as an ignition source in the case of regular expected occurrences (for example failure of a lamp)" [11].

An increased safety Ex "ec" machine, per IEC 60079-7 [12], would be appropriate for installation as EPL Gc equipment, for example. "Normal service" for Level of Protection "ec" electric motors (of duty types S1, S2, S6 or S9 per IEC 60034-1[13]) has excluded starting, consistent with the *NEC* [2] and CE Code [3] approach for Division 2 and Zone 2 installations.

It is helpful to go back in history several years, as the IEC standards have evolved. In 2005, there were efforts by those experienced with the *NEC* to moderate the IEC requirements for motors intended to be applied in a Zone 2 area classification, because industrial-type motors – without significant special requirements – had been used successfully since the 1940s. Prior to 2015, the IEC standard applicable for electric motors commonly installed in a Zone 2 area was non-sparking, type "nA", governed by IEC 60079-15 [14], which had minimal additional requirements. The conditional exclusion of motor starting from normal service was introduced. Beginning with IEC 60079-7, Ed 5 (2015) [12], the requirements for the type "nA" motor were migrated to this standard as Level of Protection "ec". This standard also includes more stringent requirements for Level of Protection "eb" for equipment installations principally in Zone 1, although occasionally specific country jurisdictions may require Level of Protection "eb" for Zone 2 installations. Equipment protection by increased safety is infrequently used in jurisdictions enforcing the *NEC* [2], but is becoming more common in jurisdictions enforcing the CE Code [3].

IEEE 1349 [1] has also added considerable information to the initial content on shaft voltage and discharge energy, harmonized with Annex H of IEC 60079-0, Ed 7 (2017) [11], which is described below in section V.

Consistent with the technical content of the latest editions of IEC 60079-0 [11] and IEC 60079-7[12], IEEE 1349 [1] has added two new definitions: prestart ventilation and comparable converter, where a converter is the same as an ASD.

1) *Prestart Ventilation:* "Prestart ventilation" is not the same as the purged and pressurized enclosure requirements of the NFPA, UL, or CSA standards mentioned above, and this has been clarified with the new IEEE 1349 [1] definition and in the IEC draft standard revisions that are in process. Additionally, a note in Section 6.12.1 on Pressurization, Purging, or Ventilation adds an important aspect to be considered, where prestart ventilation is described as the process of applying purging, but not the pressurization aspects of NFPA 496 [15] or UL 60079-2 [16] or CSA 60079-2 [17], prior to starting a motor to reduce the concentration of any flammable gas or vapor that may initially be present [1]. Also note, if the application conditions are so unusual that pressurization, prestart purging, or prestart ventilation is deemed necessary to reduce ignition risk, consideration should be given to the designation of the electrical area classification.

2) *Comparable Converter:* The "comparable converter" concept is important from a motor surface temperature perspective, because harmonic currents and voltages can affect the losses within a motor and influence the application considerations, particularly if the motor is installed in an environment where a low AIT material is handled. A "comparable converter" is defined as a converter where the losses in the motor supplied by the converter are not higher than the losses that would have occurred if the motor were used with the specific converter that was used during the type test [1]. Also note this converter is similar with respect to the output voltage, output current, and switching frequency specifications so the machine limiting temperatures, for maximum surface temperature and material thermal stability, are not exceeded [1]. There is work in progress on the draft of the future Edition 6 of IEC 60079-7 [12], which will give guidance on the selection of comparable converters as applied to increased safety electric machines.

III. SPACE HEATERS

A. Space Heater Example

To prevent moisture condensation when a motor is not in operation, space heaters can be installed to maintain the internal temperature of the motor approximately 5 °C above the ambient temperature. The Guide illustrates various types of space heaters provided in motor enclosures depending upon types of motor construction/enclosure.

Flexible strip heaters as shown in Fig. 3 are applied directly on the motor winding. When required to limit surface temperature, thermostatically controlled type heaters are used, typically in an enclosure. The CE Code [3] does not allow thermostatically controlled heaters in Zone 2 areas unless heaters and controls are approved for the location. Refer to Appendix A, Table A-II for additional information on space heater applications.

NOTE—Silicone insulated heater fastened onto the motor end-turns (white color in photograph).

Fig. 3 Example of a wrap around flexible space heater installed on a motor (Fig. 5 [1])

B. Test Procedures

The space heater test method is based on the temperature rise method. The machine is operated at its nameplate hp or kW until thermal equilibrium has been attained. After thermal equilibrium is observed on all the monitored temperature channels, the machine is shut down and immediately power is applied to the space heater at circuit rated nameplate voltage. The power applied to the space heaters and temperature monitoring of all the heating elements needs to remain active until all temperatures are no longer increasing and have stabilized or show a decreasing trend. The highest temperatures seen during the test are taken as reference temperatures to determine the suitable temperature nameplate in accordance with the *NEC* [2] or the CE Code [3]. The 40 °C standard reference ambient is then added to the calculated temperature rise delta to obtain the final maximum operating surface temperature. For ambient temperatures higher than the standard reference ambient, the maximum operating surface temperature should be adjusted.

