How to Specify a Motor with the Smorgasbord of Standards

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Abstract – How does today's process industry engineer even specify a motor with the plethora of industry standards from various standards development organizations around the globe? This paper provides a basic overview of the issues that are essential in the decision process when purchasing a new motor and is directed toward the engineer who must specify motors but is not a motor specialist. Since project engineers are regularly expected to justify options selected and purchase recommendations, this paper provides guidance. Process industry motor standards are used in review of motor requirements and options available today.

Index Terms – Motor standards, motor specifications, severe duty motor, petrochemical industry motor, motor reliability, premium efficiency, ASD motor, induction motor.

I. INTRODUCTION

Motor manufacturers adhere to a litany of motor standards and specifications. The impetus in developing this paper was to provide a road map to these documents for engineers who specify and purchase motors. These documents will be grouped into categories which provide guidance on the significance of the standard or specification and illustrate the interaction of these documents among one another to complete the requirements for manufacturing a motor. Some of the important items to consider when specifying a motor along with some issues that can occur are addressed. Finally, several case histories are presented that demonstrate problems experienced when a motor is not properly specified.

II. MOTOR STANDARDS

Motor manufacturers follow numerous standards, and the following sections describe some of the most common ones. There are two standards, NEMA MG 1 [1] and IEC 60034 [2] that form the basis for all the other standards discussed here. These two base motor standards reference other supporting standards for specific tests and design practices like insulation and vibration. Next there are overlay standards that provide additional requirements to enhance the base standards to make the motors more durable and reliable. Then there are certification standards that cover requirements for safety and classified hazardous areas. There are specialty standards that cover specific situations such as application in classified locations and repair, which reference the base standards. Finally, there are supplemental practices and specifications that provide requirements to make the motor more suitable for specific applications or define user preferences.

A. Base Standards - All Motors

The National Electrical Manufacturers Association (NEMA) publishes NEMA MG 1, which contains information concerning performance, safety, testing, construction, and manufacture of ac and dc motors and generators. It covers fractional hp motors through the large synchronous generators. The International Electrotechnical Commission (IEC) produces the 60034 series of standards, which covers similar material to NEMA MG 1. These standards are the base standards, and along with their referenced standards, either NEMA MG 1 or IEC 60034 is sufficient to describe motors for manufacturing. However, the purchaser must supply the motor parameters and make some decisions (ratings, enclosure, bearings, etc.) to fully define an individual motor, and this information is usually provided by the overlay standards and specifications [3].

NEMA publishes American National Standards Institute (ANSI) C50.41 [4], which covers the same subjects as MG 1 but is oriented to the realm of power generation. The overlay standards discussed in this paper do not reference ANSI C50.41.

Table I provides a partial list of the subject matter covered by both NEMA MG 1 and IEC 60034 along with a cross-reference among the corresponding parts and standards.

B. Reference Standards

The NEMA MG 1 and IEC 60034 base standards refer to additional standards for certain design and manufacturing details. The standards that are referenced by NEMA MG 1 are from ANSI, American Standard Test Method (ASTM), Canadian Standards Association (CSA), IEEE, IEC, International Organization for Standardization (ISO) and National Fire Protection Association (NFPA). Examples are IEEE 112 [5] for testing induction motors and IEEE 115 [6] for testing synchronous motors.

A similar set of standards is referenced in IEC 60034. Most of the references to IEC 60034 are in the form of "dash" documents or other IEC documents. For instance, one reference is IEC 60034-18 [7] is "functional evaluation of insulating systems".

TABLE I
CROSS-REFERENCE OF SELECTED TOPICS COVERED BY NEMA MG 1 & IEC 60034 [1,2,5-10]

NEMA MG-1 Part or Std.	IEC 60034 Dash or Std.	Topics from NEMA MG 1
1	1	Referenced standards.
2	8	Terminal markings. Markings for all leads and accessories.
3	1	High potential tests. Winding tests during motor manufacturing.
4	7 and IEC 60072	Dimensions, tolerances, and mounting. All standard frame sizes.
5	5	Classification of degrees of protection (IP code). The size of openings in motor enclosures, especially water ingress.
6	6	Methods of cooling (IC code). Defines air flow and various cooling methods from fins to liquids.
7	14	Mechanical vibration, Measurement and limits.
9	9	Sound power measurement and limits.
10	1	Ac and dc small and medium motors.
12	12	Tests and performance for ac and dc motors. Examples:
12	1, 11	-- temperature rise (complete definition of “B” rise)
12	2, 30	-- efficiency (all the tables)
IEEE 112	2	-- efficiency testing.
12	1	-- stall time minimums and maximum load inertia
13	1	Frame assignments.
14	1	Application data ac and dc. Usual and unusual conditions, effects of the system on the motor such as voltage magnitude and unbalance, altitude, and ambient temperature. Description of belting.
20	1	Large induction motors. Similar to Parts 10, 12, and 14, except for larger machines. “Larger” is described in a table, but generally more than 500HP 4 pole and all motors 450 rpm and slower.
21	1,16	Large synchronous motors. Similar to Part 20, except synchronous motors and generators.
20, 21	IEC 60038	Standard voltage ratings.
30	18-41,42	Application considerations for constant speed motors used in ASD applications. The definitions and science.
31	18-41,32	Definite purpose inverter-fed polyphase motors. The physical requirements of the standard.
IEEE 522	15, 18	Evaluation of insulation systems.
IEEE 43 & 1434	27	Insulation testing partial discharge, dissipation factor (capacitance), insulation resistance.

C. Overlay Standards

There are several overlay standards that can be used, depending on the power rating and type of motor, and several are identified below. The API and IEEE overlay standards, which are the key standards used in the petroleum and chemical industry, are covered in more detail in Section III.

IEEE 841 [13] identifies the requirements for chemical industry severe duty squirrel-cage induction motors, 370 kW (500 hp) and below that are manufactured to North American standards.

Similar to IEEE 841, IEEE 841.1, which is currently being developed, identifies the requirements for chemical industry severe duty squirrel-cage induction motors, 370 kW (500 hp) and below, except manufactured to IEC 60034 standards instead of North American standards.

American Petroleum Institute (API) - API 541 [14] includes induction motors rated 375 kW (500 hp) and larger.

API 546 [15] includes synchronous motors rated 500 kVA and larger.

API 547 [16] was developed to provide a more standardized severe duty general purpose induction motor with a more compact specification and motor data sheet compared to API 541 for selected hp and speed ranges.

