APPLICATION GUIDELINE FOR ELECTRIC MOTOR DRIVE EQUIPMENT FOR NATURAL GAS COMPRESSORS

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APPLICATION GUIDELINE FOR ELECTRIC MOTOR DRIVE EQUIPMENT FOR NATURAL GAS COMPRESSORS

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Application Guideline for Electric Motor Drive Equipment for Natural Gas Compressors

Foreword

The following guideline addresses the need for practical guidance on electric motor drives for gas compressors. The guideline is directed to issues which are not addressed in detail by the existing Institute of Electrical and Electronics Engineers (IEEE) electric motor standards or American Petroleum Institute (API) compressor standards. The guideline does not discuss specific electric motor designs because the intent was not to specify how motors should be designed as design standards already exist. The authors intended the following document to be used to educate the users of gas compression equipment who need to know how to specify the electric motor drive system and assure that the system design can support the power and speed range for the application.

In the last ten years, electric motor driven compression has become more common in the natural gas industry. Many of the components of an electric motor drive system have undergone technological changes to meet the needs of gas compressor applications. While many electric drive systems are currently operating successfully, electric motor technologies, variable frequency drives, variable speed gear systems and advanced bearing technologies are still evolving to provide a more efficient drive system with a larger and more flexible operating envelope. This guideline focuses on the mainstream electric motor technology currently employed for gas compressor applications.

Among the most challenging issues for electric driven gas compression are system start-up and method of meeting capacity demands of the pipeline through speed variation. This guideline addresses these issues by providing a description of the various drive train configurations available for variable speed, and the multiple starting methods available to the operator. The important parameters involved in assessing the motor power and torque curves for the gas compressor operation are also covered. Other influential drive train components (bearings, couplings, and shaft design) are discussed. In some areas, it is appropriate to refer the reader to the relevant standards which cover some of these topics more extensively. The guideline also provides guidance on factors affecting motor performance in terms of life, maintenance, reliability and efficiency.

In Appendix A-1, basic electric motor definitions and formulas are provided as a reference. The appendix also provides a checklist of the common issues that should be reviewed when designing an electric motor driven compressor station.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Application Guideline for Electric Motor Drive Equipment for Natural Gas Compressors

1.0 INTRODUCTION

The following guideline was developed for designers and users of electric motor driven systems and the related components in an electric motor drive system for a natural gas compressor. Unlike traditional mechanical drivers, where standard packages with predefined operating envelopes exist, electric motor drive systems encompass many variations in drive train configurations and cannot be described in a "standard" implementation. The motor, motor drive, electric power, cooling system, gearbox, and coupling, which make up the electric motor drive system, are often supplied by various vendors as individual components. The system, as a whole, may not be adequately considered or reviewed for all possible process variations.

In the last ten years, the advances in electric motor technology and variable frequency drive (VFD) hardware have enabled more sophisticated control schemes and higher power, higher speed electric motors. Due to these advances and other economic or environmental factors, electric motor drives are becoming more common for centrifugal and reciprocating compressors. As with any new technology, the electric motor drive system (which includes the adjustable speed drive, gearbox, bearings and frame) offers some advantages at the cost of some limitations compared to conventional technology. The appropriate drive technology and the selection of the primary components are somewhat a function of the compressor operation. This guideline provides the necessary background information and key points that should be considered in "bridging the gap" between the electric motor drive system and the natural gas compressor operational requirements.

1.1 Purpose of the Guideline

This guideline is to be used as a reference for the natural gas industry to provide direction on the selection, installation, and operation of electric motor drives for gas compression systems. The issues addressed for electric motor drive compressor applications will equip an operating company engineer with the fundamental knowledge needed to design the drive system to meet his company needs.

Specific gas compression systems will have different operating requirements which will affect the motor type, motor size, motor drive system, power requirements, gearbox, coupling, and operational methodologies. This guideline provides an objective view of the system design and selection of electric motor drive systems without requiring that specific components or operational methodologies be used.

The guideline is also intended to address many of the start-up and operational issues that should be considered in the selection process of the electric motor drive system. These issues will impact the ability of the motor drive to deliver the required torque at specific operating points or the ability to bring the motor online.

1.2 Types of Electric Motors

The two most common AC types of electric motors used for natural gas compressor drives are AC synchronous motors and asynchronous motors or (as more commonly referred to) induction motors. Permanent magnet motors are a subset of synchronous machines which have recently advanced to the point that these motors may be applied for new high speed applications (above 3,600 rpm) with high efficiencies. High speed, squirrel-cage induction motors may also be used for high speed applications with appropriate controls. The motivation for a high speed motor is often based on eliminating the speed-increasing gearbox. Direct current (DC) motors of the brushless type may also be used in combination with speed control and AC to DC power converters, but these are typically not found in gas compressor installations. The two most common types of motors for gas compressor installations are reviewed below.

Both of the synchronous and induction types of electric motors have basically two windings or electrical circuits. One winding, called the stator, is stationary and is connected to the three-phase AC input voltage. The other winding is rotating on the motor shaft is referred to as the rotor. The following section provides a basic description of these two most common types of motors for gas compressor installations.

1.2.1 Asynchronous Induction (AC) Motor

The induction motor works by inducing current in the rotor through the small air gap between the stator and rotor. The stator current generates a rotating magnetic field in the air gap between the stator and rotor. The interaction of the induced rotor current with the rotating magnetic field generates a torque on the rotor. The induction motor has the advantages of being self-regulating and capable of balancing the torque demand of the load with the output of the motor.

The two primary induction motors are the squirrel-cage and wound-rotor type. The difference between the squirrel-cage and wound-rotor type is the rotor winding. The wound-rotor type has a rotor winding that is available for control though slip rings and brushes. The squirrel-cage type has a rotor winding that is fixed and not available for control. The winding is composed of a series of longitudinal conductors (bars) embedded or surface mounted in steel rings. The rotor bars are connected at each rotor end creating the rotor electrical circuit. Most large induction motors for the natural gas industry compressor drives are of the squirrel-cage type. The wound rotor type is not commonly used for natural gas compressor drives due to its higher hazard risk and higher cost.

The base speed of the induction motor is based on the number of magnetic poles of the machine. The number of poles or the windings in the stator determines the speed of the rotating magnetic field or synchronous speed of the motor. If there is no load on the motor shaft, the rotor will turn at a speed that slightly lags the synchronous speed, which defines the slip of the induction motor.

As the motor is loaded, the difference between the synchronous speed and rotor speed increases which will increase the percent of slip. When slip increases, a higher current is induced in the rotor bars, the interaction of the two currents become stronger and a higher torque is provided to the motor load. Typical operating speeds for induction motors for a no-load and full-load case are given in Table 1-1 below.

Table 1-1. Operating Speeds for Induction Motor with Typical Slip

No. of Poles	Synchronous speed with no slip, in rev/sec (and RPM) for 60 Hz Supply	Actual speed with full load and slip, in rev/sec(and RPM) for 60 Hz Supply
2	60 (3,600)	58.8-59.4 Hz (3,528-3564)
4	30 (1,800)	29.4-29.7 (1,764-1782)
6	20 (1,200)	19.4-19.8 (1,164-1188)
8	15 (900)	14.7-14.8 (882-888)

The National Electrical Manufacturers Association (NEMA) defines four design classes (classes A-D) for induction motors. Some natural gas industry compressor drives require Design Class B or Design Class C. Design Class D is often used for high torque applications. The majority of motors over 500 hp fall outside of NEMA specifications and may not have explicit design specifications. A more detailed description of NEMA and other applicable standards are described in later sections of this guide.

If the natural gas compressor requires variable speed operation, the induction motor speed can be controlled. There are four basic methods used to control the speed of the induction machine. They are varying the input voltage, varying the input frequency, changing the winding pole number or by varying input frequency and voltage together. A more thorough description for induction machine variable speed control is provided in later sections of this guide.

However, compressor variable speed operation can also be provided by an induction motor running at a constant speed and utilizing a variable speed gearbox.

In order to achieve the higher rotational speeds required by many compressor drive applications, a speed-increasing gearbox is often used instead of a direct couple to the compressor.

1.2.2 Synchronous (AC) Motor

A synchronous motor contains a rotor which rotates in synchronism with the stator’s magnetic field (no slip). The rotor of a synchronous motor is primarily a single winding with the same number of magnetic poles as the stator. Unlike the induction machine, the rotor of a synchronous motor is excited with an external DC current to provide the rotor magnetic field. In the synchronous motor, the rotor mechanical speed is equal to the stator synchronous speed. The synchronous motor cannot be run directly from the AC power line as synchronous motor controller is required for rotor control. To start a synchronous motor in a fixed speed application, a separate starter winding is utilized and the starting is similar to an induction motor.

The required motor controller is used to control the rotor magnetic field by controlling the field current. Once a synchronous motor is operating at rated speed, the angular displacement between the stator and rotor magnetic fields will change with the load. The angular displacement along with the field current affects the motor input power factor. Thus, control of the rotor field can be used to control the motor input power factor.

The speed of the synchronous motor can be controlled in the same manner as the induction motor (through the four variable speed methods) to provide for variable compressor operation.

Some synchronous motors are being developed as permanent magnet (PM) motors for high speed applications. In permanent magnet motors, the rotor magnet field is provided by permanent magnets mounted on the rotor without the need for field excitation. The torque density (achievable torque for a given size and weight) is significantly higher for these types of motors. Permanent magnet motors tend to have less substantial cooling requirements and in most cases, due to the lower cooling requirements, these motors achieve higher efficiencies. The drawback to the permanent magnet motor can be the high initial cost of the lack of high power motors available for the compressor drive application. PM motors are not discussed extensively in the following guideline due to their only recent utilization in this area and evolving design.

1.3 Drive Train Configurations

Meeting the operational speed range of the compressor is important in gas compression systems because centrifugal compressors and most reciprocating compressors operate most efficiently in terms of capacity control by varying speed. To vary flow rate without speed control, for centrifugal compressors involve suction or discharge throttling or recycling gas. Both of these capacity control options are significantly less efficient than changing the rotational speed of the centrifugal compressor. For reciprocating compressors, capacity may be varied by other means besides recycling flow and speed variation, such as opening volume pockets, deactivating the head-end of a cylinder, or delayed valve opening/closing. However, speed variation provides substantially more rangeability and control of the reciprocating compressor throughput. For these reasons, a large majority of electric motor driven gas compression systems will require design for adjustable speed, typically accomplished through a variable frequency drive (VFD) controlling the motor or a variable speed hydraulic drive (VSHD) with a fixed speed motor. An alternative that is rarely used is to use a multi-speed motor, available in 2-speed, 3-speed, or 4-speed configurations.

Meeting the operational speed range of the gas compressor is the primary issue specific to this application in the selection of the electric motor drive train configuration. However, other common electric motor issues must also be considered for the gas compressor application as well. The cost, complexity, and reliability of the drive train will be impacted as more components are added. The four common drive train arrangements are summarized below.

1.3.1 Direct Drive Train (With and Without VFD)

The preferred option for the drive train (because of simplicity and cost) is to drive the compressor with a motor operating at the same speed – see Figure 1-1. This eliminates the need for a gearbox. The motor speed must be controllable over a workable speed range of the compressor.

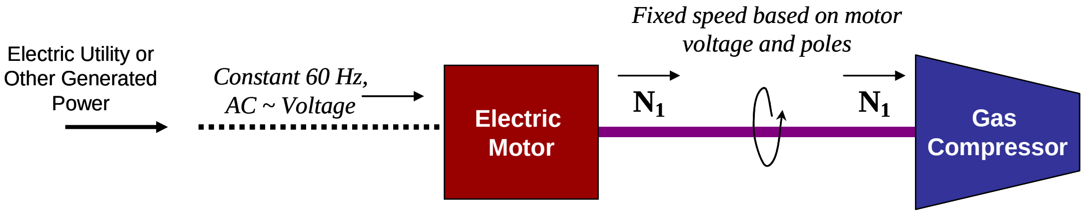

Figure 1-1. Single Motor Directly Driving Gas Compressor at Fixed Speed

1.3.1.1 Direct Drive Train with VFD

A variable frequency drive (VFD) may be used in a direct drive train to vary the compressor speed. The VFD works to vary the input frequency and voltage supplied to the electric motor, thus changing the effective synchronous speed of the motor. The motor speed changes in proportion to the VFD controller. The mechanisms for changing the input motor frequency and the VFD's best suited for the two motor types are discussed in Section 2.5. In sizing the electric motor with a VFD for the compressor application, the relationship between power and speed provided by the VFD must be understood – see Figure 1-2 and application sections 6.0 and 7.0[1].