C. Space Heater Temperature Limits

Various temperature limits are based on the *NEC* [2] and CE Code [3] for the Division and Zone systems. Those limits are summarized in Table A-II in Appendix A.

Heaters on machines, when assessed for the specified maximum surface temperatures as discussed above, require a dedicated nameplate for the space heaters to determine suitability for the area classification and AIT. The nameplate includes heater circuit voltage, maximum total space heater watts, and the maximum measured surface temperature (based on 40 °C ambient) as determined above. Alternatively, the suitable temperature class (T Code), per the *NEC* [2] and CE Code [3], can be listed.

IV. TEMPERATURE TESTS

High stator and rotor temperatures are possible sources of ignition; therefore, significant data has been accumulated over the years on machine temperatures. The original data has been supplemented by new data collected since the previous edition of the Guide was published.

In most applications, the rotor has the higher loaded temperature rise. The rotor temperature is more difficult and expensive to measure, particularly while the motor is running. Various methods have been used to determine rotor temperature, where these test methods are described in IEEE 1349 Clause 8 and Appendix I [1]. Below are discussions for the new PM motor temperature test, general machine temperature overview and observations, sine wave power machine temperature test results, and ASD test configurations with ASD fed motor temperature test results.

A. New Permanent Magnet (PM) Motor Test Method

One type of machine that is new to the Guide is the PM motor where the rotors do not carry any fundamental or slip frequency current, causing different temperature distributions. A new unique rotor temperature test method, “Open circuit voltage for PM motors,” was introduced in the Guide test method section that enables determination of the PM temperature. This method relies on the fact that a PM’s flux density decreases with its temperature. For typical rare earth magnets, the flux density decreases by about 0.1% per °C, however exact data should be obtained from the magnetic material supplier. If a motor rotates without the stator being connected to a supply, i.e., on coast-down, it will act as a generator and the no load terminal voltage at a particular speed will be dependent on the flux density and therefore the PM temperature.

To do the test, the known ambient temperature motor should be accelerated to some speed on ASD power, then allowed to coast down while open circuited. Simultaneously, the output voltage and frequency are measured. The motor is then run on load until the stator temperature is stabilized and the open circuit coast down voltage and frequency again measured. The change in output voltage at a particular frequency can then be determined while using the known flux density versus temperature relationship; therefore, the change in rotor temperature can be determined. The rotor temperatures listed were obtained by adding 5 °C to allow for “Hot Spot” differences. Many of the traditional methods such as thermocouples, heat sensitive paint and sensitive stickers can still be used, but this method does not require later dismantling of the motor.

Note that at a particular temperature, often below 200 °C, the PM material loses its magnetism and does not return to its pre-heating levels; therefore, overloading should be avoided.

B. General Machine Temperature Overview and Observations

The Guide provides general discussions on causes of temperature rises in various designs and provides some AIT data of flammable gases commonly encountered in the petrochemical industry. In a hazardous (classified) location, the machine's exposed surface temperature should not exceed the AIT of the potential flammable gas. There are now 29 tables of temperature data for hundreds of motors and generators from fractional hp to 66 000 hp included in Appendix H [1]. Tables are broken down into power rating, synchronous or induction or PM motor, enclosure type, loading, cooling method, and fixed or adjustable speed application.

As a reminder, engineers and operators should be aware of the 2001 observation, during the Working Group laboratory tests, when operating motors did not ignite a flammable mixture, but when the motors were shut off with a low AIT gas present, the heat rise and loss of circulating air immediately caused an ignition in some motors where the rotor operating temperature was significantly greater than the published AIT of the gas. Each application involves engineering judgment as noted in Annex H.3 [1], "Temperature Test Observations." Motors should be shutdown in a programmed and controlled manner to minimize the introduction of unknown effects on the surrounding environment. However, it is recognized there are times when quickly shutting motor-driven systems down when a gas release occurs may be preferred over a slower controlled shutdown [8].

C. Sine Wave Test Results – Motors and Generators

Most of the 13 tables of fixed speed data are at rated voltage with results of machines tested at 1.0 SF load summarized in Fig. A-1 with a graph showing the average of maximum measured rotor temperature with ± one standard deviation of the motors tested. These test results were used to develop the motor operating temperature for Common Application conditions, Table 1 [1] with excerpts shown in Table A-I herein that identifies the maximum recommended exposed surface temperature limits of 200 °C or 180 °C.