Japanese Standards Association (JSA) – JSA – “JIS C 4213 Low voltage three phase squirrel cage induction motors - Low voltage top runner motor” [17] covers motors similar in rating to IEEE 841.1 (Top runner motors mean the most energy efficient motors). IEC 60034 is the basis for this standard.

D. Certification Standards

Certification standards address requirements associated primarily with hazardous area classification and safety. Some of these are identified below.

Underwriters Laboratories (UL) is one of many independent testing laboratories and creates compliance standards. A manufacturer must submit its product to an independent or third party for testing and certification to verify conformity to the compliance standards. The following is a list of the typical UL compliance standards for motors:

1. UL 1004-1 Standard for Safety of Rotating Electrical Machines [18]
2. UL 1004-2, Standard for Safety of Impedance Protected Motors [19]
3. UL 1004-3 Standard for Safety of Thermally Protected Motors [20]

CSA 22.2 [21] applies to motors going into Canada and is derived from NEMA MG 1. No.100 covers all motors and No. 77 covers motors for classified locations.

The IEC 60079 series of standards covers the requirements for machines installed in classified locations (e.g., IEC 60079-0, General Requirements [22]; IEC 60079-1, Flameproof (Ex “d”) [23]; IEC 60079-2, Pressurized (Ex “p”) [24]; and IEC 60079-7, Increased Safety (Ex “e”) [25]). The IEC 60079 series supplements the IEC 60034 series requirements. The UL and CSA 22.2 standards have adopted derivative versions of the IEC 60079 series of standards, and these are identified by corresponding numbers (e.g., UL 60079-1 [26] and CSA 22.2 No. 60079-1 [27]).

IEEE 45 [28] is the American Bureau of Shipping (ABS) standard for motors in shipboard use. It references both NEMA MG 1 and IEC 60034. IEEE 45 prescribes the ability of shipboard motors to withstand water above deck and pitching/yawing in all locations.

IEEE 334 [29] is the standard for qualifying motors used in Nuclear 1E applications. It describes the certification procedure to assure motors will withstand operation in and around nuclear power facilities. It is mentioned here as representative of other standards used outside the oil and gas industry.

The Mine Safety and Health Administration (MSHA) produces Title 30 [30], which is a classified location specification that includes specifics associated with motors in mining applications. The document also provides testing and material specifications.

E. Specialty Standards

Specialty standards cover requirements such as repair and application in classified hazardous areas. Some examples are as follows.

IEEE 1068-2015 [31] covers the repair and rewinding of ac electric motors.

The Electrical Apparatus Service Association, Inc. (EASA) develops motor repair standards, such as ANSI/EASA AR100 [32] that covers the repair of rotating electrical apparatus.

IEC 60034-23 [33] provides the procedures necessary to ensure the satisfactory repair, overhaul, and reclamation of all types and sizes of rotating electrical machines covered by IEC 60034.

IEEE 1349 [34] provides guidance for application of motors in Zone 2 and Class I, Division 2 hazardous locations. Most induction motors can be safely applied in these locations.

F. Supplemental Specifications

Supplemental specifications or practices identify additional requirements for specific applications or facilities where necessary. A few examples of these are given below.

NEMA MG 2 "Safety Standard for Construction and Guide for Selection, Installation and Use of Electric Motors and Generators" [35] is a free publication from NEMA describing application and selection of motors and generators for safety. It has a complete description of enclosures, common tests, and a discussion of safe practices for application and installation. Much of the content is similar to NEMA MG 1.

Process Industry Practices (PIP) – PIP ELSMT01 [36] covers induction motors up to and including 500 hp (370 kW), the same scope as IEEE 841. This practice describes the requirements for design, construction, and testing for NEMA MG 1 premium-efficiency, horizontal or vertical, polyphase, squirrel cage induction motors. NEMA MG 1 is the basis for this overlay specification.

The International Association of Oil & Gas Producers (IOGP) initiated Joint Industry Programme 33 (JIP33) in 2016 with support from the World Economic Forum Capital Project Complexity Initiative in response to industry-wide overruns on cost and schedule of more than 40%. They have created overlay specifications for the IEEE 841 and IEC 60034-1 standards.

Many companies have their own specifications that overlay and supplement the various standards with additional requirements. These are generally based on experiences and standardized practices within the individual company, facility, or project.

G. Summary

Fig. 1 shows the overall relationship among these groups of commonly used motor standards and specifications in an organization chart. NEMA MG 1 and IEC 60034 are the base motor standards used by all the other documents. The bottom layer of standards includes reference standards utilized by the base standards for specific subjects in these documents. Next there are motor overlay standards, and the one used is based on the specific application or preference. Then there are certification and specialty standards for specific situations for motors, such as classified locations or repair. Finally, there are supplemental specifications that cover requirements for specific applications or user preferences.

III. MOTOR OVERLAY STANDARDS FOR PETROLEUM AND CHEMICAL INDUSTRY APPLICATIONS

There are three industry standards commonly used as specifications for induction motors applied in petroleum and chemical industry and other process industry facilities. These are IEEE 841, API 541, and API 547. In addition, a fourth standard, IEEE 841.1, is currently being developed and expected to be published in 2022. Finally, API 546 is the industry standard used for synchronous motors. All these standards are overlays based on either NEMA MG 1 or the IEC 60034 series of motor standards. These IEEE and API overlay standards add requirements to the base standards to improve the durability and reliability of motors and are the ones primarily considered in this paper.

The choice of the standard to use for specifying a given motor depends on the characteristics of the motor, such as induction or synchronous, power, voltage, speed, type of bearings, type of enclosure, etc., and the type of application, such as centrifugal load, reciprocating load, critical service, spared or un-spared, etc. Guidance for choosing the appropriate standard for a particular motor is provided below. Additional information can be found in [37] and [38].

A. IEEE 841

IEEE 841, which has NEMA MG 1 as the underlying base standard, is used to specify totally enclosed fan cooled (TEFC) or totally enclosed nonventilated (TENV) motors rated up to 370 kW (500 hp) with antifriction bearings. Hydrodynamic sleeve bearing motors and explosionproof motors are not included in this standard. The voltage rating for these motors is usually less than 1000 volts but can be up to 4000 volts. The windings usually consist of random wound coils but can use form wound coils too, especially for voltages greater than 1000 volts. Two, four, six, and eight pole motors are included and can be either horizontal or vertical mounted. They can be either supplied from a sine wave utility source for fixed speed operation or supplied from an adjustable speed drive (ASD). These motors are intended for severe duty applications, such as those found in the petroleum and chemical industry. They are manufactured with standard technical features, such as premium efficiency, longer bearing life, low vibration, acceptable for Zone 2 or Class I, Division 2 locations, etc., which make them suitable for many applications as off-the-shelf motors that can be stocked by motor distributors and quickly available. Optional features, such as auxiliary terminal box, ambient temperature above 40˚C, insulated bearings, special ASD requirements, etc., can also be specified as needed for certain applications.