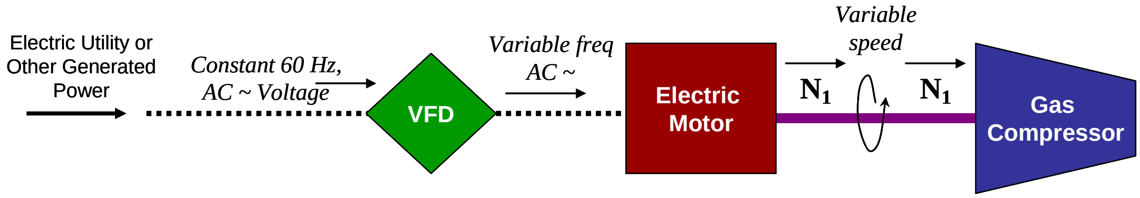

Figure 1-2. Single Motor Directly Driving Gas Compressor with VFD

1.3.1.2 Direct Drive Train Without VFD: Multi-Speed Motors

An alternative means of accommodating compressor variable speed capacity control requirements without the use of a VFD is to use a multi-speed motor on a direct drive. This method will only provide the ability to change the compressor speed between limited points as the maximum available multi-speed motor is a four-speed motor. A single winding with a different number of poles is used on a two-speed adjustable motor with a speed ratio of 2 to 1. Two windings and two-pole combinations on each provides a four-speed motor. These motors can have speeds with different ratios because the windings are different.

1.3.2 Conventional Speed Motor with Gearbox (With and Without VFD)

The next simplest configuration is to use a gearbox to increase (or decrease) the rotational speed of the gas compressor relative to the electric motor speed.

1.3.2.1 Motor with Gearbox

If the fixed speed motor speed does not fall within the compressor speed operational window a speed changing gearbox is required. The gearbox is used to increase the motor speed to match compressor running speed as shown in Figure 1-3. Sizing the gearbox appropriately to drive the compressor at the desired operating speed point (with some speed margin) is important in this drive train design. The gearbox ratio should account for the maximum speed rating of the motor and the required driven speed of the compressor. For induction motor systems, the gearbox ratio selection should take into account the slip speed of the motor in the effective speed margin[2].

As with the direct drive option previously discussed, a multi-speed motor coupled with a gearbox can be used to provide a limited number of compressor operational speed points.

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[1] The use of a VFD also helps in the starting of the electric motor because the in-line current may be reduced initially and gradually brought up as the motor reaches its design speed. For constant-speed compressor applications, the full-size VFD may be difficult to justify (because the operation does not require constantly varying the speed), but it may be possible to implement a smaller start-only VFD.

[2] A smaller motor (and smaller gearbox) may be weighed against a larger horsepower motor for the same compressor selection. The larger horsepower motor will require a larger gearbox ratio to meet the same compressor speed requirements but will be capable of more power at off-design conditions.

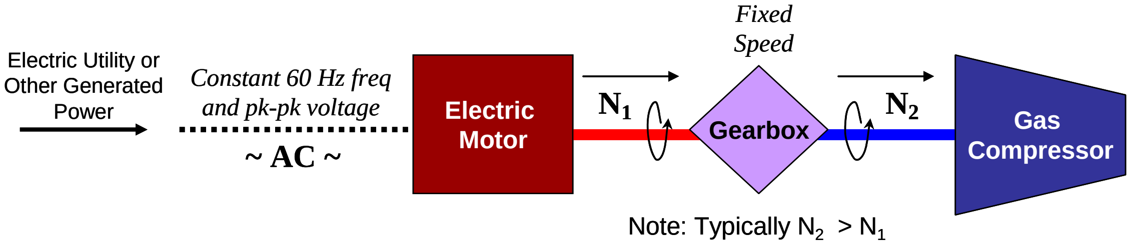

Figure 1-3. Electric Motor with Gearbox Drive – Without VFD

1.3.2.2 Motor with Gearbox and VFD

A motor and variable frequency drive may be used in combination with a speed-changing gearbox, especially for centrifugal compressor applications. The VFD is used for the drive with the gearbox to vary the output motor speed (which is then changed by the gearbox ratio) to meet a variable speed operation for the compressor as shown in Figure 1-4.

In this instance, the motor supplier and VFD supplier must review the required operating speed range of the compressor and insure the motor will perform correctly over this range. The gearbox should be sized based on the motor maximum speed and should account for the difference between motor and compressor maximum speed. A detailed discussion of the mechanical issues surrounding operation of the motor/compressor over a variable speed range is covered in the application sections 6.0 and 7.0.

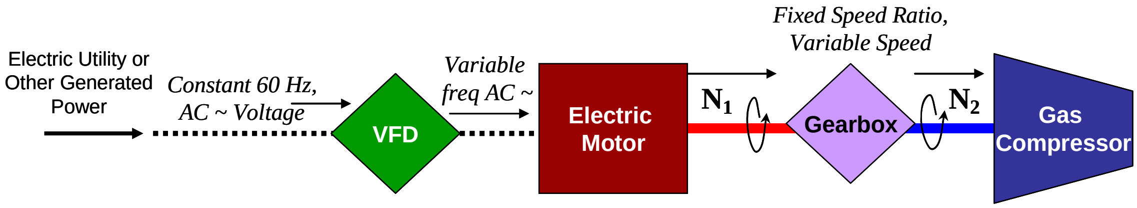

Figure 1-4. Electric Motor with Gearbox Drive – With VFD

1.3.3 Variable Speed Hydraulic Drive

A variable speed hydraulic drive may also be used to vary the speed and torque supplied to the compressor. This system uses a mechanical gearbox in combination with a variable speed hydraulic pump and motor. Mechanical energy from the motor shaft is transferred to the compressor coupling using the hydraulic pump/motor/gearbox assembly. A planetary gear assembly may also be used to vary the effective gearbox ratio with the hydraulic drive. These drive systems are typically called hydrostatic drives and come in many configurations and transmission system options. The hydraulic coupling may be directly coupled or used with a gearbox.

Hydraulic couplings are also used in this configuration. The hydraulic coupling changes the output shaft speed as a function of the hydraulic controller. The hydraulic coupling decouples the motor from the drive system. Hydraulic couplings can also be used to effectively dampen any torque ripples produced by the electric motor.

In a VSHD, the motor is typically operated at constant speed in this configuration because the VSHD accommodates the variable speed requirements of the compressor. This may impose additional demands on the motor at start-up – see Section 5.0.

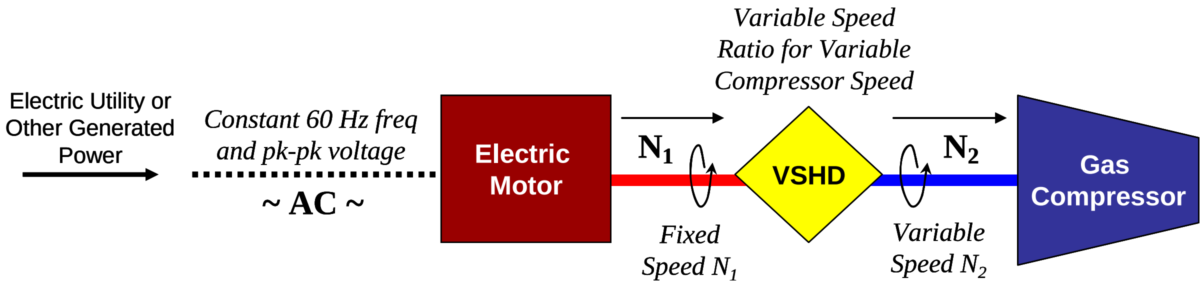

Figure 1-5. Electric Motor with Variable Speed Gearbox Drive

1.3.4 Other Configurations with Auxiliary Motors

In some cases, an auxiliary motor may be configured on the other end of the gas compressor shaft to provide additional torque to the compressor for peak periods. Hybrid systems are also possible, where an electric motor is used for high power demands in combination with a primary gas turbine driver. In these cases, if a VFD is also included in the drive train configuration, it is typically used to control torque (not speed) of the electric motor.

1.4 Methods of Starting Electric Motors

Starting of the electric motor drive is a major issue for consideration in this application because of the large motor size. On motor start, large motor currents and large acceleration torques are generated as the motor comes up to operating speed. The electrical supply, whether self-generated or supplied by a utility, will have supply limitations that must be considered during start. As large motors are started, motor in-rush currents are typically 500%, or more, greater than running currents. Supplying these currents will result in supply voltage drops.

Managing the associated supply voltage drop while supplying the needed starting current will need to be addressed. The coupling and shaft will also have a torque limit that may exclude certain start-up options. Considerations on unloading the compressor during start will play an important part in considering the appropriate method for starting the electric motor.

The basic methods used to start an electric motor for gas compressor applications are given below and are discussed in detail in Section 5.0.

- **Method 1: Across-the-Line Start** – The most common option for smaller motors and still should be considered for larger motors. This is the lowest cost option and does not require additional hardware. It must consider the current in-rush and associated voltage drop and its impact on the overall electrical system providing power to the motor.

- **Method 2: Soft-Start with Full Size VFD –** A simple option to consider for installations where a VFD is already required to meet the variable speed requirements of the application. The soft-start methods vary by manufacturer and type of VFD.

- **Method 3: Small VFD Sized for Soft-Start –** Another method considered for large motors without a VFD requirement. The smaller VFD can be installed at a somewhat lower cost and will ease the torque loads and voltage drop associated with starting the motor across the line, similar to the full size VFD.

- **Method 4: Smaller Starter Motor at Reduced Load –** If the compressor can be unloaded using a suction throttle or bypass loop to reduce the motor load, it may be possible to start a smaller motor across the line and use it as the starter motor for the primary electric motor driver. Once the primary driver has been brought online, the load can be applied and the smaller motor can be taken offline.

- **Method 5: Smaller Starter Motor with Torque Converter –** Similar to Method 4, this method unloads the motor from the compressor using a hydraulic torque converter on the drive train. This is common with the variable speed hydraulic drive systems and more efficient than suction throttling or bypassing gas during the start-up period.

- **Method 6: Lower Voltage Options for Reduced Load Start –** If the compressor load can be reduced, several electrical methods of reducing the voltage to the motor are available. These methods vary in cost and complexity but may be a consideration to ease the impact of bringing a motor online with an across the line start. These methods would be considered in lieu of a smaller VFD or smaller motor for starting purposes.

1.5 Relevant Standards

A number of standards are relevant to the selection and design of electric motors for driven gas compressor equipment. For the natural gas compressor application, an electric motor drive must be designed per a manufacturer’s internal standard or, more commonly, the natural gas industry standards: API 546 for synchronous motors or API 541 and API 547 for induction motors. Although many other IEEE and API industry standards and recommended practices address the use of electric motors for the petrochemical industry, these standards do not specifically address the additional design and selection details required for adapting adjustable (or constant) speed electric motors to the gas compressor application, where peak torque and speed are not necessarily coincident. Careful consideration of operating the electric motor outside the design point is critical for reliable, guaranteed operation during start-up, for different gas compositions, and for varying suction and discharge pressures. This guideline addresses the additional requirements and forethought which must be part of the selection process for the electric motor and the associated adjustable speed drive options.

The following section describes the primary standards that are recommended for additional design and selection guidance.

1.5.1 API Standards

- *API 546 Brushless Synchronous Machines 500 kVA and Larger* — Defines the synchronous motor standard for use with gas/petrochemical equipment. The standard applies to motors with a constant rotational speed independent of load. The API 546 standard restricts the in-rush starting current to 500% of the rated full load torque.

- *API 541 Form-Wound Squirrel-Cage Induction Motors 250 hp and Larger* — Defines the induction motor standard for use with gas/petrochemical equipment. The standard divides induction motors into the squirrel-caged design. In the case of induction motors, the in-rush (locked rotor) current is allowed to be 650% of the rated full load current. NOTE: *For API 541 and 546, data sheets are provided for the motor spec*ifications. Use of these data sheets is essential for purchasing.

- *API 547 General Purpose Squirrel-Cage Induction Motors 250 hp and Larger* — Applies to the downstream portion of the gas industry and specifically addresses large (>250 hp) form-wound squirrel-cage induction motors that drive centrifugal compressors. The torque-current characteristics of the motor must meet the power-speed ratings defined in NEMA MG1 Part 12 for Design B installations. These motors are typically much simpler and designed for lighter duty compared to API 541 motors.

- *API 617 Axial and Centrifugal Compressors for Petroleum, Chemical and Gas Industry Services* — Applies to axial and centrifugal compressors and specifies the compressor speed and power requirements. This standard also provides design guidelines, sizing requirements, and specifications for the driver of the compressor.

- *API 618 Reciprocating Compressors for Petroleum, Chemical and Gas Industry Services* — Specifies motor drive requirements for current pulsation levels, power matching to compressor and starting torque. Provides guidance on bearing housing, bearing types, and shaft extensions for reciprocating compressor applications.