Most of the tables correlated extremely well with previous data in earlier editions of the Guide. For WP II enclosures, above 300 kW (400 hp) with axial duct or non-ducted rotor cooling, significant differences were identified between induction and synchronous machines and the table was split into Table 13a [1], induction, and Table 13b [1], synchronous. The WP II induction motors had an average rotor temperature of 160 °C; while, the WP II synchronous motors had an average rotor temperature of 100 °C. See Fig. A-1 for motor test data comparisons.

Results of motors tested at 1.15 SF load are shown in Fig. 2, illustrating that the rotor temperature in some cases may exceed the maximum recommended surface temperature. Table H.17 [1] is for TEFC motors tested at 90% voltage where the stator and rotor temperatures increase +5% to +15% from rated voltage.

D. ASD Tests – Configurations and Results

Understanding test configurations for ASD fed motor tests is paramount to interpreting the test data results. Annex H includes eight new ASD test configuration illustrations showing various motor/ASD test setups developed to align with the motor/ASD test data provided in Annex H [1] for real world applications. Refer to Fig. A-2 in Appendix A for the test configuration ASD-LV-1 which was typically used for low-voltage (LV), pulse-width-modulated (PWM) applications without filters. The dynamometer simulates the load. Refer to Fig. 4 for the test configuration ASD-MV-E [18], an illustration of a "back to back" test for large MV machines with two ASDs and two motors where one operates as a motor and the other as a generator.

Most LV and MV systems can generally be tested directly with a dynamometer such as Fig. A-2. However, for larger motors, it is usually preferred to keep utility energy costs low by recovering as much of the energy as possible. Therefore, in these situations some form of "back to back" test is performed, such as Fig. 4. Load testing of large ASD fed machines generally requires them to operate at full load from either the "on site" or the "comparable" ASD, typically at the specified or designed speed range. The Guide includes schematics of various loading arrangements including that shown in Fig. 4 [18] used on a 23 MW system where the plant power system only had to supply the losses.

Most of the data presented in the tables was obtained using the "on site" ASDs. One requirement that has recently been introduced for testing of motors on ASDs is for the "comparable converter" discussed in II.C.1) herein when the "on site" ASD is not used for testing.

There are nine data tables of temperature readings supplied for ASD fed motors from 2 hp to 31 400 hp operated at various speeds and loads. For ASD fed TEFC motors up to 370 kW (500 hp), the stator temperature rise was within 95 °C when operated at rated speed and 1 per unit torque, except one 450 hp motor had a 101 °C stator temperature rise. There are spreads in the data with typically only one or two machines of similar ratings in any particular group, but it does appear that a motor on an ASD does have slightly higher temperatures than on a sine wave power at the same load and speed.

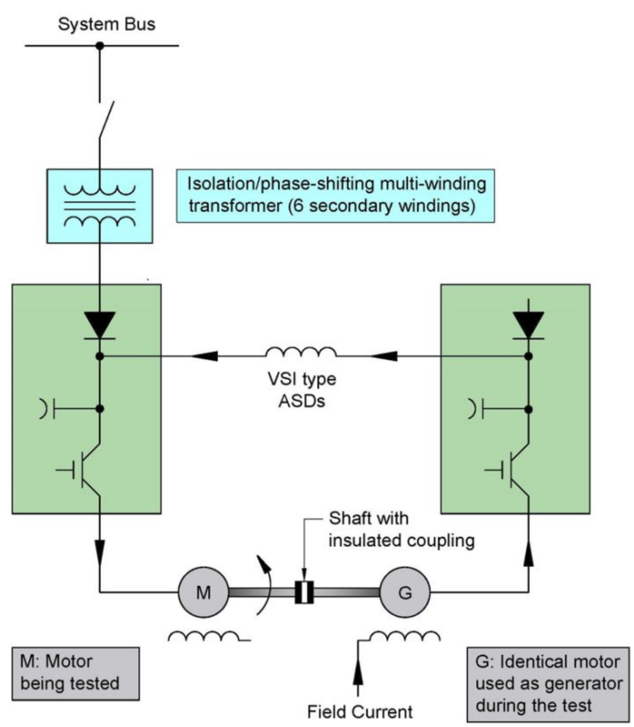


Fig. 4 Test configuration ASD-MV-E [18]
Back to back with two ASDs and two motors where one operates as a motor and the other as a generator (Fig. H.11 [1])

Motors driving “constant torque” loads, such as positive placement pumps, at reduced speed do have higher temperatures at the reduced speed. ASD tests typically establish the minimum speed for “constant torque” loads where the cooling from the fan becomes inadequate.