IEEE 841 should be used for TEFC or TENV motors rated up to approximately 185 kW (250 hp) with two, four, six, or eight poles where North American standards are used. This is also the usual standard for similar type motors rated above 185 kW (250 hp) up to 370 kW (500 hp) where antifriction bearings are required. Some motors that are outside the ranges above, such as slightly larger than 370 kW (500 hp) or more than eight poles, but otherwise have the characteristics of an IEEE 841 motor can be provided as an "IEEE 841 Features" motor. The allowable options are given in IEEE 841, and the manufacturer should be consulted for availability. Also, some users may require hydrodynamic bearings for motors rated above185 kW (250 hp) up to 370 kW (500 hp), and for these applications either API 541 or API 547 should be used.

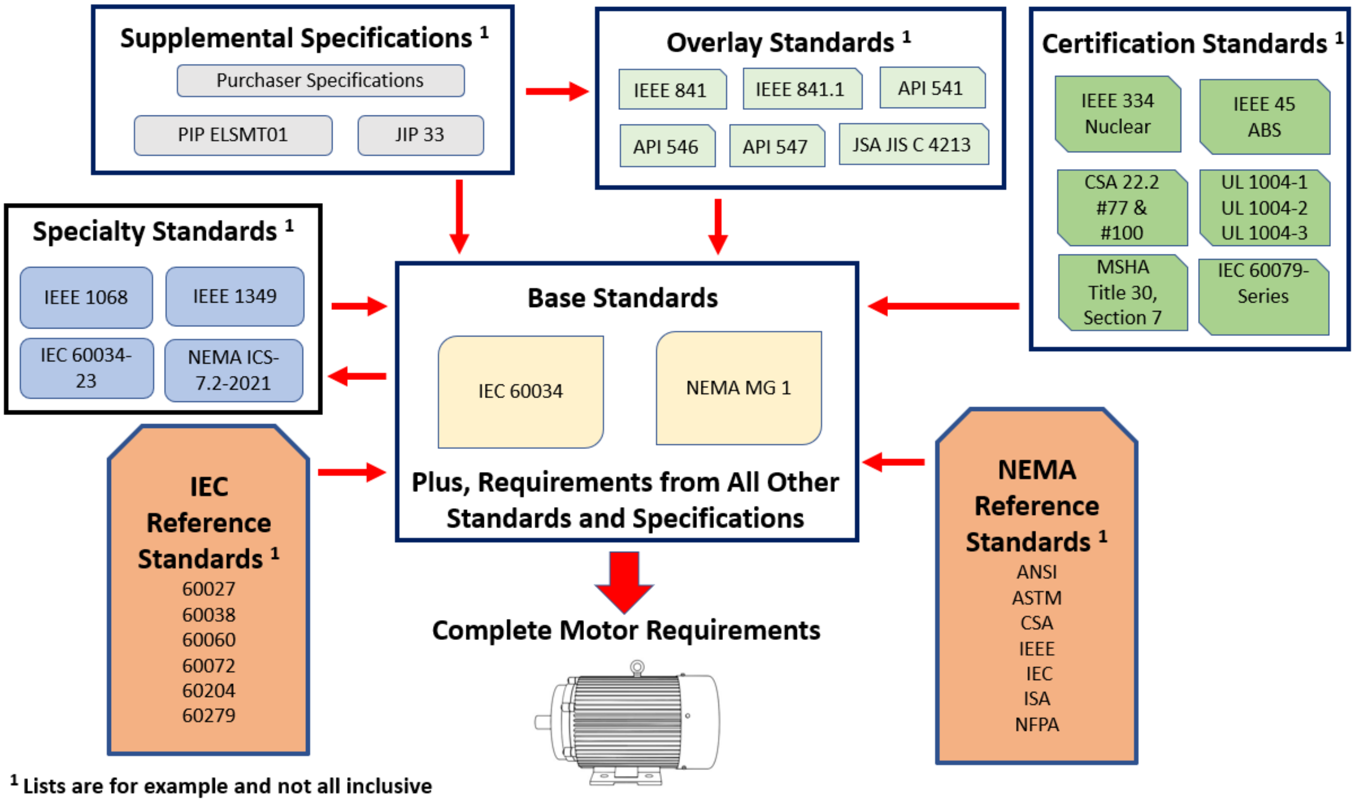

Fig. 1 Illustration of motor standard interrelationship and order of precedence [1,2,4-36,42]

B. IEEE 841.1

IEEE 841.1 is a new standard for specifying premium efficiency, severe duty motors like those covered by IEEE 841 except using IEC 60034 instead of NEMA MG 1 as the base standard. IEEE 841.1 motors are TEFC, TENV, or totally enclosed air over (TEAO) designs rated up to 370 kW (500 hp) with antifriction bearings. Like IEEE 841, hydrodynamic bearing motors and Ex "d" flameproof motors are not included in IEEE 841.1. However, this standard can be used as a basis to specify a motor of increased safety type of protection (Ex "ec" and Ex "eb") to IEC 60079-0 and -7, where necessary, for application in Zone 2 or Zone 1 locations. Other features including maximum voltage, winding coil types, number of poles, suitable for use on ASDs, standard features provided, and optional features available are essentially the same as in IEEE 841 described above.

IEEE 841.1 should be used for those motors that are like IEEE 841 applications in facilities where the IEC 60034 underlying base standards are required instead of the North American standards. That is, motors rated up to 370 kW (500 hp) with antifriction bearings in these facilities. As described for IEEE 841 motors, some motors that are outside the ranges above, such as slightly larger than 370 kW (500 hp) or more than eight poles, but otherwise have the characteristics of an IEEE 841.1 motor can be provided as an "IEEE 841.1 Features" motor. The allowable options are given in IEEE 841.1, and the manufacturer should be consulted for availability. Also, in the power range above 185 kW (250 hp) up to 370 hp (500 hp), some users may require hydrodynamic bearings instead of antifriction bearings, and either API 541 or API 547 should be used for these applications.