- *API 684 RP Rotordynamics Tutorial* — Recommended practice to provide guidance on rotordynamic analysis and methods of addressing unbalanced systems, stability, and rotor balancing. Lateral critical speeds and torsional critical speeds are discussed and methods of analysis provided.

- API 617, API 618, and API 684 should be consulted to aid in evaluating the lateral and torsional rotordynamics of the design.

1.5.2 IEEE Recommended Practices and Standards

Several IEEE standards exist on the use of electric motors in the petrochemical industry. The following list comprises the major relevant IEEE papers for the natural gas compressor driven application.

- *IEEE Standard 303 (2004):* Recommended Practice for Auxiliary Devices for Rotating Electrical Machines in Class I, Division 2 and Zone 2 Locations — This standard provides basic surge protection, other protection, and auxiliary equipment requirements.

- *IEEE Standard 841 (2001):* Severe Duty Totally Enclosed Fan-Cooled Squirrel-Cage Induction Motors Up to and Including 370 kW (500 hp) — This standard specifies service conditions, power load fluctuations, voltage and frequency ratings, and design parameters for the shaft, rotor, and bearings. Insulation, frame and cooling requirements are provided. Full load efficiency of the enclosed motor is specified for 2-pole through 8-pole designs up to 500 hp. NOTE: The 2009 version of IEEE standard 841 should have only minor updates compared to the 2001 version.

- *IEEE Standard 1068 (1996): Re*commended Practice for the Repair and Rewinding of Motors for the Petroleum and Chemical Industry — Pre-repair, repair, and post-repair responsibilities, inspection procedures, and facility requirements are provided. Specifics for reconditioning of the bearings, stator and rotor are given, for both electrical and mechanical aspects. NOTE: The 2009 version of the IEEE standard 1068 will have extensive revisions compared to the 1996 version.

- *IEEE Standard 115 (2002):* Test Procedures for Synchronous Machines — Specifies methods of taking resistance measurements, alternating voltage, and frequency testing measurements. Tests are divided into efficiency, temperature, load excitation and voltage regulation, torque, and sudden short-circuit type tests.

- *IEEE Standard 112 (2004):* Standard Test Procedure for Polyphase Induction Motors and Generators — Provides six different methods for determining efficiency, measurement procedures, and types of machine losses.

- *IEEE Standard 43-2000:* IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery — Defines the methods of testing electrical insulation and provides background on insulation resistance and polarization index. Factors affecting test results are also given.

- *IEEE 1566 - 2005:* IEEE Standard for Performance of Adjustable Speed AC Drives Rated 375 kW and Larger — Describes performance requirements of large adjustable speed drives and includes data sheets to assist with specification and bid review.

1.5.3 NEMA Standards

- *NEMA MG 1-2006:* Motors and Generators — Assists in the proper selection and application of motors and generators. Practical information is given on the performance, test, and construction of AC and DC motors. The standard provides extensive information on induction and synchronous motor power factors, voltages, rated speeds, torque limits, and power relationships.

- *NEMA MG 10-2001 (R2007):* Energy Management Guide for Selection and Use of Fixed Frequency Medium AC Squirrel-Cage Polyphase Induction Motors — Selection of induction and synchronous motors including installation, operation, and maintenance activities.

- *NEMA ICS 7.1-2006:* Safety Standards for Construction and Guide for Selection, Installation and Operation of Adjustable-Speed Drive Systems — Applies to all electrical drive systems, including VFD's used on motor-drive equipment.

- *NEMA ICS 2.4:* NEMA AND IECD Devices for Motor Service — This standard discusses the differences between the NEMA and IEC standards. The two standards allow different name plate labels, contactors, overload relays and controllers. NEMA nameplates require the motor size, horsepower, voltage, and continuous current be stated on the nameplate. IEC nameplates require hp/kW rating, utilization category, thermal current, rated operational current, insulation voltage, operational voltage, and standard designation.

- NEMA Application Guide for AC Adjustable Speed Drive Systems — Gives advice on applying AC adjustable speed drives for all motor ratings.

2.0 SELECTION FACTORS FOR ELECTRIC MOTOR DRIVE

The electric motor drive selection is influenced by a number of factors. The most prominent of these factors is the compressor operational and load requirements, which are discussed in the context of compressor application sections 6.0 and 7.0 and in the context of using a VFD in section 2.5.

The compressor application will determine the torque loading, the operating environment, the power at a given speed, and if variable speed operation is required. Once the application is well-defined, other selection factors will be considered. A checklist of items to consider in the initial design stages for an electric motor drive compressor station is provided in Appendix A-2. In the following sections, several selection factors for the electric motor drive train are discussed.

2.1 Electrical Power Supply Considerations

Electric power will be supplied to the motor from a utility company via a substation or will be generated onsite by the operating company. These two supply options and how they are implemented for the motor at the compressor station will vary greatly. Considerations for the potential process disruptions as a result of electrical supply issues will need to be evaluated. If power is generated onsite, some more flexibility is available in terms of voltage selection and possibly motor start-up options (depending on other power requirements). If power is supplied by a utility company, the electric company will need to be included extensively in the design process.

Listed below are several of the initial design considerations associated with the electrical supply. These considerations will need to be thoroughly addressed during the system design.

2.1.1 Short Circuit Ratio

The short circuit ratio (SCR) is used to quantify the effect of starting a motor across the line on the voltage regulation capability of the electrical supply. The ratio is calculated according to Equation 1 based on the fault current capability of the source and the motor load current values.

Greater motor start-up currents can be tolerated if the short circuit ratio is relatively high. The higher SCR system is more resilient to voltage sage during start-up events. The minimum possible short circuit ratio defines the worst case voltage regulation condition for the system. The minimum SCR should be provided by the electrical supply line and used in the evaluation of motor start options.

2.1.2 Transformer Impedance

For utility supplied power systems, a substation with a step-down transformer will serve as the power source for the motor drive. The step-down transformer converts the utility incoming high voltage distribution or transmission voltages via the transformer turns ratio to the selected motor voltage nominal value.

The transformer impedance rating is defined as the percentage of nominal primary voltage required to drive full load current through a short circuited secondary winding. For example, a 6% impedance transformer requires 6% nominal input voltage to drive full load current through a short circuited secondary. If the load is primarily reactive, as with a motor starting, the currents will produce a significant voltage drop through the transformer, where the impedance is also mostly reactive. If the load is mostly resistive as in a heater or a loaded motor, the vector derived voltage drop will not be as great as when the motor is starting.

The transformer impedance is a significant part of the overall system SCR for the motor drive. Motor start-up current, the system short circuit current, and the transformer maximum kVA capacity should then be calculated based on the transformer impedance.

The transformer should typically be sized by the utility company so that the short circuit capability produces less than a nominal voltage drop. The transformer impedance has a non-linear effect on the short-circuit capacity. The transformer impedance rating should be evaluated against the line voltage and the motor start-up current to assure that voltage drop for the utility power system will not exceed acceptable levels.

2.1.3 Self-Generated Power

If the power supply to the electric motor is generated onsite (such as on a drilling platform), then some additional flexibility is provided in the voltage selection. Across-the-line starts may be evaluated by directly interfacing with the electrical generation team (possibly part of the operating company). However, self-generated power typically limits the ability to start a motor across-the-line because the short circuit ratio will be lower due to the limited fault current of the system. In self-generated applications, the motor’s affect on the overall electrical system will be much more pronounced[3].

2.2 Influential Factors in Electric Motor Selection

Several factors influence the electric motor performance. These factors will also influence starting capability, operating cost and operating range. These factors will either be specified by the motor purchaser (service factor, motor poles, motor speed rating, current in-rush and motor voltage) or determined by the installation (power factor, class of enclosure, and insulation class.) These specifications are often decided on a case-by-case basis. A general description of these factors and their influence on the motor selection is provided below.

2.2.1 Service Factor

The motor service factor (SF) defines the allowable power output for continuous duty operation. The service factor allows the rated horsepower of the motor to be exceeded if the input voltage is maintained to the motor design values. The motor may be overloaded by this allowable amount, which is typically in the range from 1.0 to 1.15. Service factor applies to output horsepower. The running current at-service factor loading may be specified by the manufacturer, as well in-service factor amperes (SFA). It should be noted that API 541 does not recognize service factors above 1.0 because typical high horsepower motors are specified with a 1.0 SF.

Motor performance ratings will be based on a service factor of 1.0. If the service factor exceeds 1.0, the motor is permitted to operate at a 10ºC higher winding temperature according to NEMA standards. The service factor is used in conjunction with the insulation class and the operating temperature of the motor to determine the motor life. The primary factor affecting motor life is the failure of the electrical insulation due to high temperature operation. As a rule of thumb, insulation life halves for every 10ºC

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[3] Note: Combined heat and power (CHP) systems normally operate at plant voltage but can be stiffer for the electrical system than purely self-generated power applications.

extra temperature rise. Thus, to achieve service factors on the order of 1.10 to 1.15, it may be necessary to require higher class insulation systems (up to Class F or H depending on the ratings) to meet the additional winding temperature rise. In addition, the user should be cautioned at operating the motor continuously at a higher than 1.0 service factor, as this will lead to faster insulation degradation. Service factors should not be used to allow for continuous higher than rated horsepower operation because the other motor characteristics (efficiency, power factor, and speed) will vary from their rated values at the higher load. In addition, the motor life is limited by operating at higher than rated horsepower for long periods. Service factor should be used to handle short-term or occasional overloads. The service factor can be used in combination with the operating temperature rating to account for higher ambient temperatures, which would otherwise require a custom motor design.

According to the API standards, the service factor for conventional electric motors is not required to be greater than 1.0. Some specific applications may require service factors greater than 1.0. The IEC standards which are used outside North America, do not recognize service factors. The service factor rating can be misleading as it does not guarantee that the design matches the operating conditions.

2.2.2 Service Conditions

Usual and unusual service conditions are defined by NEMA MG-1 for both induction and synchronous AC motors. The standard recommends that the motor manufacturer be consulted for operation in unusual service conditions. Most fixed speed compressor applications will fall under the usual service conditions.

For compressor operation at speeds other than rated speed using a VFD, the electric motor will fall under the unusual service conditions definition. In this application, the motor manufacturer should be consulted further to assess the conditions and the effect of running at non-rated speed.

Use of a variable ratio gearbox or VSHD will not affect the motor speed, such that the use of the motor in this drive train configuration can still be considered under the usual service condition definition by NEMA.

The usual service conditions defined by NEMA are as follows:

1. Ambient temperature in the range of 0-40ºC or when water cooling is used, in the range of 5-40ºC.
2. Altitude not exceeding 3,300 feet (1,000 meters).
3. Location and supplementary enclosures such that there is no serious interference with the ventilation of the motor.

Departure from these service conditions will require that the motor be designed for unusual service. Examples of typical unusual service conditions are covered in the NEMA MG-1 standard.

2.2.3 Power Factor

There are several terms related to power measurements in utility systems. They are apparent power, real power, and reactive power. Apparent power is a simple product of line voltage and amps and is a measure of the power that needs to be generated by the utility or local power system (see Equation 3). Apparent power is measured in volt amps or kilovolt amps (kVA). Real power is a measure of the power that is needed to produce real work. Real power is measured in watts or kilowatts (kW) or horse power in the case of a mechanical system. Reactive power is a measure of the power necessary to produce magnetic fields in inductors and electric fields in capacitors. Reactive power is measured in volt amps reactive or kilovolt amp reactive (kVAr).

The apparent power, real power, and reactive power are related to each other by the power factor. Apparent power is the root sum square of the real and reactive power terms (Eq. 4). The power factor is the ratio of the real power to the apparent power (Eq. 5). Another representation of power factor is the cosine of the angle between the fundamental current and the fundamental applied voltage.

In large electric motor systems, there is a large amount of reactive power required by the electric motor especially during starting. The effect of the reactive power requirement is that the motor typically operates at a low power factor.

Local electrical utilities monitor power factor and will penalize the user if the power factor demand falls outside of the specified limits. Low power factor requires more generating capacity from the utility. The electric utility company charges for real power consumed by the motor but will penalize users that consume more generating capacity for the same amount of real power due to a low power factor. Utilities usually charge for low power factors below 0.95.

For self-generated power applications, a low power factor will require that a larger size generator to generate the same real power for the motor compared to a high power factor system.

In addition to increasing generator capacity, power factor influences the system's branch capacity. Low power factor causes additional losses in the distribution system. Voltage drops will arise in systems with an excessively low power factor.

If the total system electrical load results in a lower than expected power factor, power factor correcting capacitors may be a possible low-cost solution to rectify the power factor. NEMA MG-2-2001 recommends that the corrective kVAr value for the capacitor on the load side not exceed the value required to raise the no-load power factor of the motor to 1.0. High corrective values will cause overexcitation of the utility line and create a utility stability problem.