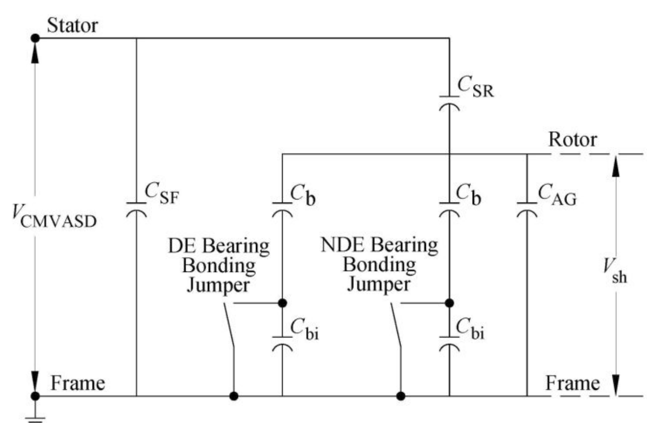
V. DISCHARGE ENERGY DUE TO CMV

A. Overview of Common-Mode Voltage (CMV)

The ASD output operates with a switching mode, dc to ac, therefore motors fed by ASDs have a CMV appearing between the neutral and ground. The magnitude of the CMV depends on the system voltage, the ASD topology, remediation measures such as filters, the cable type, and cable length. The CMV develops a shaft voltage that can discharge in bearing causing electric discharge machining (EDM). IEEE 1349 [1] recommends that the insulation and bonding should be discussed with the motor manufacturer and maintained to prevent damage to bearings. To prevent EDM, shaft bonding devices may be used without explosionproof enclosures provided it’s determined that this discharge energy is nonincendive for the flammable vapor that may be present as noted in *NEC* 501.125(B)(5) [2].

Various calculation and measurement methods are used to determine the capacitive discharge energy. Table G.1 [1] is included in IEEE 1349 to give a comparison of the available calculation and measurement methods as well as their suitability for various applications. There are multiple capacitances internal to a motor as shown in Fig. 5. Because of capacitive coupling, there is a voltage induced between the rotor-shaft assembly and the frame which charges the capacitance and stores energy. This energy may be discharged as capacitive discharge energy through a spark.

The Guide gives an example of the calculation methods to determine the available energy in the charged-up rotor to frame total capacitance, C. The calculation requires construction details of the motor such as rotor, stator and air gap dimensions, number of stator slots, coil ground wall insulation, bearing data and magnitude of expected or measured CMV of the ASD.



NOTE—For C_{SF}, this capacitance bypasses some of the CMV energy away from the rotor to frame capacitance. C_{SF} can be measured or calculated; however, it is generally not considered, which is a more conservative energy calculation.

Fig. 5 Motor voltage schematic, general (Fig. G.6 [1])

In Fig. 5,

- C_b is the capacitance between the shaft and the bearing at each end, with lubricant as the dielectric (farads)
- C_{bi} is the capacitance of the bearing to frame insulation (if any) (farads) (This capacitance is often bypassed at one or both ends by a bonding jumper.)
- C_{AG} is the capacitance across the air gap between the rotor and the stator laminations. (farads)
- C_{SR} is the capacitance between the stator winding and the rotor (farads)
- C_{SF} is the three-phase capacitance between the stator winding and the frame (farads)
- V_{sh} is the peak shaft voltage (volts)
- V_{CMVASD} is the CMV of the ASD output (volts).

The discharge energy (spark energy) can be calculated using Equation (1).

$$E = \tfrac{1}{2} C V_{sh}^2 \qquad (1)$$

where

E	is the discharge energy (joules)
C	is the total capacitance, sum of all capacitances of the rotor to the frame including the bearings across which the voltage, V_{sh}, appears (farads)
V_{sh}	is the peak shaft voltage (volts)

An example of a four- lobe sleeve bearing illustration included in the Guide is shown in Fig. 6 describing the data used to determine C_{bi}. In the design phase all three cases - none, one, or both of the bearings with a bonding jumper - can be analyzed to aid motor construction decisions.

At first glance, the capacitance across the air gap between the rotor and the stator laminations C_{AG} should be simple, however for salient-pole rotors, the proportion of the rotor circumference where there is actually a non-continuous air gap is used for the calculations as shown in Fig. 7.

Historically, the shaft voltage (V_{sh}) induced from the CMV of the stator has been taken as 10% of the CMV of the ASD, assuming it is similar at the motor terminals, which is often conservative, especially with larger machines.