C. API 541

API 541 covers induction motors rated 375 kW (500 hp) and larger, so it essentially starts where IEEE 841 and IEEE 841.1 end in terms of power rating. The voltage rating can be as necessary for the application, nominally up to 13.8 kV. The insulation system uses form-wound vacuum pressure impregnated (VPI) coils. All speed ranges are covered including application on ASDs and operating speeds greater than 3600 rpm. Both horizontal and vertical mounted motors are included. From a rotor dynamic standpoint, the first lateral critical speed can be either below maximum operating speed, flexible rotor design, or above the maximum operating speed, rigid rotor design. The bearings are hydrodynamic oil lubricated type for most applications. Antifriction bearings with grease lubrication can be specified if desired, but this is rarely done for API 541 motors. Efficiency can be optimized based on initial cost and operating cost of the motor to achieve the best practical efficiency for each application. Most types of motor enclosures from open to totally enclosed can be used, depending on the application, area classification, and severity of the installation environment. Either NEMA MG 1 or IEC 60034 can be specified as the base standards, and this choice usually depends on the requirements of the facility where the motor will be installed. API 541 motors are normally designed for a specific installation based on the characteristics of the driven equipment and other requirements for that application, so if a motor is moved to a different service, its characteristics should be verified as suitable for that service.

API 541 should be used for motors rated 375 kW (500 hp) and above where a special purpose motor is needed. These include applications that are considered critical service, must operate for long periods of time without interruption, do not have an installed spare, drive high inertia or reciprocating loads, are supplied from an ASD, or are installed in very hostile environments. Special purpose motors also include those that have four poles or more and are rated more than 2250 kW (3000 hp); are totally enclosed with two poles and are rated 600 kW (800 hp) or more; have an open enclosure with two poles and are rated 930 kW (1250 hp) or more; or are vertical mounted and are rated 375 kW (500 hp) or more. These larger and higher speed motors have sufficient complexity, potential issues, and investment to justify the increased attention provided by API 541 even though they may not otherwise be installed in a special purpose application.

D. API 547

API 547 covers induction motors rated 185 kW (250 hp) through 2240 kW (3000 hp), depending on the speed, for general purpose applications. These motors are like API 541 motors with form wound VPI coils for the windings, optimized efficiency, and hydrodynamic bearings for horizonal motors. API 547 requires antifriction bearings for vertical motors. Antifriction bearings can also be specified for horizontal motors, but this is seldom done for API 547 motors. Available voltage ratings are normally up to 6600 volts. Two, four, six, and eight pole motors are included. From a rotor dynamic standpoint, these are rigid rotor motors that operate below their first lateral critical speed, and API 547 motors can be specified for use on an ASD in consultation with the manufacturer. Motor enclosures can be either TEFC or weather protected Type II (WP-II). Either NEMA MG 1 or IEC 60034 can be used as the underlying base standards as required. Unless otherwise specified, the motor torque characteristics meet the requirements of the applicable NEMA MG 1 or IEC 60034 standards instead of being designed for a specific application. This and inclusion of the other standard features enable API 547 motors to be stocked by distributors as off-the-shelf motors that can be quickly available for use in several applications. Optional features, such as vibration monitoring probes, special testing, etc., can be specified and often are, and these may require specially ordering the motor instead of purchasing it off-the-shelf with quick delivery.

API 547 should be used where a 185 kW (250 hp) to 2240 kW (3000 hp), depending on speed, general purpose horizontal motor with hydrodynamic sleeve bearings is needed. These are motors that are in noncritical or spared applications and drive standard inertia centrifugal loads. The covered motor power and speed ranges are 185 kW (250 hp) to 2240 kW (3000 hp) for four, six, or eight pole motors; less than 600 kW (800 hp) for two pole TEFC motors; and less than 930 kW (1250 hp) for two pole WP-II motors. API 547 is also an alternative to IEEE 841 or IEEE 841.1 for vertical motors rated less than 375 kW (500 hp). Finally, API 547 is an alternative to IEEE 841 or IEEE 841.1 for horizontal motors rated up to 375 kW (500 hp) where hydrodynamic bearings are required instead of antifriction bearings.

E. API 546

API 546 requirements are very similar to API 541 except synchronous motors (and generators) are covered instead of induction motors. Synchronous motors rated 500 kVA and larger at all speeds, including those greater than 3600 rpm, are within the scope. Requirements that are characteristic of synchronous motors but not induction motors, such as the different types of rotor construction and the field excitation system, are covered. Other basic requirements that are described above for API 541 are the same for API 546.

API 546 should be used for synchronous motor applications in the petroleum, chemical, and other process industries where durability and reliability are important considerations.

IV. MOTOR STANDARDS – WHAT IS REALLY IMPORTANT AND WHAT CAN GO WRONG

If no overlay specification, such as API or IEEE is used by the purchaser, the manufacturer will provide a motor built to at least NEMA MG 1 or IEC 60034. The motor will operate but may not have the durability or reliability of a motor built to one of the IEEE or API standards. Depending on the application, this can have significant adverse safety, production, and cost impacts on the facility where the motor is installed.

IEEE 841, IEEE 841.1, API 541, API 546, and API 547 all include datasheets for specifying the motor. It is essential to complete the datasheets to properly specify the motor and to be certain the motor will be suitable for the specific application. The datasheets also serve as check sheets to make sure all items needing consideration are addressed. The API standards include a guide to assist with completion of the datasheet.

Once the speed, hp, voltage, and enclosure are properly selected, the motor will usually turn the load, especially for motors less than 1000 hp, 1800 rpm or below, and driving a centrifugal load. However, if a motor is improperly applied or specified, the mitigation may be as easy as changing a coupling or as tough as replacing the motor. Following is a brief description of several important items to carefully consider and some issues that can occur if they are not. Refer to [35] and [39] for additional guidance.

1) *Local codes:* Motors will generally comply with national code requirements, such as the NEC [40] or CE Code [41], but sometimes there are additional local or city codes that apply and add requirements. If the manufacturer is not made aware of these requirements and they are not satisfied, startup of the motor may not be permitted until compliance is provided. In many cases, it can be difficult and time consuming to provide compliance after the motor is manufactured.

2) *Classification of the hazardous location:* It is important to get this right to avoid an unsafe or expensive misapplication. Motors suitable for Zone 2 or Class 1, Division 2 locations are most frequently specified for oil and gas facilities since flammable gas is not normally present but could be during unusual conditions. These motors normally do not have additional requirements for the location, except the auxiliary devices must be suitable for the location to avoid being a source of ignition. Zone 1 or Class 1, Division 1 motors for locations where flammable gas is frequently present have special requirements and are significantly more expensive, so these should only be used where necessary for the hazardous location.