2.2.3.1 Motor Drive and Power Factor Without VFD

For fixed speed motors operating without a VFD, the motor power factor will be a significant consideration in the motor drive system selection. For induction motors, the power factor will be a function of motor load. Induction machines achieve their highest power factor at full load. Partial load operation will cause the power factor to drop. During starting, the induction machine power factor is very poor resulting in the large starting currents required by these machines. Most utilities require an operational power factor higher than achievable by the induction machine without any power factor correction.

The synchronous machine, due to the separately excited rotor, has the capability to control power factor. These machines will operate at a power factor close to 1.0 and are often "overexcited" to run at a leading power factor to compensate for other lagging power factor loads through the entire operating range from full load to partial load.

2.2.3.2 Motor Drive Power Factor With VFD

For both induction and synchronous motors operating at a variable speed though a VFD, the motor power factor will not be reflected back on the utility line. Depending on the type of VFD and the control methodology used, the drive system power factor will vary dramatically. Most VFDs can be designed to operate at a power factor a high as 0.97 to 0.98. The identification of the VFD power factor should be a significant factor considered in the motor drive system design.

2.2.4 Current In-Rush and Locked Rotor Current

Starting a motor across–the-line will cause large current draw, up to 500-700% of full load current. When this occurs, the voltage of the electrical supply will drop in proportion to the magnitude of the current in-rush. The voltage reduction will usually be limited to 6-10% of the nominal operating voltage. However, for some power systems, the percentage reduction may be allowed to be higher. Direct, across-the-line starting is possible if the power to the system has a high availability for short circuit current. As mentioned previously, the short circuit ratio can be used to determine the maximum current possible in an across-the-line start.

The amount of voltage drop by the electrical supply system (and ability to handle an across-the-line start) will be proportional to the current in-rush, the short circuit available fault capacity of the power supply, and the impedance of the transformer. The voltage drop will also result in lowering the motor current and effective starting torque. The motor must be able to withstand this reduction in voltage order to start across-the-line.

The locked-rotor current is the current drawn by the motor when the rotor is in a locked position and is a measure of the amount of current in-rush in an across-the-line start. The NEMA MG-1 standard designates a motor based on the defined locked-rotor kilovolt-amperes-per-horsepower. The NEMA letter designations span a range of 0.0 to 22.4 kVA per horsepower.

2.2.5 Motor Voltage Selection

The motor voltage selection is specified by the compressor station designer and will be decided by a number of factors. Large electric motors range in voltage from 2300 to 13,800 volts. The electric supply substation step-down transformer will convert the supply transmission or distribution level voltage to the motor nominal voltage. The supply voltage available feeding substation at the compressor location will provide an upper limit for the motor voltage. As a consideration for motor voltage selection, the electric personnel for the operating company may only be certified for a given threshold voltage and, therefore, prohibited from working with voltages above the certified limit.

The higher voltage motors will provide more flexibility for system design. The nominal value available from the step-down transformer must be de-rated slightly to accommodate voltage drop in the distribution system. The motor nameplate voltage should be set slightly lower than the transformer no load voltage to allow for voltage drop in the system. For example, on a 4160 Volt system, the motor nameplate voltage is usually 4000 Volt.

API 541 and 546 and NEMA MG-1 define the allowable range of voltage limits for most motor types and applications. To assure that motor temperature rise remains within the design limits of the motor for the rated horsepower, NEMA MG-1 specifies motors should not be operated on power sources that deviate more than 10% from the motor nominal voltage.

Frequency and voltage variation cannot exceed the arithmetic sum of 10%. Balance between phases should also be evaluated to assure that the voltage unbalance does not exceed 1%. Exceeding the specified motor voltage will cause additional motor losses and reduce motor life. Applying a voltage under the rated limit will reduce the motor speed or not provide adequate torque.

For an induction motor, voltage deviations from nominal will affect motor heating and subsequent insulation life, power factor (voltage increase will reduce power factor), available torque and slip.

2.2.6 Synchronous vs. Induction Motors

For high-speed motor applications, squirrel-cage induction motors are often evaluated against synchronous motors to determine which type of motor is best suited to the application. Each type has its own advantages.

Induction motors are characterized by high starting torque, the ability to balance the torque demand of the load with the output of the motor without any special controls and operating less than synchronous speed with a slip. Induction machines are also characterized by special considerations associated with starting and the need for power factor correction if not coupled with a VFD.

Synchronous motors are characterized by limited starting torque, the ability to actively control power factor and less current in-rush than the induction motor. The synchronous motor also requires active matching of torque demand with motor output. Synchronous motors started “across-the–line” also produce oscillatory torques at the twice slip frequency during acceleration (i.e., starting at 120 Hz and decreasing to 0 Hz at full speed). These torques generally require additional transient torsional analysis because of the potential for damage.

Synchronous motors are usually advantageous on slow speed applications (e.g., low speed reciprocating compressors operating from 200-400 RPM) and also on machines larger than about 10,000 to 15,000 HP.

With both motor types, it is important to match the compressor torque versus speed requirements with motor torque versus speed capabilities as discussed in Sections 6.0 and 7.0. Both induction and synchronous motor types can be coupled with a VFD for variable speed operation.

2.2.7 Motor Poles and Allowable Over-speed

The number of motor poles determines the rotational speed of the AC motor system (Eq. 6-7). Typically, motor poles vary from 2-pole to 8-pole systems for electric motor drive compressors. The number of poles affects the design of the motor and, to a certain extent, its size.

For centrifugal compressor applications, two poles or four poles are most commonly used to produce a motor base synchronous speed of 3,600 or 1,800 rpm. These applications will almost always require a gearbox as it is not always possible to directly run the motor and compressor at the same speed. For reciprocating compressor applications, the number of poles may be used to adjust the motor speed and possibly align a fixed speed compressor to the motor speed. This will eliminate the need for a gearbox, which is advantageous to simplify the complexity of the drive train and reduce cost.

For motors operating with a VFD, the motor speed given by Equation 7 is considered the base speed. The VFD will allow for motor operation above the base speed by providing the motor with a frequency greater than 60 Hz. This mode of operation is called over-speed operation and is limited by motor/VFD design.

NEMA MG-2-2001 defines the momentary allowable percent over-speed for high horsepower motors (above 200 hp), for both induction motors and synchronous motors. Table 2-1 provides the percent of allowable over-speed as specified by NEMA. Continuous over-speed capabilities should be discussed with the motor manufacturer.

Table 2-1. NEMA Defined Over-speeds for Motor Type/Speed Range

Motor Type	Speed Range	Percent Over-speed (over 200 hp motor)
Induction	1800 rpm and below	25 %
Induction	Above 1,800 rpm	20 %
Synchronous	1,499 rpm and below	25 %
Synchronous	Above 1,500 rpm	20 %

2.2.8 Classification of Motor and Enclosure

A complete list of enclosure types for large induction and synchronous AC motors is provided in NEMA MG-1-2006. The operating environment for the motor will determine what type of enclosure is necessary. In North America, NEMA MG-1, Part 5 addresses the enclosure types as a function of the ability to withstand dust and water. The International Electrotechnical Commission (IEC) Publication 60034-5, “Degrees of Protection Provided by Enclosures,” governs enclosures and cooling requirements outside of North America. These two standards have been harmonized to standardize the nomenclature.

2.2.8.1 NEMA Motor Enclosure Standard

In the NEMA standard, the enclosure type depends on the surrounding atmosphere of the motor location and the corrosion resistance required. The motor classifications fall into three classes depending on the ventilation mechanism:

1.) Open Machines: Ventilated openings in the enclosure permit passage of external air over and around the winding of the motor.

    a. Drip-proof (DP): Designed for internal ventilation by ambient air. Openings restrict drops of liquid or solid particles from entering the enclosure at angles between 0 and 15 degrees from vertical. Typical for clean, indoor applications.

    b. Weather Protected Type I (WPI): Constructed with ventilating passages to minimize rain and airborne particles from contacting electrical parts. Prevents any passage diameter greater than ¾”.

    c. Weather Protected Type II (WPII): Designed to allow ventilation of intake and outborn particles. Objective is to discharge any particles to prevent direct contact with electrical parts of motor. WPII motors have provisions for inlet air filtration.

2.) Totally Enclosed: Prevents the free exchange of air between the inside and outside of the motor but may not be considered air tight. A subclass of totally enclosed motors are the enclosures designed for hazardous, classified locations (Class I Explosion Proof and Class II Dust-Ignition Proof).

a. Totally-Enclosed Fan-Cooled (TEFC): Shaft driven fan external to the motor

b. Totally-Enclosed Air-Over (TEAO)

c. Totally-Enclosed Non-Ventilated (TENV)

d. Totally-Enclosed Blower Cooled (TEBC)

e. Totally Enclosed Water to Air Heat Exchanger (TEWAC)

f. Totally Enclosed Air to Air Heat Exchanger (TEAAC)

g. Class I Explosion Proof (Div I or Div II)

h. Class II Dust-Ignition Proof (Div I or Div II)

3.) Piping Ventilated (PV): Motor is cooled by piping in the outside air.

2.2.8.2 IEC Motor Enclosure Standard

The international standard for motor enclosures relies on a two-digit designation to represent the amount of protection provided by the enclosure. This system is becoming more common and provides a more specific method of describing the enclosure. The international standard uses the IEC publication. Enclosures are designated with IP##, where the two digits represent the following descriptions:

1.) The first digit describes the amount of protection against entry of solid objects such as dust, wire, tools, or fingers. This value ranges from 0-5 where 0 = no special protection and 5 = complete protection including the entry of dust.

2.) The second digit gives the amount of protection of the machine from damage due to water entering the enclosure. This value ranges from 0-8, with 0 = no special protection and 8 = protection against submersion indefinitely. X = protection is unspecified.

In some cases, a letter will follow the second numeral to add supplementary information. For example, a *W* following the second digit indicates suitability of enclosure for weather protection.

2.2.9 Class of Insulation

The allowable temperature rise of the motor windings is determined by the insulation class specified for the motor. Insulation has a direct effect on motor life. The most common insulation classes are based on an ambient temperature of 40ºC. The enclosure type and service factor also affects the specified ambient temperature for the machine. NEMA MG-1 provides temperature rise limits for all four insulation classes based on service factor and enclosure type. Corrections for ambient temperature differences are also provided in the standard.

The common insulation classes are:

Class A (Maximum operating temperature, T_{max} = 105ºC)
Class B (T_{max} = 130ºC)
Class F (T_{max} = 155ºC)

Class H (T_{max} = 180ºC)

Virtually all modern motors in industrial use have Class F or Class H insulation. Low voltage motors often have Class H insulation while larger higher voltage machines usually have Class F insulation, but are designed to operate with a Class B temperature rise.

Figure 2-1 provides examples of variations in allowable temperature rise for different insulation classes, enclosures, and service factors. Insulation materials are expected to operate for 20,000 hours without failure for the maximum temperature specified by the insulation class. Since 20,000 hours is only about 2.5 years, Class F insulation with Class B rise is typically used to extend the applicable insulation life. The insulation life doubles for every 10ºC reduction in temperature.

Motor electrical insulation is required to guard against short circuits within the motor windings. Squirrel-cage motors will have insulation on the stator winding and the core lamination but not on the rotor cage winding. Synchronous motors will be designed with insulation on all three components.

To increase motor life, the operating temperature and insulation class may be used in conjunction to over-specify the motor insulation in order to provide more protection. For example, if the max operating temperature is designed to be 105ºC, Class A insulation would suffice. To increase operating life of the motor, Class B insulation would be selected with a temperature limit of 130ºC.

This approach uses one class higher than the required insulation to establish the maximum temperature or temperature rise on the stator windings. The motor life is influenced by other factors as well, primarily the number of starts and stops per day and the electrical supply fluctuations.