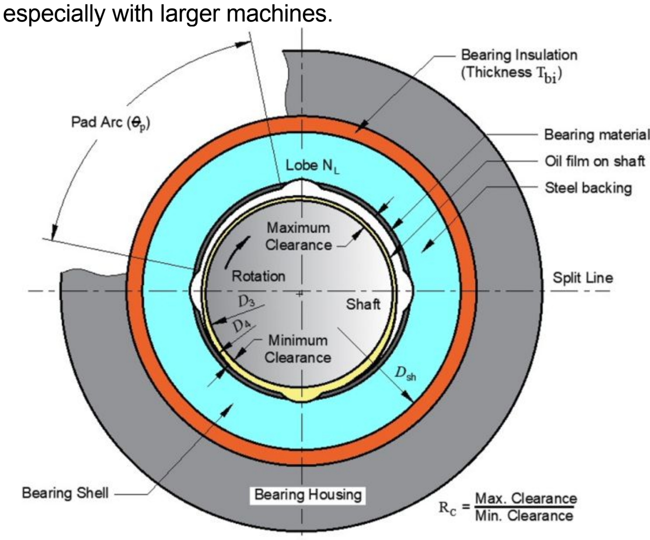


Fig. 6 Example of four-lobe sleeve bearing (Fig. G.4 [1]).

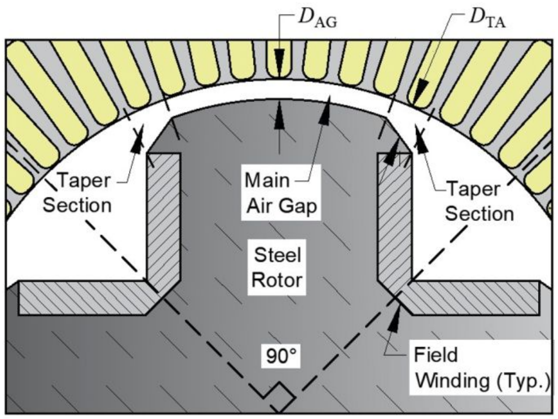


Fig. 7 Salient-pole rotor; proportion of the rotor circumference where there is actually a non-continuous air gap, Ps (Fig. G.5 [1]).

B. Overview of IEEE 1349 Discharge Energy Calculator

The Guide and the IEEE 1349 Discharge Energy Calculator [6] spreadsheet includes induction motors, salient pole and cylindrical rotor synchronous machines with hydrodynamic bearings, and also gives information on NEMA Frame machines with antifriction bearings. Examples in the Guide are the data used in the Discharge Energy Calculator spreadsheet which is freely available from IEEE. The spreadsheet uses the same formulas as the calculation method. Where it has been possible to compare calculated values with measured ones, the predicted and measured figures are similar.

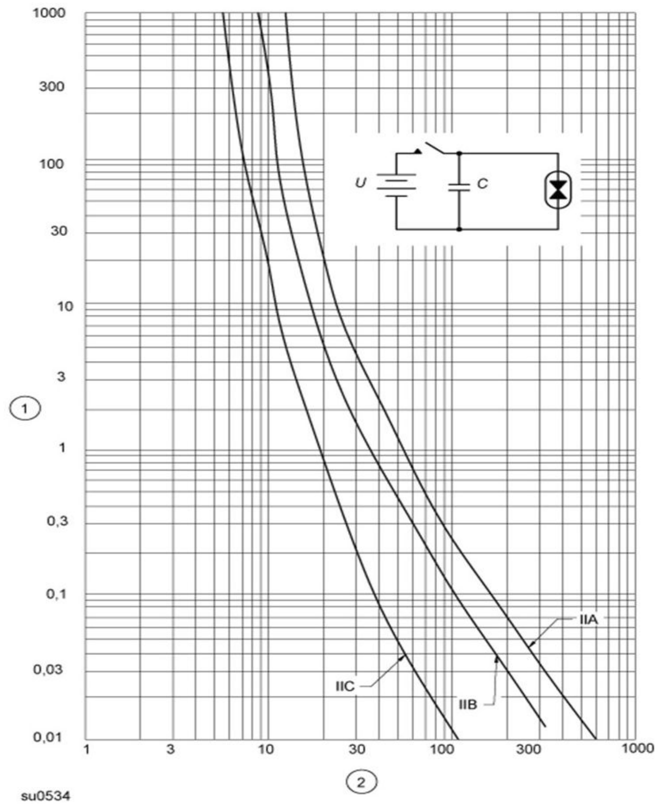
Although both the supplied formulas and the spreadsheet give useful data on discharge energy based on supplied machine and predicted data, it is also possible to enter measured data on capacitances and CMV levels into the calculations. Adjustment factors are included in the equations and spreadsheet for use as needed. Files are available in the IEEE 1349-2021 directory located at: https://standards.ieee.org/downloads.html [6].