Incorrect specification of the hazardous area classification may create an unsafe condition and may require a different motor as the corrective measure in some cases. For example, an induction motor without arcing or sparking devices can be applied in a Class I, Division II classified area without other special requirements per the NEC and with guidance from IEEE 1349. If the Class I, Division II area was incorrectly specified as Unclassified, the motor may still be acceptable, but any of the motor auxiliary devices having arcing or sparking contacts would have to be changed to those suitable for the classified area. Also, the surface temperature of any space heaters would have to be verified as suitable for the classified area and changed if necessary. If the area was actually classified as Class I, Division I, the entire motor would have to be changed to one suitable for the area.

3) *Ambient temperature:* Specify the ambient temperature if above 40°C maximum or below -20°C. (The minimum temperature varies between different standards, so consult the applicable standard being used.) The manufacturer must de-rate the motor or use special materials for ambient temperatures outside this range. If the ambient is too high, motor insulation and bearing life will be reduced. If the ambient is too low, component materials may fail and bearing life is shortened.

4) *Altitude:* This must be specified if above 3300 ft. elevation and the motor de-rated accordingly. The less dense air above 3300 ft. dissipates heat less efficiently, so the motor will run hotter, thereby reducing life expectancy if operated at near normal full load.

Altitude also increases partial discharge activity. Where this is a potential issue, many manufacturers use an insulation system that is rated for the next higher voltage (e.g. use 6.6 kV insulation on a 4.0 kV application) for motors designed for higher altitudes.

5) *Vertical or horizontal:* Most motors are horizontal mounted. However, there are applications requiring vertical motors, such as vertical pumps. Vertical motors have additional mechanical options requiring consideration that must be addressed with the manufacturer. These include type of mounting, hollow or solid shaft, reverse ratchet, thrust capability of bearings, lock on the shaft to prevent the rotor from sliding down, and mechanical resonance (reed critical frequency).

6) *Enclosure:* A totally enclosed design, such as TEFC for smaller motors or TEWAC (totally enclosed water to air cooled) for larger motors, is almost always best to protect the motor from environmental conditions. IEEE 841 and IEEE 841.1 motors are always totally enclosed as are many API motors. Totally enclosed is more costly for larger motors, so an open enclosure, such as WP-II, is sometimes used for these motors. A key consideration of the enclosure choice should be the environmental conditions and potential effects on the specific motor. Refer to the API standards for guidance.

7) *Power rating, hp or kW:* Select the motor power rating as necessary for the driven load plus a suitable safety margin to account for uncertainties in the load characteristics. Consult with the driven equipment manufacturer and the responsible process engineer for the characteristics and uncertainties in the load that should be considered. Service factor ratings are not recommended by IEEE and API standards. However, if the motor has a service factor rating anyway, it should only be used for occasional short time overloads to minimize reduced motor life due to the higher operating temperature.

8) *Voltage Rating:* Normally use a standard motor voltage from NEMA MG 1 (460V, 2300V, 4000V, 6600V, 13,200V) or IEC 60034 (400V, 690V, 3000V, 6000V, 10,000V). Induction motor rated voltages are a few percent less than the system bus nominal voltage to account for voltage drop across the system conductors. However, synchronous motor rated voltages are normally at the system bus nominal voltage since operating at unity power factor does not cause a significant voltage drop and operating at a leading power factor causes a voltage rise. Be especially careful to select the proper voltage rating depending on the motor type, either induction or synchronous.

9) *Speed:* Motor rated synchronous speed, such as 3600 rpm, 1800 rpm, and 1200 rpm, is selected as necessary for the driven equipment. Slower, less than 3600 rpm, is usually more robust with fewer potential mechanical issues if there is flexibility in the choice. Available rated speeds for fixed speed applications are given in the NEMA MG 1 and IEC 60034 standards. Speeds above 3600 rpm are also available for motors applied on ASDs.

10) *Temperature Rise*: Class B temperature rise as defined in NEMA MG 1 and IEC 60034 is required in all the IEEE and API standards. It is better to specify Class B rise than the actual temperature rise in degrees since Class B rise has different temperatures depending on the method of measurement (by resistance or by embedded detector) and the power and voltage ratings of the motor.

Many of the issues that arise due to improper specification or application can cause the motor to operate at a higher temperature than rated. Excessive temperature will reduce the life in both the windings and the bearings. A degradation of insulation life of 50% is generally accepted as a reasonable estimate for every 10^0C increase in operating temperature beyond motor rated.

11) *Insulation Class:* The insulation temperature rating required by the IEEE and API standards is Class F as a minimum, which has a higher temperature rating compared to the Class B allowed operating temperature, and this provides for a long insulation life. Depending on motor size, Class H insulation with an even higher rated temperature may also be available. Be aware that insulation systems must be tested as systems, not simply components. Excessive operating

temperature may also reduce bearing life, so it usually is best to maintain the Class B operating temperature limit even if an insulation class higher than Class F is provided.

12) *Bearings*: The bearing choice is very dependent on the application. Hydrodynamic (sleeve) bearings have a very long life and will last longer than the motor with very little maintenance as long as the lubricating oil is maintained in good condition. Antifriction bearings (ball, roller) have a finite life and must be periodically regreased, except for those that are sealed. The bearing choice often depends on the longevity necessary for the application and the maintenance practices of the facility.

The API and IEEE motor standards give guidance in determining where antifriction bearings are acceptable expressed as a dN factor, which is the product of the bearing bore diameter (mm) and the speed (rpm). These standards also give minimum life requirements that the antifriction bearings must satisfy. In general, antifriction bearings are used for motors rated 500 hp and smaller; that is, those covered by IEEE 841 and IEEE 841.1. Hydrodynamic bearings are used for motors rated larger than 500 hp; that is, those covered by API 541, API 546, and API 547. There is overlap in these ratings where some motors will use antifriction bearings for ratings larger than 500 hp and some will use hydrodynamic bearings for ratings less than 500 hp based on the user preferences or requirements for the specific application.

For grease lubricated bearings, the grease must be compatible with the maintenance grease used by the installation facility. Otherwise, the lubricating quality of the incompatible grease mixture will be compromised and bearing life will be reduced. The type of grease to be used by the motor manufacturer for original lubrication of the bearings should be specified as necessary to avoid this potential problem. The default grease for IEEE 841 motors is polyurea-thickened type, which has a proven record for being superior to other types. Additional information on bearing lubrication can be found in [42-44].

13) *Load inertia:* If the driven load has inertia values above the NEMA MG 1 standard values, the motor manufacturer must be advised so a motor with sufficient starting capability is provided. Many fans, mills, and applications that are geared above the motor speed exceed the NEMA MG 1 standard inertia. Load inertia beyond the standard values increases the starting time and the resulting rotor temperature, which may cause mechanical damage to the rotor if not properly designed and protected.

If the inertia is too high, the motor may not be able to accelerate up to normal operating speed. Frequent rotor failures may be an indication of excessive load inertia or excessive number of starts.