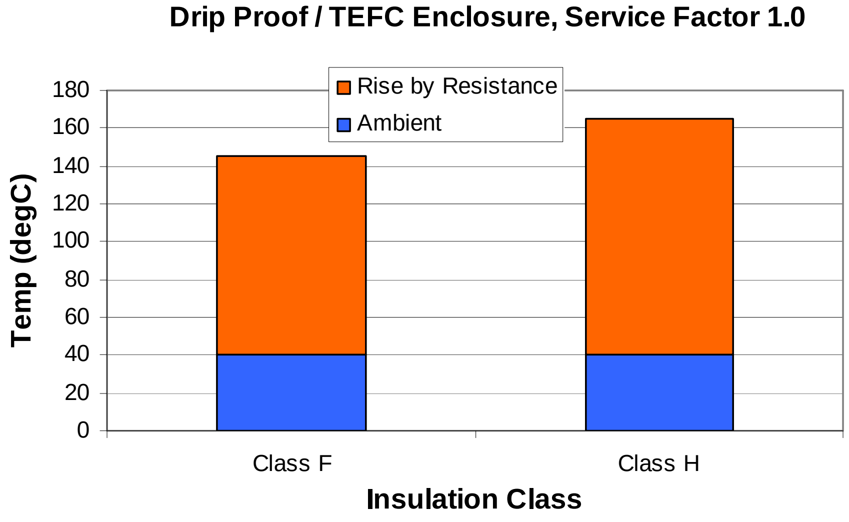

Figure 2-1. Service Factor 1.0 Temperature Rise vs. Insulation Class

2.3 Primary Components in Drive Train

Three important components that will influence the life and performance of the drive train are the shaft(s), bearing(s), and coupling selection. Depending upon the application (centrifugal compressor versus reciprocating compressor) and the use of a gearbox or variable speed hydraulic drive, the shaft requirements will vary.

2.3.1 Shaft and Bearing Selection

The following guidelines are recommended in the motor shaft design and bearing selection process:

- The motor shaft must be capable of handling the torque for the motor and the compressor. For direct driven systems, the minimum motor drive shaft diameter should be greater than the driven equipment stub shaft in most cases.

- The use of bearing diameters smaller than the nominal drive shaft diameter at the coupling hub should be avoided, if possible, for both reciprocating and centrifugal compressor applications. This typically results in a significant motor shaft diameter decrease at the bearing, which increases the localized stress and can adversely affect the rotordynamics of the design.

- Keyways should be avoided whenever possible due to the large stress concentration factors associated with these features, which have historically resulted in many torsional failures. Alternative coupling hub attachment methods, such as interference fits or integral flanges, should be considered.

- The ultimate tensile strength of the motor shaft has a major impact on the damage tolerance of the equipment and should be maximized through the use of alternative materials or heat treatments when deemed necessary. Typical materials (4140 and 4340 steels) are capable of achieving UTS values in the 120-130 ksi range with proper heat treatments. However, depending on the materials involved, extreme heat treatments may cause the resulting shaft to be excessively brittle. This should be considered in conjunction with the results of a torsional forced response analysis and a review of the stress concentration factors for the geometry to determine the optimal UTS value for each application.

- Generous fillet radii should be used for each diameter change in the shaft to reduce the resultant stress concentration factors.

- Integral spider bars are preferred over the welded type due to the potential for high stress concentration factors at the welds. In cases where this type of construction is absolutely necessary, considerations should be made to ensure that the welds are of sufficient quality to avoid significant stress concentration.

2.3.2 Bearing Types

The most common types of bearings used for natural gas electric motor driven compressor applications are described below. Bearing choice will affect the lube oil system selection for the electric motor package, if any type of bearing is specified, which requires lube oil. Bearings are a high maintenance item, and may need to be replaced regularly depending on the operation of the motor and the application.

The bearing stiffness and damping coefficients have a significant influence on the lateral rotordynamic characteristics of the motor.

The following issues should be considered in the selection of the bearings:

- Availability of replacement parts (anti-friction bearings are more common and easily replaced).
- Replacement interval (certain bearing types will remain effective at longer time intervals). Typically, bearings will provide a 10-year to 15-year service life.
- Required inspection intervals (sleeve bearings will require more frequent inspections).
- Mounting positions (some bearings require horizontal mounting whereas other types have more flexibility).
- Lubrication requirements, relubrication intervals and oil type compared to other drive train components oil.
- Any required electrical insulation needed to protect against bearings conducting currents from the shaft.

2.3.2.1 Fluid Film Bearings

These bearings are usually composed of a circular journal, multi-lobe, offset halve, or “lemon bore” arrangement. The oil film provides a mechanism to provide effective lateral support stiffness through the generation of a hydrodynamic wedge generated by shaft rotation within the journal.

One major drawback of the circular journal involves the potential for “oil whip” or “oil whirl” type instabilities, usually occurring at subsynchronous frequencies in the range of 45-55% of running speed. Although generally less complicated, this type of bearing arrangement does not allow for the feasible application of preload, which can have a significant impact on the load carrying capacity, stiffness, and damping generated by the oil film. These factors, in conjunction with the shaft stiffness and distributed mass characteristics, determine the lateral critical speeds.

The offset halve, multi-lobe, and “lemon bore” arrangements generally provide mechanisms for alteration of the preload, load carrying capacity, delivery of the lubricating oil, stiffness, and damping properties of the bearing. These designs also tend to produce lower cross-coupled stiffness terms when compared to the cylindrical journal type, reducing (but not eliminating) the potential for instability.

In general, the behavior of fluid film bearings may be significantly influenced by the viscosity and temperature of the oil supply.

2.3.2.2 Tilting Pad Bearings

Tilting pad bearings are a subclass of standard fluid film bearings, which represent a large number of installations. The self-centering pads introduce several unique features. One aspect of the pads is to reduce the likelihood of large cross-coupled stiffness values, which tends to greatly reduce the likelihood for subsynchronous instability.

The pads provide a convenient mechanism for introducing preload. The stiffness and damping properties can also be significantly influenced by changes in pivot offset, load direction (between or on the pad), and the pivot type. For these reasons, the tilting pad bearing is one of the more common types found on large industrial machines currently in production.

2.3.2.3 Rolling Element Bearings

This type of bearing involves less dependence on the lubrication method, as the support stiffness is principally supplied by the rolling elements, which are typically cylindrical or spherical in shape. Some bearings in this category are sealed and lubricated with grease, eliminating the need for an external oil supply.

Rolling element bearings can generate significant stiffness but do not commonly produce useful levels of damping. Multi-row rolling element bearings provide a convenient mechanism to add thrust carrying capacity to a lateral bearing.

2.3.2.4 Magnetic Bearings

Magnetic bearings have the potential to offer several interesting characteristics but are generally not widely used in the United States for industrial motors at the present time. Magnetic bearings are being considered for some applications to avoid common lube oil system issues.

Some other potential benefits of this type of bearing include: active vibration control, reduced operating friction, and minimal component wear. This bearing type involves significant complexity in the electronic controls used to energize the bearings. The “touch down” or backup bearings utilized in case of magnetic bearing failure can also present significant design and maintenance challenges.

2.3.2.5 Thrust Bearing Considerations

Another common issue with bearing selection is the thrust bearing. Some electric motors may not include a thrust bearing in the design. This may be due to methods utilized to essentially cancel the axial thrust load produced by the motor core, or the design may depend on having axial loads be absorbed by a thrust bearing located in the gearbox or compressor.

Unbalanced thrust loads can result in significant axial “shuttling,” allowing shifts in the magnetic center of the motor, which can cause significant coupling component wear, and potentially affect the efficiency of the air gap. For large industrial electric motors, it is recommended that a thrust bearing be seriously considered in order to prevent significant axial movement of the rotor, avoid overload of the driven equipment thrust bearings, potential coupling component wear, and possible reductions in motor efficiency. Transient thrust capability is designed into most horizontal motors with anti-friction bearings.

2.3.3 Couplings

The choice of which coupling(s) to use in a train plays a major role in determining the associated torsional and lateral critical speeds, primarily due to the selected torsional stiffness, hub inertia, and hub weight characteristics. The coupling selection should be based on a thorough torsional analysis of the train and lateral analyses of the motor and driven equipment.

It should be noted that the coupling selection process involves several variables, including: 1) ensuring that the coupling produces adequate separation margins between calculated critical speeds and operating speeds; 2) can safely transmit the anticipated mean (loaded) torque in addition to any alternating torque generated by the power drive system and/or driven equipment (such as reciprocating compressors) and 3) can handle peak torque levels generated during transients (such as start-up or short circuit events). Each of these considerations are addressed by the steady-state, forced response, and/or transient torsional analyses. The predicted peak torque levels for each mode of operation should be carefully compared to the torque ratings provided by the coupling manufacturer(s) in order to determine acceptability.

In certain cases (such as some types of reciprocating compressors or synchronous motor drives), high alternating torque levels may require the use of coupling designs which are generally more costly and maintenance intensive than other types. This is primarily due to a need to provide more damping to the system and, in some cases, also involves providing additional torsional flexibility in order to provide an isolation mechanism between the excitation torque and the remainder of the system.

For reciprocating compressor applications, torque ripple effects will tend to be insignificant compared to the torque pulsation levels generated by the compressor.

The most common coupling types and issues in use today for large industrial motor driven machinery are briefly described in the following sections.

2.3.3.1 Flanged Coupling

This type of coupling is a relatively rigid style that can prove useful in situations where a high torsional stiffness is required, and excellent alignment can be reliably achieved and maintained. Some advantages to this coupling design include reduced mechanical complexity and maintenance requirements, since one interface is eliminated through the coupling design.

2.3.3.2 Disc Pack Coupling

Disc pack or diaphragm type couplings are one of the most commonly specified coupling designs for industrial equipment, primarily due to the inherent misalignment capability. However, mechanical complexity is generally increased compared to the flanged type, while torsional stiffness tends to be reduced.

2.3.3.3 Elastomeric Coupling

The elastomeric coupling can provide significant damping and is useful in circumstances where the machine must run near a torsional critical speed for a portion of the operating envelope.

Potential disadvantages to this type of coupling include increased maintenance cost and associated downtime. The stiffness and damping properties of the elastomer can also introduce some level of uncertainty in the analysis of the torsional behavior. This is primarily due to the nonlinear behavior and wear characteristics associated with the elastomer.

2.3.3.4 Belt Drive

Belt drives are occasionally used on trains involving small reciprocating equipment. The advantages of this type of coupling mechanism include relatively low cost, ease of mechanical assembly, reduced maintenance complexity, and less likelihood of damaging the attached equipment during failure. In addition, the belt will typically accommodate much more misalignment than traditional couplings or gear drives. However, this coupling mechanism also presents significant uncertainties in determining the torsional behavior, as the belt stiffness tends to be nonlinear and highly dependent on belt tension (preload). In addition, it is sometimes difficult to obtain an accurate estimate of the torsional damping associated with the belt.

2.3.3.5 Coupling Fit Methods

The primary types of coupling hub fits in use today involve keys or interferences imposed by differential heating or hydraulic methods. As discussed in Section 3.3.1, the interference fit methods are generally preferred from a torsional damage tolerance standpoint, due to the attendant decrease in stress concentration.

The advantages to the keyed method include ease of maintenance and reduced cost. The primary disadvantage to this type of fit is the potential for high stress concentration at the keyway, which can lead to shaft failures. Some of this risk can be mitigated through careful design of the key seat, including providing proper fillet radii in the geometry. In cases where keyways are absolutely necessary, they should include fillet radii consistent with or exceeding the requirements put forth in ANSI B17-1, paragraph 8.

The interference fit coupling hubs generally fall into two categories: hydraulic fit and mechanical interference, which is induced by heating or cooling one of the components during assembly.

The advantages of interference fit coupling hubs primarily involve a reduction in the potential for stress concentration, thereby increasing the damage tolerance of the train. Some potential disadvantages include: possible need for a tapered shaft, increased maintenance complexity, possible increased cost and added weight and inertial loads, which can cause an adverse effect on the lateral and torsional critical speeds. Interference fit coupling hubs can be difficult to remove in the field (mechanical fits often require heat in a classified area, and the hydraulic fit types often require increased space requirements between the shafts to attach removal tools).

2.4 Fixed-Ratio and Variable Speed Gearbox Considerations

Fixed ratio gearboxes and variable speed hydraulic drives (for variable gearbox ratios) require a separate process of sizing and matching the power and torque to the centrifugal compressor. These design guidelines are discussed in Section 6.0 on the centrifugal compressor application. In addition, maintenance and reliability issues associated with these components are provided in Section 8.0. The reciprocating compressor application rarely requires a speed increasing fixed ratio gearbox or variable speed increasing gearbox because of the lower speeds utilized by reciprocating compressors.

2.5 Variable Frequency Drive Selection Factors

Variable frequency drives in the electric motor application are often referred to interchangeably as adjustable frequency drives.

The VFD can be used to control the motor speed. In most VFD systems, the motor speed is controlled by varying the motor input volts and frequency or volts per Hertz. The volts per Hertz applied to the motor are changed to keep the input power factor close to unity and to operate the motor within its design parameters. Many of the common VFD topologies are named after different functionality or individual components. A basic overview of the types of adjustable frequency drives naming schemes is provided in section 2.5.1.

The response time and the voltage amplitude resolution of the VFD output will affect the amount of control available on motor. VFD systems will vary in the speed and accuracy of the system frequency response, current waveform fluctuations and sensing hardware to control motor speed and load. The most distinguishing factors between different VFD systems are their operating power factor, harmonic characteristics, the power conversion and inversion process, and the torque signature.