C. Compare Discharge Energy to Minimum Ignition Energy (MIE) Method or Alternative Graph/Table Method

To perform an evaluation of CMV, compare the capacitive discharge energy to the MIE of the potential flammable gas, “comparison method.” The Guide includes the NFPA 497 [19] listed MIE of more common flammable gases, e.g., the MIE of ethylene is 70 microjoules and methane is 280 microjoules. The calculated discharge energy can be determined using the equations in Annex G.3 [1], IEEE 1349 Discharge Energy Calculator [6] spreadsheet, or actual measurements of “C” and “V_{sh}”. “Measurement methods” are described in Annex G.3.4 [1].

IEEE 1349 [1] also provides an “alternative graph/table method” shown in Fig. 8, a graphical plot of shaft voltage, V_{sh}, versus total capacitance, C, to determine which applications for the gas group are nonincendive, when data plots on the left-side of the applicable curve. With permission, IEEE 1349 [1] uses the IEC Capacitive Ignition Curves [11], Fig. 8.

Tests and analysis methods described in IEEE 1349 [1] indicate that sparking caused by ASDs typically should not cause problems; however, analysis should be done on applications involving gases such as acetylene and hydrogen with low MIEs, 17 microjoules and 19 microjoules, respectively.



Legend: 1 is total capacitance, C (μfarad); 2 is shaft voltage V_{sh} (volts).
Fig. 8 Capacitive Ignition Curves
IEC 60079-0 ed.7.0 [11] © 2017 IEC Geneva, Switzerland. www.iec.ch

VI. CONCLUSIONS

IEEE 1349-2021 is the premier Guide for the application of electric machines in hazardous (classified) locations as referenced in the *NEC* [2] and CE Code [3]. The techniques provide proven methods to prevent overtemperature and sparking in locations where flammable gases may be present.

The Guide provides a significant update of surface temperature measurements that were conducted on many types and sizes of fixed speed and ASD fed motors. The influence of applicable global IEC standards has also been incorporated in the text of the Guide. A space heater temperature test method was added to provide nameplate data used to prevent overtemperature. A new PM motor rotor temperature test provides vital information for this new technology.

A major expansion, over 20 pages, added details for determining discharge energy due to CMV to analyze if the energy is nonincendive. The informative Annex presents several methods, including a free download IEEE 1349 Discharge Energy Calculator [6] spreadsheet and measurement techniques, to determine discharge energy. These form the basis for future investigative work to validate the calculations.

VII. ACKNOWLEDGEMENTS

It is our honor to present this paper on behalf of the dedicated Working Group members, experts, contributors, and balloters that shared their time and expertise to provide the latest technologies. Thank you to our reviewers for providing valuable feedback.

VIII. REFERENCES

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[3] CAN/CSA C22.1-2021, Canadian Electrical Code® (CE Code®) Safety Standard for Electrical Installations.

[4] IEEE Std 841™, IEEE Standard for Petroleum and Chemical Industry—Premium-Efficiency, Severe Duty, Totally Enclosed Fan-Cooled (TEFC) Squirrel Cage Induction Motors—Up to and Including 370 kW (500 hp).

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IX. VITAE

Lorraine K. Padden (M'80-SM'94) is Co-founder and President of Padden Engineering, LLC, Katy, TX. Ms. Padden provides electrical engineering services, specializing in power system design and analysis, arc flash risk assessment, and coordination studies. She received a BSEE degree from SDSM&T and worked for Shell. Ms. Padden is Chair of IEEE Std 3004.8 (Motor Protection) and Chair/Co-Chair of IEEE Std 1349 (Machines in Hazardous Locations) for 2001, 2011, and 2021 editions and contributes to several IEEE and API standards. Ms. Padden is a recipient of the IEEE Standards Medallion and IEEE PCIC David C. Azbill awards and is a Licensed Professional Engineer in the states of California, Texas, and Washington.

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APPENDIX A
MOTOR SURFACE TEMPERATURE AND SPACE HEATERS

TABLE A-I
MOTOR OPERATING TEMPERATURE FOR COMMON APPLICATION CONDITIONS [a] (Table 1 [1])

Size	Enclosure types	Rotor cooling Type [b]	Typical rotor operating temperatures at full load [c] (°C)	Maximum recommended exposed surface temperature at full load (°C)
Three phase—NEMA frame sizes – Induction				
Up to 335 kW (450 hp)	ODP	Nonducted ventilation	115–150 [e]	200
Up to 300 kW (400 hp)	TEFC	Nonducted or axial duct ventilation	105–160	200
Three phase—above NEMA frame sizes – Induction				
100 kW to 300 kW (125 hp to 400 hp)	TEFC	Nonducted or axial duct ventilation	120–175	200
Above 300 kW (400 hp)			120–195	200
Above 300 kW (400 hp)	WPII	Nonducted or axial duct ventilation	115–205	200
Three phase—above NEMA frame sizes – Synchronous				
Above 300 kW (400 hp)	WPII & ODP	Nonducted or axial duct ventilation	90–110	180
Above 300 kW (400 hp)	TEFV & TEWAC	Nonducted or axial duct ventilation	85–115	180
Three phase—above NEMA frame sizes – Induction & Synchronous				
Above 110 kW (150 hp)	All [f]	Axial duct and radial duct ventilation	90–135	180
Three phase—above NEMA frame sizes – Permanent Magnet				
Up to 100 kW (125 hp)	TEFC	Nonducted or axial duct ventilation	110–160	180