14) *Frequent starts:* If the motor will be started often, the details should be specified. What constitutes frequent starting is not clearly defined and varies considerably with the motor design and application, like a high inertia load. For smaller motors, covered by IEEE 841 or 841.1, more than one start per hour may be considered frequent. For larger motors, covered by API standards, more than one start per day may be considered frequent, although API standards inherently require a greater starting capability than NEMA MG 1 or IEC 60034 standards. The life of the motor will be prolonged if the number of starts is kept as low as practical.

15) *Belted applications*: The NEMA MG 1 shaft and bearing specification is based on the rated belt tension required to transmit rated hp. Higher belt tension will reduce bearing life unless the motor design accounts for the increased load. Roller bearings are frequently applied for belted applications because of their ability to handle the associated radial loads.

16) *ASD application*: The base motor standards, NEMA MG 1 and IEC 60034 series, cover ASD applications only when the motor is specified for ASD operation. A motor not specified for ASD application may not be suitable for such service, which may result in a shorter life or may not be workable at all in the worst case. Normal, simple ASD applications driving variable torque loads at or below motor rated speed are supported by the IEEE and API standard motors. Other applications, such as constant torque, constant hp, very slow speeds, and above rated speeds, are possible with the IEEE and API based motors but require more detailed engineering and review. The specific requirements for an ASD application should always be provided to the motor manufacturer so the motor selection or design adjustments can be made as necessary. Refer to NEMA ICS-7.2-2021 [45], which is available from NEMA at no cost, for more application information on ASD systems.

17) *Accessories*: Details of necessary accessories must be specified by the purchaser. These include devices such as RTDs, space heaters, vibration monitoring, tachometer, brake, surge protection, accessory conduit boxes, etc. Other motor details, such as main conduit box location and type of shaft extension, need consideration.

18) *Noise:* Limits for sound pressure levels are defined in the IEEE and API standards. Some facilities may require lower sound pressure levels to satisfy local requirements. These lower noise levels and noise abatements are often available but may require a larger footprint, a different type of enclosure (such as totally enclosed instead of open), or perhaps unidirectional operation to reduce fan noise.

19) *Efficiency*: Motors purchased to the IEEE and API standards have premium efficiency, and these efficiency requirements are defined in the underlying NEMA MG 1 and IEC 60034 standards. Efficiency may be used for life cycle cost evaluation of competitive motor proposals. For evaluation, the dollars per kW of losses to be used in the evaluation should be provided to the motor manufacturers. This provides the opportunity for each manufacturer to optimize the motor offered for the best efficiency versus cost benefit.

20) *Factory Testing:* Required routine tests, such as insulation resistance, overpotential, winding resistance, and no-load vibration, are specified in the standards. These routine tests are usually sufficient for smaller motors, like those specified to IEEE 841, IEEE 841.1, or API 547. Additional optional testing may be required for new motor designs, unfamiliar manufacturers, and larger motors or special purpose motors, such as those specified to API 541 or API 546. Examples of optional tests include the complete test to determine temperature rise, efficiency, and rotor thermal stability and the unbalance response test to determine the rotor system lateral critical speeds. Fortunately, few motors fail the factory tests, but there are enough failures to justify extensive factory testing for important motors to avoid problems in the field. The required and optional tests and the test methods are described in the IEEE, API, and underlying standards. In addition, the API standards include guidance on selection of the optional tests.

21) *Replacing existing motors*: For replacement motors, the foundation mounting arrangement and the shaft coupling may be different between motor manufacturers and even between generations of motors from the same manufacturer. It

is especially important to communicate mounting and coupling details when replacing existing motors. When necessary, transition bases for mounting can be manufactured, motor shafts can be dimensionally specified to match existing couplings, or a new coupling can be procured to satisfy the new dimensional requirements.

22) *Communication:* In some cases, the purchaser may not be sufficiently experienced in the details of specifying a motor or the motor is being ordered separate from the driven equipment and may lack necessary details. Fortunately, the motor vendor or distributor sales team frequently understands this and assists to check the specification before it is committed to manufacturing. Clear and frequent communication between the purchaser and the manufacturer is important. Careful review of proposal data against user requirements and meetings to understand and resolve discrepancies can minimize issues.

V. MOTOR STANDARDS – CASE HISTORIES AND LESSONS LEARNED

The following are a few case histories derived from the authors' aggregated 100 plus years of experience. In essence, these are examples of what can go wrong if the motor is not properly specified, and the lessons learned from these experiences.

A. Motor Sizing

During the early 1990's a new Debutanizer Unit was being added at a large refinery. This project used existing towers and vessels that were out of service. The process engineer over the project was attempting to implement this project in a very cost-effective manner by utilizing as much salvage equipment as possible, and he provided a list of motors and their hp ratings required. However, all the motors for the unit had to be procured new since the number and sizes required were not available in the salvage equipment. Once the unit was brought online, numerous motor failures were experienced, and subsequent failures of the replacements occurred.

Following further investigation, it was determined the process engineer, who knew the motors would be procured with a 1.15 service factor, had understated the base hp requirements by the 1.15 service factor to reduce the motor sizes and thereby costs. This resulted in the motors being undersized and continuously overloaded in normal operation, which ultimately resulted in the failures. To resolve this issue new motors sized to the appropriate load base hp were ordered and installed.

Motor service factor rating should be used only to accommodate occasional and short time overload conditions. The IEEE and API standards caution against sizing motors based on using the service factor rating, and the IEC 60034 standards do not define a service factor rating at all. The motor base power rating should be selected as necessary to satisfy all load conditions to provide for a long service life. The reason for this recommendation is that the motor service factor rating is established simply by allowing the motor to operate at a higher temperature rise than at the base rating, which results in a shorter life for the insulation and bearings. Motor torque characteristics do not increase above the base values at the service factor rating, which might be an issue for some applications (e.g., the motor not having adequate accelerating torque for the imposed shaft load torque). While it is common to see motors that are manufactured to North American standards with a service factor rating, the effects on motor insulation and bearing life should be carefully considered before making use of this rating.

B. System Integration

During the early 1990's a new Lime Cone was being installed in the boiler house for the boiler feed water at a large refinery. A process engineer specified the various components of this system, which consisted of several pre-packaged pieces of equipment. The lime hopper gravity fed lime onto a conveyor belt, which fed the lime into the top of a tank that had mixers mixing the water lime mixture. There were various other components, a control system, and analytics. The motor on the conveyor was driven by an ASD. During start-up and for many months, thermal issues were experienced with this motor, which shut the conveyor and overall system down.