For the synchronous motor application with a VFD - speed or current feedback control is added to the VFD to stabilize the motor speed as compressor speed and load requirements change. Position feedback is also required for precision control at low speeds and start-up.

Table 2-2. Common VFD Naming Methods

Adjustable Frequency Drive Common Naming Schemes	**Common Examples**	**Notes**
Based on regulation of Volts/Hz	Load commutated inverters (LCI)	Commonly used for large synchronous machines
	Autosequentially Commutated Current Fed Inverter (ASCI)	
Based on type of inverter	Variable voltage inverter (VVI)	
	Voltage source inverter (VSI)	
	Current source inverter (VSI)	Often used in combination with Pulse Width Modulation (PWM)
Based on drive output waveform	Pulse width modulation (PWM)	Commonly used with voltage source inverter and IGBT switch
	Pulse ampitude modulation (PAM)	
Based on inverter device	Insulated Gate Bipolar Transistor (IGBT)	Commonly used in combination with PWM or variable voltage inverters
	Silicon Controlled Rectifier (SCR)	Older VFD technology, not as common for large drive systems
	Gate Turn Off Thyristors (GTO's)	Older VFD technology, not as common for large drive systems
	Integrated Gate Commutated Thyristors (IGCT)	Modern multi-voltage drives often use these

2.5.1 Basic VFD Components

The basic components of a VFD can be described by four functions: 1) AC-DC Converter: To convert the line frequency to a constant current or voltage source; 2) DC Link: To transfer and filter the DC signal to the inverter; 3) DC-AC Inverter: Convert the DC signal back to an AC signal at the controller determined frequency for the motor speed requirement; 4) Controller: Control output voltage and frequency based on various control techniques which are manufacturer specific or technique specific (such as Pulse Width Modulation). The three common types of VFD systems and a basic description of these system components is provided in Table 2-3**.**

Table 2-3. Basic VFD Components and Examples for Common VFD Systems

	PRIMARY VFD COMPONENTS				
	1. AC - DC Converter	**2. DC Link**	**3. DC-AC Inverter / Switch**	**4. Controller**	
Purpose of → Component:	*Convert line frequency from AC to DC*	*Filter DC and conduct DC to inverter*	*Take DC and convert to specified voltage and frequency*	*Control output voltage and frequency in inverter based on motor*	
Common Types for Electric Motors					**Notes on Harmonics**
PWM VSI	Uses input diode bridge	Receives constant DC voltage	Use IGBT or transistor switching on and off DC to convert to AC, IGBT switches at > 10Khz frequency, Others are at 1 KHz.	Implements pulse width modulation to maintain constant ratio of volts/ Hz	Determined by duration of pulses and spacing between them (higher frequency switching produces less)
ASCI	Uses thyristor bridge and current regulator	Constant current delivered, Voltage ripples are filtered out by controller	Thyristor used to store energy in diodes	Thyristor controls frequency	Only amplitude is controlled by the current regulator, voltage ripples determine amount of harmonics
LCI	Uses thyristor bridge as controlled source of current	Delivers constant current to inverter	Natural commutation through motor (load) determines switching	Must be controlled between synchronous motor type and inverter	Harmonics will be particularly destructive using LCI with an induction motor. Only synchronous motors recommended with LCI drives.

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	1. AC - DC Converter	**2. DC Link**	**3. DC-AC Inverter / Switch**	**4. Controller**	
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Common Types for Electric Motors					**Notes on Harmonics**
Pulse Width Modulation (PWM) Voltage Source Inverter (VSI) or Current Source Inverter (CSI)	Uses input diode bridge	Receives constant DC voltage or current	Use IGBT or transistor switching on and off DC to convert to AC, IGBT switches at > 10Khz frequency, Others are at 1 KHz.	Implements pulse width modulation to maintain constant ratio of volts/ Hz	Determined by duration of pulses and spacing between them (higher frequency switching produces less)
Autosequentially Commutater Current Fed Inverter (ASCI)	Uses thyristor bridge and current regulator	Constant current delivered, Voltage ripples are filtered out by controller	Energy storage in capacitors for voltage source drives or inductors for current source	Thyristor controls frequency	Only amplitude is controlled by the current regulator, voltage ripples determine amount of harmonics
Load Commutated Inverter (LCI)	Uses thyristor bridge as controlled source of current	Delivers constant current to inverter	Natural commutation through motor (load) determines switching	Must be controlled between synchronous motor type and inverter	Harmonics will be particularly destructive using LCI with an induction motor. Only synchronous motors recommended with LCI drives.

2.5.2 Types of Variable Frequency Drives

Variable frequency can be divided into two categories based on the type of inversion scheme: voltage-fed and current-fed inverters. Both voltage-fed and current-fed VFDs convert electrical supply power (three-phase AC) to DC. Both of these inverter types use the DC link to isolate the converter from the inverter. The input converter on any of these implementations will determine power factor and harmonics as seen by the electrical supply for the VFD. After the DC link, power is inverted back to AC to drive the motor. The inverter side of the VFD will determine the major motor-side harmonic characteristics. Interharmonics can also be significant between the motor and the VFD as a system.

The internal components of the VFD function to convert the electrical supply three-phase AC voltage to a different voltage amplitude and frequency in order to change the synchronous speed of the electric motor. The primary functions of any VFD are to:

- Communicate with an external process controller or a local control keypad to receive the user signals and commands and to transmit the status of the drive.
- Calculate both the voltage and frequency necessary to maintain the motor speed at either the reference torque or speed set-point and maintain the desired machine flux (or V/Hz).
- Generate control signals required to control the power semiconductor in order to synthesize the three-phase output AC voltages or currents.
- Monitor the voltage across power semiconductor devices, motor current feedback, and VFD internal temperatures to determine whether it is safe to operate the VFD.
- Monitor motor and compressor parameter for safe operation.
- Provide electrical isolation between the power conversion logic and the main power circuit.

2.5.2.1 LCI and ASCI Type VFD

Three common types of current fed inverters are the LCI, CSI PWM and ASCI types. In current-fed circuits, the inverter output is supplied in the form of current. In current-fed inverters, the inverter output to the motor is supplied in the form of current. Motor voltage is a function of the motor design and the associated load, irrespective of the inverter. The current-fed VFD uses a solid-state converter to convert the electrical supply AC to DC. An inductor in the DC link provides constant current to the inverter which regulates the output frequency of the motor AC three-phase current. The different types of current-fed VFD's include the ASCI, FCI, LCI and IGCT types. However, most current fed VFD's use the LCI or IGCT technology with large electric motors.

In current-fed inverters, the solid-state converter controls the amplitude of the current. The power factor will be the load power factor multiplied by a ratio relative to motor speed, and reactive power from the motor will be passed back to the line. A DC link reactor is used, but the energy storage is very low. The inverter in the VFD of a current-fed type controls only the output frequency. Supply-side high order harmonics are typically high in current-fed VFD's.

LCI types are used almost exclusively for synchronous motors and the induction motors typically use the ASCI or GTO types. LCI types can support high power applications, up to 100,000 hp and can be built to supply all of the motor current. In synchronous motors, the LCI drive is part of the circuitry and connected to the motor windings. The VFD and motor are delivered as a package or as matched components, i.e., these must be designed into the project as a corresponding drive pair.

The induction motor usage of current fed inverters relies on the IGCT type of VFD but this application is generally limited to an upper limit around 7,500 hp.

2.5.2.2 PWM Voltage Source Inverter or Current Source Inverter VFD

In voltage-fed VFD inverters, the output of the inverter to the motor is a voltage. In the voltage-fed VFD, the DC conversion is accomplished with a rectifier bridge. The DC link is heavily filtered using electrolytic capacitors. The voltage amplitude and frequency of the output to the motor are controlled power semiconductors using a variety of different control techniques. The current source inverter also can also apply pulse width modulation by varying current amplitude and frequency control through semiconductors.

The motor and load determine the amount of current. The use of a rectifier bridge to power the DC link helps to reduce the harmonics for these types of VFDs. The electrolytic capacitors used in the DC link have very high energy storage and are often a life-limiting component in the VFDs.

Many current-fed and voltage-fed VFDs control the motor voltage/current amplitude and frequency using a control technique of pulse width modulation (PWM). In PWM the VFD turns the motor voltage on and off at a frequency much higher than that of the desired AC power. The motor inductance is used for filtering the resulting motor-side harmonics. The pattern and implementation of the pulse width modulation (PWM) is highly dependent on the particular type and manufacturer of the VFD.

2.5.2.3 Input and Output Filters for VFDs

In general, most types of VFD’s may require input filtering. All LCI VFD types will require input filters because of the supply-side harmonic voltage levels generated in the converter. These typically use a 12-pulse front end type filter.

The PWM voltage-source VFDs may require an input filter depending upon the different levels of current harmonics from the rectifier. Voltage harmonics are not as common with these types of VFDs. Some PWM voltage-source VFD types can function for the gas compressor/electric motor application without input filtering, depending on drive topology.

The VFD output filtration requirements are typically not as severe as those for the input. Output filtering can, in most cases, reduce the operating temperature of the motor as the higher order harmonics in the VFD output are filtered before reaching the motor. Most LCI types should seriously consider the use of some amount output filtering. If shaft cogging effects are present, an output filter can be added to the system to remove this effect.

The LCI type of VFD’s will interact most severely with reciprocating compressors and the associated pulsating load. Applying the LCI type of VFD for a reciprocating compressor drive application is not recommended because of the associated effects of the motor-side harmonics on the torque waveform and the reciprocating compressor load.

2.5.2.4 VFD System Grounding

System grounding is critical for reliable operation of the motor drive. Proper grounding is not only required for safety reasons, but also controls common mode currents that will cause electrical noise and premature system failures, especially in the motor bearings. This is an increased concern for devices that are liquid cooled. For these liquid cooled installations, electrical isolation should be added between the device and the cold-plate interface or by using resistive grounding techniques.

2.5.3 VFD Usage in Compressor Applications

Variable speed applications will encounter some of the same selection constraints as constant speed motor applications: specific load requirements, insulation integrity, vibration, quality of materials, and construction, etc. For constant speed applications, the API standards address the primary issues in designing and selecting the electric motor drive system.

However, three additional areas should be addressed when specifying motors for adjustable-speed applications: 1) Common mode voltage; 2) Harmonics or electric distortions and 3) Starting considerations. These essential issues are summarized below.

2.5.3.1 Common Mode Voltage

Common mode voltage on motor windings results from the modulation of the motor input power by the VFD to provide the correct volts/Hertz for a given motor speed. This effect is most pronounced during motor low speed operation or during motor soft-start. The common mode voltage affects the motor design. The motor operation at low speed or soft-start with a VFD will have the net effect of potentially doubling the voltage stress on the motor windings. Although this induces more stress on the system, most motors are designed to tolerate this starting mechanism by a VFD. Even motors which do not require a VFD for the actual compressor operation and are implemented with a smaller VFD for starting will see this effect. In fact, smaller VFD's used for starting purposes often have more severe common mode voltage issues because of the less expensive hardware[4].

Common mode voltage problems can be eliminated with an input transformer. This should be considered if an isolation transformer is not being used to feed the VFD.

The amount of common mode voltage seen by the motor depends on the drive topology of the VFD. This must be evaluated carefully because of the potential level of inductive and capacitive currents flowing into motor bearings. The common mode electrical current can affect bearing and seal life.

2.5.3.2 Electric Distortions or Harmonics

Harmonics tend to be overlooked on electric motors but are one of the most relevant issues for large electric motors driven with VFD systems. There can be voltage harmonics and/or current harmonics associated resulting from the VFD. Different VFD topologies and methods of control of the motor will result in differing levels of distortion. These distortions must be classified based on where the distortion occurs:

1) On the input side of the VFD, as harmonics reflected back onto the grid system and is referred to a supply-side harmonics.

2) On the output of the VFD and input into the motor, as current and/or voltage distortions. These are referred to as motor-side harmonics.

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[4] In addition to the common mode voltage issues, the electric motor drive system (EMD) should be evaluated in a variable-load situation to determine if the EMD can take an input voltage disturbance.

3) On the output side of the motor, as torque ripple effects.

The levels of the distortions in each location will affect the effective power factor of the VFD and the motor system. As harmonics cause additional heating in motor windings the level of distortions will have an effect of the overall efficiencies of the VFD and motor system.

2.5.3.2.1 Supply-side Harmonics (Reflected Back on Power Source)

These distortions occur in the power conversion process from AC–to-DC in the VFD. They are reflected back on the grid and result in reducing the effective real power transmission capability of the grid system. The utility companies require adherence to the IEEE 519 specification, which specifies the tolerable level of harmonics and is referred to as percent harmonics. The percentage of harmonic levels compared to the input current depends on the quality of the VFD.