[a] Table A-I is based on a small sampling of motors. Engineering judgment should be used and users should confer with the motor manufacturer. Temperatures are based on Class B rise at 1.0 SF, low-slip induction motors and synchronous motors, with a 40 °C ambient, rated voltage, and rated frequency.
[b] See H.1.2 [1] for a discussion of the rotor cooling types. See also Figure 2 [1], which shows axial and radial ventilation ducts in the rotor.
[c] Average rotor temperature of tested and calculated values within 1 standard deviation (rounded up to the nearest 5°). (In the Guide [1], see Table H.8, Table H.9, Table H.10, Table H.11, Table 13a, Table 13b, Table H.14, Table H.15, Table H.16, and Table H.18.)
[d] (not included in excerpt)
[e] Typical range is primarily based on motor manufacturer's calculated rotor temperatures on NEMA Design B motors. (Refer to Table H.8 [1].)
[f] Radial rotor ventilation is currently not used for NEMA frame-sized TEFC enclosures and is rare for above NEMA frame-sized TEFC enclosures.

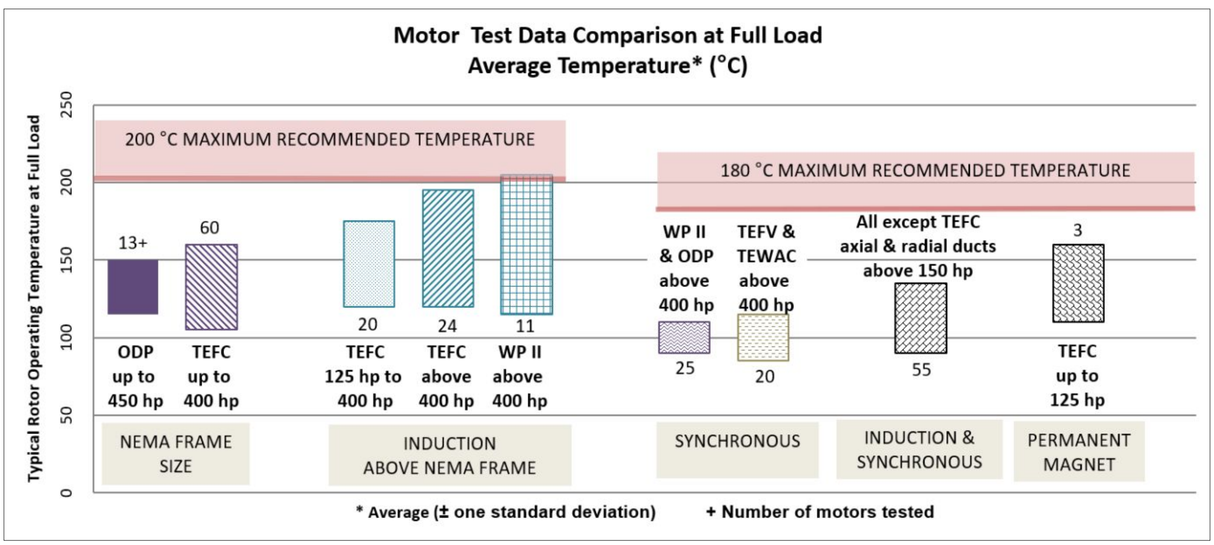

Fig. A-1 Motor Test Data Comparison at Full Load – Fixed Speed – Rotor Operating Temperature