Investigation found the following: 1) the motor operated below its minimum required speed to provide adequate cooling; 2) the lime coated the motor, which restricted cooling and compounded the thermal issues; and 3) the ASD, motor, conveyor, and control system were procured as individual components by the process engineer and thus were not designed as a comprehensive system. There was no easy fix for this application. Corrective measures implemented in attempt to mitigate the issues were operator rounds to increase housekeeping to keep the motors clean, program changes in the controller and ASD to limit the lower end speed of the motor, and stocking a spare motor in the warehouse. These were not ideal changes as they only made the system workable but did not eliminate the issues. For complex applications such as this one, a systems engineering approach including all applicable technical disciplines is necessary to address any adverse conditions the motor will experience and to ensure it will function properly and reliably when integrated into the overall system.

C. ASD Application

As part of an upgrade to a vapor recovery system in an oil production facility, a 350 hp, 460 V, 1800 rpm induction motor with antifriction bearings and driving a rotary screw compressor was installed with an ASD. The speed range was 200 to 1800 rpm for this constant torque load. This was an off-the-shelf motor from a distributor, and communication with the motor manufacturer concerning suitability for use on an ASD did not occur. The motor failed after approximately two months of operation.

The cause of the failure was excessive heating due to the ASD operation (harmonic frequencies and insufficient cooling for the constant torque load at lower speeds) that caused axial thermal growth in the rotor shaft. This thermal growth of the shaft created axial loading on the bearings, which caused overheating of the bearings and eventual failure.

The motor manufacturer was consulted, and a replacement motor properly designed for the ASD application was installed. The replacement motor included rotor bars designed to minimize harmonic losses and an external blower for improved motor cooling when operating with a constant torque load at reduced speeds. Operation of the new motor was successful without further issues. More details of this motor failure and corrective measures are given in [46]. This experience highlights the need for communication between the user and all pertinent equipment manufacturers and contractors for unusual motor applications, such as applied on an ASD with a constant torque load.

D. Importance of Electrical System Data

A new 5000 hp, 4 kV, 1800 rpm induction motor driving a centrifugal compressor was being added as part of a process unit update at a large refinery. This motor would be installed on a 13.8 kV – 4.16 kV captive transformer. The motor was specified using API 541 and included a design review meeting with the manufacturer.

While reviewing motor speed torque characteristics at the design review meeting, the manufacturer indicated that the motor was designed for starting at the standard minimum 80% of rated voltage required by API 541 since the electrical system impedance data necessary for precise starting voltage calculations had not been provided on the data sheet. This starting voltage is normally satisfactory for most applications, but it should be verified, and special attention is needed where a captive transformer is used. The captive transformer had recently been ordered with a standard impedance. The engineering contractor intended to provide the system impedance data later after the electrical power system studies were performed, but this was too late for the motor manufacturing cycle. A simple calculation found that the voltage would drop to approximately 70% of rated during starting, and comparison with the compressor speed-torque curve for starting showed that the motor would be unable to accelerate up to normal speed. This is indicated in Fig. 2 by the intersection of the load torque curve with the motor 70% voltage torque curve at 80% speed. The motor would most likely accelerate only to approximately 80% of normal speed. Note API 541 requires a minimum 10% separation margin between the motor torque curve and the load torque curve throughout the speed range up to normal operating speed.

It was too late in the motor manufacturing process to make significant changes to the design without substantial costs and delivery delays. However, since the transformer had only recently been ordered, the kVA rating and impedance could still be adjusted as needed to maintain the minimum 80% motor rated voltage during starting without a significant impact on cost and schedule, and this was the solution implemented. Fig. 2 shows the motor 80% voltage torque curve is sufficiently above the load torque curve to ensure acceleration up to normal speed.

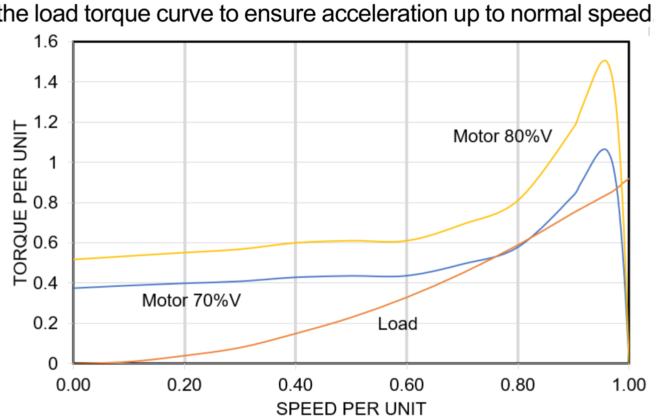

Fig. 2 Speed torque curves for motor and compressor.

This experience demonstrates the importance of providing all pertinent system data to the motor manufacturer before the motor design has been finalized. It illustrates the importance of having an API 541 design review meeting for important motors, especially those with unusual requirements, and this should be done after design drawings are issued for approval but before the design is finalized so it is not too late to correct any issues.

E. Impact of Driven Equipment

At an oil production facility, two new skid packages were installed that included two 1500 hp, 1200 rpm, 4 kV induction motors driving reciprocating compressors. The motor rotors were a fabricated copper bar cage design. The motors were not specified to API 541, and the motor manufacturer was not originally consulted on the application details. After less than a year in operation, the first motor rotor experienced several brazed joint failures and broken rotor bars at or near the copper bar to end ring interface. See Fig. 3 for the failure location shown on a typical rotor and Fig. 4 showing the bar to end ring joint failure. The rotor was repaired and returned to service. A few months later, a similar failure occurred on the second motor, and there were also cracks found on the rotor fans. The rotor was repaired, but this second failure raised concerns about a system problem and the need for further investigation. A few months after this, the first motor experienced a similar failure again.

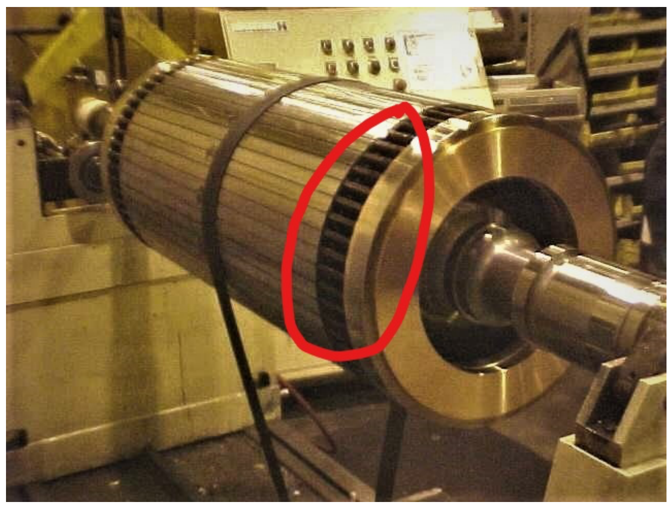

Fig. 3 Typical induction motor rotor with fabricated copper bar cage. (Courtesy of ABB.) Failures, which are not shown, occurred at or near the bar to end ring interface identified by the elliptical marking.