Where required, input filters must be used to reduce high levels of supply-side harmonic – refer to Section 2.5.1.3 above. If necessary, a study should be performed to determine if the supply-side harmonics meet the IEEE 519 specification.

2.5.3.2.2 Motor-side Harmonics (Output Waveform Imperfections to Motor)

The degree to which the electric motor can tolerate motor-side harmonics depends on the susceptibility of the motor. VFD systems will greatly increase the sensitivity and damage potential of a given electric motor as a result of the harmonics. Harmonic voltages and currents in induction and synchronous motors will also increase the amount of heating and required cooling. Correspondingly, the additional heating due to harmonics can cause a motor to be more sensitive to overload conditions and, in some cases, cause motor shutdown of the motor or failure of the windings when these conditions occur.

Another concern on the motor is the resultant heating due to voltage imperfections. The amount of heating that can be tolerated is a function of the rotor type and cooling scheme used.

2.5.3.2.3 Torque Ripple Effects

Motor drive harmonics can result in torque ripples (alternating torque occurring at various frequencies, depending on the type of drive system) being generated by the motor that can affect the performance of either reciprocating or centrifugal compressors. The effect of harmonics on the delivered torque to the driven equipment should be analyzed, as described in the rotordynamics Section 4.0.

2.5.4 Requirements for VFD Performance

The VFD manufacturer and motor manufacturer should work closely to provide the user company and compressor manufacturer with the expected efficiency and level of distortion in the output torque supplied by the motor. The current waveform distortion from the VFD will affect the torque supplied by the motor to the driven compressor. The frequencies and amplitudes of the harmonics should also be supplied to the compressor manufacturer and operating company. Any assumptions used by the VFD and motor manufacturer in determining efficiency should be clearly stated.

2.5.5 Starting Considerations with a VFD

Starting an adjustable speed motor will often allow more options on starting than a constant speed application because some of the hardware to vary speed may also be used to reduce the current draw upon start-up or unload the drive train. The means of controlling the motor speed during operation may also be used to produce a soft-start or reduced voltage input to the motor to reduce the current in-rush at start-up. For adjustable speed applications, a VFD or VSHD will be used for ramping up the drive system during the start-up process. This has many advantages as opposed to an across-the-line start. The starting methods and recommendations of this guideline are discussed in Section 5.0.

2.6 Critical Speed Options for the Motor Drive System

The selection of the drive train speed range is a critical part of the design process. Although some compressors may have a large operating window, the rotordynamic analyses (either torsional or lateral) may limit the speed range. The torque and power limitations of the motor can restrict the operational window as well. Successful system design frequently involves a compromise between offering as wide a speed range as possible to allow for increased operational flexibility and efficiency, while simultaneously avoiding rotordynamic problems. For reciprocating compressors, a wider speed range may also aggravate more compressor piping system resonances. Other constraints on the speed range can result from machinery speed limitations and/or a requirement to avoid certain process conditions (overload, low pressure, high pressure, etc).

For motor applications not using a VFD, the maximum operating speed of the motor may be very near or at the motor synchronous speed. The NEMA MG 1-20.13 standard requires that the motor be able to accommodate operating at a speed above synchronous speed. Depending on the synchronous speed, the max speed may be 20% or 25% over motor synchronous speed. For analysis of the motor power and torque requirements over the operating speed range, the actual load requirements should be stated clearly for all parties. Different gas compositions and pressures/temperatures will affect the torque requirements of the motor. The linearity assumption for speed and power is not always valid - see discussion of application specific issues in Sections 6.0 and 7.0. The motor must be capable of accelerating the load and functioning within the stated operational boundaries. Many times, when only one design point is considered, the motor torque will not be sufficient at a different operating point. The torque speed curve for the motor should include margins for operational variability.

When the motor must operate over a range of speeds, additional analyses should be performed to characterize how the compressor torque requirements vary with the speed. If any torsional or lateral critical speeds overlap the desired operational speed range, additional analyses should be preformed to characterize the prevalent excitation energy at the overlapping speeds. If the rotordynamics are not analyzed, the resulting vibration levels at or near the critical speeds have the potential to cause significant cumulative fatigue damage and possibly lead to failure of drive train components.

Three approaches (or any combination thereof) may be considered for dealing with lateral or torsional critical speeds that fall within the speed range of the motor and compressor system:

1) Method 1: *Modify the design of the system to place the critical speeds outside the planned operating speed range*

   This approach is preferred and is generally possible if the rotordynamics are characterized early in the design process. By avoiding any coincidence between the critical speeds and significant excitation energy, the possibility of extremely high vibrations or life-reducing events is reduced. However, this approach may result in a more costly system, especially if the modifications are not contemplated early in the design process. Typical modifications include changes to the coupling stiffness and hub characteristics, flywheel inertia, shaft diameters, shaft strength (material changes, additional heat treatments, or both), bearings, loading conditions, etc.

2. Method 2: *Practice critical speed avoidance by changing the operating speed range*

   This option may allow the drive train to be designed with more flexibility without reducing the operating range of the compressor significantly. The anticipated separation margins between the calculated critical speeds and operating speeds should account for any uncertainty in the rotordynamic analysis. This option requires active control in the VFD or VSHD system to avoid the critical speed windows and is especially useful in cases where a sufficient operating window is available above or below the calculated critical speed of concern. However, it should be noted that if the critical speed is below the planned operating speed range, a quick transition through the critical speed will be necessary during start-up events. The potential for damage during transition through the critical speed should be evaluated, and this case becomes a subset of item 3 below.

3. Method 3: *Allow short-term operation near critical speeds with sufficient damping*

   A less desirable (and not recommended) option is to allow the critical speeds to exist within the operational range so long as the response is well-damped, and prolonged operation at the subject speed is avoided (locked out) such that fatigue damage is limited. (This option is not as commonly practiced and typically the operation at mechanical resonance speeds is blocked out to avoid long-term fatigue damage). It should be noted that damping mechanisms may be time-dependent (examples include viscous dampers, elastomeric couplings, bearings, etc.) and will require frequent monitoring of damping levels or preplanned maintenance if this option is to be implemented successfully. This may be the only option for some applications with large, variable speed motors installed on drive trains requiring a large speed range. However, this option should be weighed against increased long-term costs associated with maintenance and the implications of high vibrations (and possible fatigue failure) if operation near the critical speed is allowed to occur for longer than planned, or with insufficient damping present in the system.

   NOTE: On reciprocating compressor applications, use of this method will require a torsional damper or elastomeric coupling.

2.7 Compression Train Configuration and Installation

2.7.1 Lube Oil System

The lube oil system for the compression train can be either a common lube oil system or a group of separate lube oil systems for each piece of equipment. The use of a common lube oil system will require the coordination and construction of a lube oil system that will support all of the attached equipment. The use of separate lube oil systems will not require the coordination effort of a common lube oil system through the bid and proposal phase and construction phase but will require multiple coolers, filters, pressure regulators, and may require different lubricants for different pieces of equipment.

2.7.2 Compression Train Installation

The compression train can be mounted to a foundation using a common skid or base plate or two skids that bolt together, or the one or more of the train pieces can be mounted on a concrete pedestal in the field. The unit control panel (UCP) is usually remote mounted with some site installed cable runs. The cooling systems for lube oil, drives, and motors are usually not integral to the compression package and must be site erected and installed. The lube oil tank and system may be internal to the compression train package or may be a separate module that will need to be installed.

2.7.3 Frame

For large motors covered by the NEMA MG 1-20 standard, NEMA does not specify the frame assignment or any basic dimensions. The frame size is determined by the motor manufacturer.

2.7.4 Mounting and Alignment

Motors may either be skid-mounted or sole plate mounted depending on motor size, site access, and availability of equipment. Determination of the mounting plan should be done in the early stages of the project, as it can affect other items at the field site.

Skid-mounted motors are an integrated package that can be advantageous for minimizing installation time in the field. The motor is mounted on the skid at the factory test site and can be aligned prior to delivery. This option tends to minimize alignment issues. For larger motors, the motor will need to be removed from the skid during shipping so alignment at the field site remains an issue. The equipment on the skid and the overall skid dimensions can pose shipping issues and higher shipping costs.

For motors mounted to a sole plate onsite, the sole plate must be installed and grouted by the motor supplier or packager prior to motor delivery. This may also be the only option for large, heavy motors or offshore applications.

2.8 Motor Life and Lifecycle Cost

Many factors will affect the short-term and long-term life of the motor. Some of the most influential factors are described below. However, good design practice and proper assessment of the compressor application according to this guideline and the IEEE/API standards will help to ensure the proper motor and drive components to meet the compressor power and torque range.

2.8.1 Factors Influencing Motor Life

1. *Variations in Motor Loading* – A motor that runs at or above the rated load will generate more heat and lead to a higher temperature rise than one operating at less than the rated load. A motor should be selected that can handle the load at 1.0 service factor. For example, a higher horsepower motor of 1,150 hp with a 1.0 SF and a smaller motor of 1,000 hp at 1.15 SF will both meet requirements of the application. However, the smaller horsepower motor will run hotter and possibly have a shorter life compared to the larger motor at the higher service factor. The higher service factor motor will typically cost more up front.

2. *Frequent Stops and Starts* – A motor starting, draws six to seven times the full load current. This causes high short-term rotor copper losses and heat build-up. In the long term, the windings will fatigue due to the high current loading during start and stop operation. This is

a major factor in the long term life of these larger horsepower motors. A finite number of such events are considered normal for a motor before any problems are experienced (e.g., 5,000 lifetime full voltage starts for a random wound motor and 8,000 to 10,000 starts for form wound motors). Care should be taken that if a motor has to be stopped and restarted, there should be a sufficient interval time to allow the motor to cool down. Allowable starts and stops in a consecutive period of time are defined by API 541 and 546.

3. *Load Inertia* – Each motor has a specified standard inertia value. Accelerating a motor subject to higher inertia, during start-up, will lead to higher heat build-up and motor stress.

4. *Electrical Supply Voltage and Frequency Fluctuations* – For motors operating without a VFD, these fluctuations can lead to increased motor current, winding temperature rise and increased electrical stress on motor windings which can lead to premature motor failure. For motors operating with a VFD, these fluctuations will have less of an impact on motor life. The National Electrical Manufacturers Association (NEMA) specifies that motors should be able to sustain ±10% voltage fluctuation at rated frequency, ±5% frequency fluctuation at rated voltage, or a combination of up to absolute values of 10% voltage combined with 5% frequency change. NEMA also gives derating information for unbalanced voltage supplies, which cause rotor overheating.

5. *Motors using Variable Frequency Drives (VFDs)* – VFDs can cause harmonics that lead to localized hot spots in motor windings. Such motors generally do not have a service factor greater than 1.0 and have to be cooled by using blowers, oversized frames, and/or special materials.

6. *Operating Altitude* – At higher altitudes, the ambient air is less dense and dissipates less heat. This leads to higher temperature rises for the same cooling air flow. Derating factors to the motor horsepower are used when operated at high altitudes. The NEMA standard specifies that motors are designed for an altitude of 3300 feet or 1000 meters and contains derating formula.

7. *Ventilation* – Motors working in unventilated or unclean conditions will operate at higher temperatures.

8. *Auxiliary Equipment* – Correct operation of cooling systems, lube oil pumps and other equipment will affect the drive train life and efficiency.

2.8.2 Life Cycle Cost Analysis

A lifecycle cost analysis is recommended to assess the large cost items in the motor installation project. Tradeoffs associated with initial cost, service factor, power rating, size and overall life should be evaluated through this analysis. Process variations will determine how much torque variations are likely to impact the motor/drive train design. For some applications with constant process conditions and a narrow operating window, a lower cost, less sophisticated drive train may be possible. The lifecycle cost analysis should include:

1. Production downtime (estimated based on system availability)

2. Fuel cost and electric utility cost

3. Equipment (purchase price, transportation to site, lead time/project delay time, permitting) Air permits will be less for electric motors compared to gas turbines without back-up generators on site, design cost.

4. Installation/commissioning (estimated based on size and weight)

5. Operation and maintenance expenses (estimated based on previous performance and should include parts and tools, labor, training, and possible emissions reduction credits. Also should include vendor and subsupplier service capability, recycling/disposal of waste streams.).

6. Procurement (present value of payment schedule, re-inspection costs)

7. Engineering and project management

8. Insurance

9. Decommissioning or product retirement and phase-out (based on equipment removal and replacement, if needed, and equipment salvage value or disposal cost)

3.0 MOTOR PERFORMANCE

Motor performance is characterized in terms of torque, speed, and delivered power. In addition, the power factor and service factor are used to characterize the motor apparent power requirements and the permissible loading of the motor beyond rated conditions. Torque represents the motor rotational work necessary to match the resistance to turning of the shaft caused by the driven load. Current and torque are often expressed as a percentage of the full load values. The following additional definitions are used to characterize the motor capabilities.