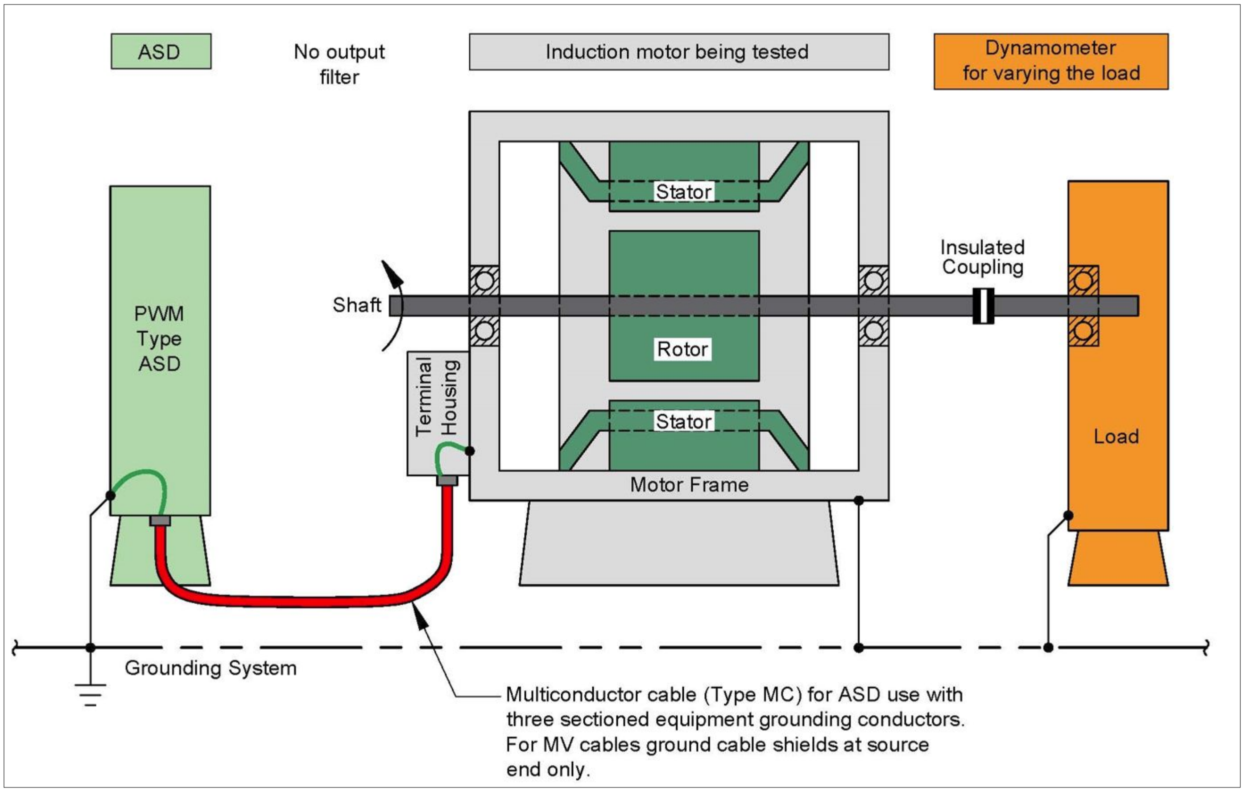

Fig. A-2 Test Configuration ASD-LV-1, PWM type ASD, no filters (Fig. H.6 [1])

TABLE A-II
SPACE HEATER TEMPERATURE UNDER NORMAL OPERATING CONDITIONS (Table 2 [1])

Zone 2 & Division 2		
Space heater tested and labeled with a T Code **Space heater tested and labeled with a maximum temperature based on the ambient**		
Applicable Code	Ambient [c]	Space Heater Temperature Limit
Zone 2 2021 CE Code Subrule 18-150 3) and Temperature Rule 18-054 [b]	40 °C	T Code temperature does not exceed the AIT
	40 °C	Maximum surface temperature [a] does not exceed the AIT
Division 2 2021 CE Code Subrule J18-150 3) and Temperature Rule J18-054 [b]	40 °C	T Code temperature does not exceed the AIT
	40 °C	Maximum surface temperature [a] does not exceed the AIT
Zone 2		
Space heater tested and labeled with a T Code		
Applicable Code	Ambient [c]	Space Heater Temperature Limit
2020 *NEC* Section 505.20 (C)	40 °C	T Code temperature does not exceed the AIT
Division 2		
Space heater marked with a maximum temperature based on the ambient		
Applicable Code	Ambient [c]	Space Heater Temperature Limit
2020 *NEC* Section 501.125 (B)	40 °C	Maximum surface temperature [a] does not exceed 80% of the AIT
Space heater identified for Class I, Division 2 (for example tested and labeled with a T Code)		
Applicable Code	Ambient [c]	Space Heater Temperature Limit
2020 *NEC* Section 501.125 (B)	40 °C	T Code temperature does not exceed the AIT

[a] See 8.3.2 [1] for space heater temperature test method.
[b] For the CE Code [3], space heaters (anti-condensation heaters) shall not have any arcing devices in general-purpose enclosures. The CE Code [3] does not permit the use of temperature-limiting controls to limit the maximum surface temperature of the heater (in case of failure of the limiter). See Figure 6 [1].
[c] For higher ambient temperatures, adjust the maximum surface temperature of the space heater. See 8.3.2 [1].