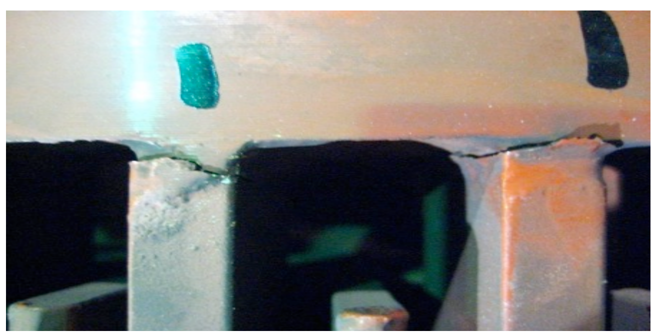

Fig. 4 Failure of rotor bar to end ring brazed joints. (Courtesy of ABB.)

At this point, the motor manufacturer was engaged, and a comprehensive investigation was undertaken. The original torsional study had examined the effects of the compressor pulsating torques on the motor and compressor shafts and the coupling in the usual manner. However, it did not examine the effects on the other rotating components in the motor. See Fig. 5 for a typical reciprocating compressor crank effort diagram showing the nature of the pulsating torque load imposed upon the motor for each revolution. An updated torsional study and a finite element analysis were conducted to examine the effects of the compressor on the motor rotor. It was found that the compressor pulsating torque effects on the rotor were sufficient to cause high cycle fatigue failure of the copper bars and brazed joints in the rotor bar to end ring interface area.

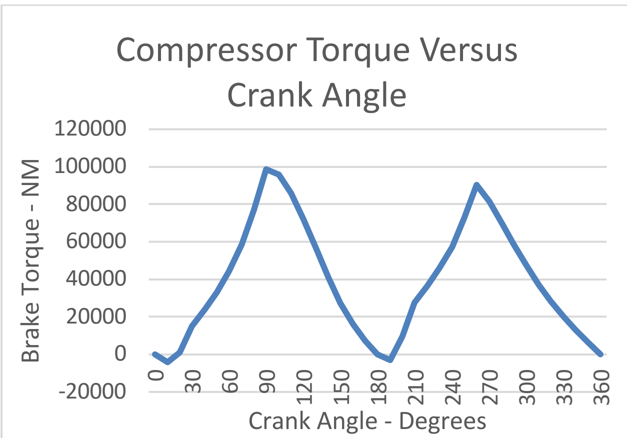

Fig. 5 Typical reciprocating compressor crank effort diagram showing pulsating torque. (Courtesy of Travis Griffith-Worley Consultancy.)

The solution selected was to replace the existing rigid coupling between the motor and compressor shafts with a flexible coupling and to add a larger flywheel. This flexible coupling and larger flywheel changed the torsional natural frequency and attenuated the amplitude of the compressor torque pulsations to acceptable values for the motor rotor.

This experience shows the importance of understanding the potential of the driven equipment to have adverse effects on the motor for certain applications, such as a reciprocating load. The motor manufacturer should be consulted in such cases and the effects analyzed as necessary to ensure a reliable installation. At the time of this problem, a torsional study normally examined the stresses on the motor and compressor shafts and the coupling but not the motor rotor cage assembly. For this reason, this problem was not found by the original torsional study. However, with this experience, the torsional study requirements of API 541 were modified to include stress analysis of the rotor cage assembly and the shaft mounted cooling fans when the motor is driving a reciprocating load, so future issues of this type can be avoided on motors specified to API 541.

F. Effect of Plant Process Conditions

A new 11,000 hp, 13.2 kV, 1800 rpm induction motor, which was purchased to API 541 requirements, driving a centrifugal compressor was being installed at a large refinery. When starting was first attempted, the motor accelerated for several seconds but tripped on excessive starting time before reaching operating speed. Investigation found that the process conditions at starting were different than originally planned, so the motor was designed for compressor speed-torque characteristics that were less severe than the actual characteristics. The motor as designed did not produce sufficient torque to accelerate the compressor to operating speed with the actual process starting conditions, similar to the torque deficiency case shown in Fig. 2.

Fortunately, operations personnel and process engineers were able to slightly modify the process conditions for startup to reduce the compressor loading. The system operating voltage was boosted approximately four percent higher, and the motor protective relay settings were reviewed and adjusted to allow as much time as possible for starting while still protecting the motor. These corrective actions taken together were sufficient to allow the motor to start.

While a workable solution was found for this application, this would not necessarily always be the case. In some applications, available solutions may be very difficult to implement, or in the worst case, there may be no viable solution other than replace the motor with a new one capable of accelerating the load. Of course, this would be a major cost and schedule impact for the facility since the manufacturing cycle for such a motor is often approximately one year. This demonstrates the importance of being sure the process conditions as they affect the motor and its driven equipment are clearly and accurately understood, and sufficient margins are included in the motor design for any uncertainties.

VI. CONCLUSIONS

The purpose of this paper is to provide guidance to the engineer who is not a motor specialist and may not be familiar with the multiple motor standards available and how they are interrelated and used when specifying a motor. Referring to Fig. 1, this paper highlights that the base motor standards are NEMA MG 1, which is primarily used for North American locations, and IEC 60034, which is primarily used for international locations. The basic motor requirements to be satisfied by all manufacturers are defined in the base standards. The NEMA MG 1 and IEC 60034 motor standards are complementary standards covering similar if not identical material. These base standards are supported by additional reference standards from IEEE, ANSI, IEC, ASTM, etc., which further define requirements for materials, testing, etc. Then there are the overlay standards, such as those from IEEE and API, which provide additional requirements to improve motor durability and reliability. Next are certification standards, which provide requirements for use in hazardous classified areas, safety, etc., and specialty standards, which provide guidance for repair, special applications, etc. Finally, there are the supplemental specifications, which add user preferences.

It is important to be aware of this litany of standards that guide specification, manufacturing, performance, and application of motors, but it is not essential to be an expert on the standards to specify a motor. The IEEE and API overlay standards provide datasheets that when properly completed will result in specification of a motor that minimizes potential issues, such as those described in this paper.

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VIII. VITAE

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