- *Locked Rotor Torque:* The motor minimum developed torque from the at rest position, with the rated voltage applied at rated frequency.

- *Breakdown Torque:* The motor maximum developed torque by an induction motor with the rated voltage applied at rated frequency without abruptly dropping its speed.

- *Pull-up Torque:* The pull-up torque defines the minimum torque developed for an induction motor between the standstill condition and the pull-in condition (synchronous speed). For AC induction motors, this is the minimum torque developed in accelerating from at rest to the speed where breakdown torque develops.

- *Pull-in Torque:* The maximum constant torque for a synchronous motor to pull the motor into synchronous rotation at the rated voltage and frequency. Generally defined at 95% speed and represents the torque developed from the motor slip speed to the synchronous speed.

- *Pull-out Torque:* The maximum steady-state torque developed by a synchronous motor at synchronous speed with rated voltage, frequency and excitation.

- *Breakaway Torque:* The torque developed by the motor at a stand-still condition.

- *Locked Rotor Current:* The steady-state current provided to the motor in the standstill position, when applied at rated voltage and frequency.

- *Starting In-rush Current:* The amount of current drawn by the motor during starting for the first few initial cycles. This can be 200% of the locked rotor current.

3.1 Torque/Speed Curves

The torque versus speed relationship for the motor drive system must be analyzed carefully to assure that all compressor required operating points may be met with the selected system and that the transient torsional behavior of the train is acceptable. A single design point can be used to size the motor, gearbox, and drive train components. However, other operating points should also be analyzed to assure that the motor can supply the required torque for the full operating window of the compressor.

The torque and power relationships for the various drive train configurations of the centrifugal and reciprocating compressor are discussed in Sections 6.0 and 7.0.

3.2 Motor and Drive Train Efficiency

The motor losses and associated drive train component losses (including VFD, VSHD, and gearbox losses) will result in a cumulative efficiency for the drive input to the compressor. Several methods are available for assessment of motor efficiency based on either direct input/output power measurements or quantification of loss mechanisms (segregated efficiency determination). Efficiency of the electric motor drive train system should consider the following loss mechanisms[5].

1. *Stator I^2R losses:* Losses due to stator windings. Typically 1-5% of power input, will vary based on operation and speed.
2. *Rotor I^2R losses:* Losses due to rotor windings. Typically 0.2-3% of power input, varies based on speed and operation and is proportional to slip.
3. *Core loss:* Loss in iron at no load due to fundamental magnetic field. Constant power loss for a given motor design, higher percentage loss at lower power outputs, ranges from 0.2-5.0%.
4. *Stray load loss:* Stray loss in iron and eddy current losses. Range is 1-2% based on speed for large motors. IEEE 112 gives default values of stray loss between 1.8% of output for up to 125 HP down to 0.9% for 2500 HP and up. The European standards use a lower default so their machines sometimes look more efficient.
5. *Friction and windage loss:* Mechanical losses due to bearing, friction and windage. Typically these losses are very low for high power motors (< 0.5%).
6. *Power required for auxiliary items:* Cooling system, oil pump, and other powered devices associated with electrical motor operation. Typically on the order of 3-5%.
7. *Other drive train component losses (VFD, VSHD, gearbox, transformers, etc.):* Depends greatly on manufacturer of component and operation at rated speed or at off speeds. At rated speed, total loss due to other components may be as low as 5-8%. At off-design speeds, efficiency can drop severely and losses can be as high as 10-20%.

For the first two loss mechanisms, the resistance of the winding should be corrected to an ambient temperature of 25°C plus the observed rated-load temperature rise (given in the NEMA standard).

NEMA MG-1-20.21 lists test methods for determining motor efficiency. These methods are also outlined in more detail IEEE Standard 112.

Operating efficiency can be improved by certain design features, but oftentimes this will add cost to the motor. Larger motors will inherently have higher efficiencies (95% or better) than small motors. The types of motors used for compressor drives typically have full load efficiencies higher than 85% based on their size and design.

3.3 Factors Affecting Motor Efficiency

Although large electric motor drives can be designed to operate with efficiencies above 90%, there are a number of factors that influence the efficiency significantly. These effects should be considered in an efficiency analysis of the motor drive. Several of these factors are listed below.

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[5] For machines greater than 500 hp, actual losses tend to be in the lower values of the ranges shown here.

1. *Phase Voltage Unbalance:* In motors operated without a VFD, voltage imbalance between the three phases will cause a magnetic flux rotation against the rotor rotation. This will cause a higher current requirement for the same rotational speed.

2. *Terminal Voltage:* At less than full load, the voltage may be lowered to reduce the motor core losses, which are voltage (not current dependent). If the voltage reduction is not taken, core loss will consume a larger percentage of the output power because of the voltage dependency.

3. *Harmonic Distortion:* Current waveform distortions on the input of the motor will increase losses due to I^2R losses. Motor impedance increases at harmonic frequencies as well as rotor conductor resistance (due to the deep bar effect). Surface pulsations losses in the rotor and start laminations can increase as well due to harmonics.

4. *Voltage Flicker:* Periodic voltage sag below the rated level of the equipment will cause the motor current to increase and can result in voltage unbalance (effect described above.)

5. *Winding Temperature:* The resistance of the motor windings varies with operating temperature. Operating the motor at the lowest temperature possible will help reduce losses.

3.4 Performance Test Methods

Apart from the IEEE Standard 112, several other standards exist for defining induction motor test procedures including:

- IEC Publication 60034-2, Part 2, *Methods for Determining Losses and Efficiency of Rotating Electrical Machinery from Test*
- IEE Standard 115, *Methods of Determining Motor Efficiency*
- JEC-37 Induction Machine, *Standard of Japanese Electrotechnical Committee*
- Canadian Standards Association C390, *Energy Efficiency Test Methods for Three-Phase Induction Motors.* NOTE: This applies only to smaller motors up to 500 hp.
- ANSI/NEMA Standards Publication No. MG1, *Motors and Generators*

3.4.1 Efficiency Measurements

Five basic methods are available for determining motor efficiency. Three of these methods are direct measurement methods and the other two methods are indirect loss methods. The indirect measurements have an inherently higher uncertainty. These methods are described in IEEE Standard 112 or the IEC Publication 60034-2 standard. The IEEE 112 designations are: Method A – Brake Measurement; Method B – Dynamometer (Preferred method by NEMA for motors up to about 500 HP); Method C – Duplicate Machines (Back to Back test); Method E – Input Measurements (Segregated Losses); and Method F – Equivalent Circuit Calculations.

Based on the difficulty, complexity and cost involved in testing a large horsepower motor for a compressor drive application under these five methods, an alternative method should be considered. The compressor may be used to measure the output power provided by the motor. This power measurement includes the losses in the drive train. The input power is also required, which can be measured using the input real power levels provided to the motor or VFD. All test methods should include an uncertainty analysis to validate field data on efficiency.

3.4.2 Torque Measurements

Four methods are addressed by IEEE Standard 112 for measurement of motor torque output versus speed on a fixed frequency supply. These are:

1. Method 1: Measured Output – A calibrated DC generator is used to load the motor. The generator efficiency, output, rotational speed are used to back-calculate the motor torque at several operating points.
2. Method 2: Acceleration – The unloaded motor is started and motor acceleration rate is measured at various speeds. Torque is back-calculated based on rotor mass and rotational inertia.
3. Method 3: Input – Input power is measured and losses are subtracted from the input power at each test (load) point.
4. Method 4: Direct Measurement – A dynamometer is used to load the motor. Torque is either measured directly back to or calculated from the dynamometer load parameters.

Method 4 is considered to be the most accurate torque measurement because it is direct. The method is impractical for large horsepower motors. If the motor can be unloaded from the compressor it is driving, Method 2 is an option for quantifying the torque output at various speeds.

Similar to the efficiency and power measurements, the best alternative method for the compressor application is to use the compressor power and torque measurements to determine motor torque and estimate the losses in the motor and compressor drive train.

3.4.3 Site vs. Factory Testing

Factory tests of the electric motor and drive system may not be performed depending upon the factory and the size of the motor. For two bearing motor systems, most electric motors will be factor tested on a fixed frequency supply. Motor string testing becomes more costly and is less common. Power availability at the factory is usually limited and prohibits testing of larger motor systems. In addition, the drive system, coupling, and motor may be delivered by different parties and not assembled until onsite. Oftentimes, the first test of the motor and drive will be at the field site.

Field site testing will introduce higher test uncertainties in the power and torque measurements. In addition, if the performance test points cannot be met upon initial testing, it will be necessary to determine the limiting factor. This will be more difficult in the field test if previous factory testing cannot be performed. Field testing of large motors is generally impractical. API 541 and 546 define requirements for the factory testing using applied electrical loads.

3.5 VFD Effects on Performance

To determine the applicability of a particular VFD system based on efficiency and electric motor drive train performance, the user should determine the output load profile of the system. The design point and related off-design points can be plotted on a torque versus speed chart. If the compressor operation requires changes in flow and runs below 90% peak levels for significant amounts of time, or it has significant start/stop cycles, then it is recommended that a VFD be considered for use with the electric motor. Once the load profile is quantified, the next step is to select the motor. Once the continuous, peak, and duty cycle torque are known for the electric motor, the VFD can be sized.

3.6 VSHD Effects on Performance

The VSHD drive system will affect the motor and compressor performance differently from the VFD system. The main variable in the performance will be the losses in the gearbox system. Typically these are on the order of 5% and are a multiplier on the overall system efficiency. However, the loss will vary by manufacturer and may be a function of the particular speed ratio. It should not be assumed that the mechanical losses in the gearbox are linear with speed. The VSHD manufacturer should supply the performance curves or efficiencies of the variable speed gearbox in terms of the speed and power rating of the load.

4.0 ROTORDYNAMIC CONSIDERATIONS

Rotordynamic analyses are critical to trains involving electric motor drives and must be considered an integral part of the design and selection process. The analyst performing the rotordynamic analyses should verify the completeness and accuracy of input data and translate the information into accurate system models. The party performing the analyses should make recommendations for the operation of the train based on achieving acceptable rotordynamic behavior.

The first steps in conducting these types of analyses usually involve the determination of lateral critical speeds (primarily for the motor and any attached gearbox or compressor shafts) and torsional critical speeds (for the entire train). The predicted critical speeds are used in conjunction with the mode shapes and a critical speed map (lateral analyses) and/or interference diagram (torsional analyses) to determine the likelihood of exciting the critical speeds during the planned operating conditions.

Determining which type of additional analyses are necessary is primarily based on the types of equipment involved. For example, with some types of trains (especially those involving reciprocating compressors) the torsional stress and torque levels developed in the shafting during normal operation should be calculated for each anticipated loading condition and compared to allowable stress and coupling torque limits. Similarly, for some systems (especially those involving synchronous motor drives or VFD systems which produce significant alternating torque) transients, such as start-up or short circuit events, should be evaluated with torsional cumulative fatigue calculations. Additionally, lateral analyses should be conducted for electric motors, centrifugal compressors, and gearbox shafting.

The rotordynamic studies should be performed early enough in the design process to make changes if the predicted stress or torque levels exceed relevant criteria, or if the anticipated separation margins between calculated critical speeds and prevalent excitation are inadequate.

4.1 Types of Torsional Analyses

Three types of torsional analyses are generally required for electric motor drive systems:

(1) *Critical speed analysis:* Should be conducted for all compressor/motor systems

(2) *Forced response analysis:* Should be conducted for each relevant speed and operating condition – especially for reciprocating compressors

(3) *Transient torsional analysis:* Should be conducted for start-up and short circuit conditions. This analysis is especially prudent for systems involving synchronous motors, large VFD induced alternating torques, driven inertia loads exceeding the motor inertia, critical speeds below the operating speed range, long acceleration times, and for any significant compressor loading during start-up with any electric motor drive when short circuit events are considered a distinct possibility.

The analysis requirements and necessity of performing these three types for the reciprocating and centrifugal compressor applications are summarized in Table 4-1.

Table 4-1. Recommended Rotordynamic Analyses for Electric Motor/Compressor Drive System

	Torsional Steady State Analysis	**Torsional Forced Response Analysis**	**Transient Torsional Analysis (Start-up, Short Circuit Events)**	**Lateral Analysis**
Primarily Important for…	Any Train Configuration	Reciprocating compressor trains. Any train that must run near critical speed excitation.	Centrifugal compressor trains, synchronous motor applications or VFD's with large alternating torques. Also for large driven inertial loads near the motor inertia. ** If a short circuit event is likely, this analysis should definitely be performed.**	All Motors, Centrifugal Compressors, Gearboxes
Outcome of Analysis	Torsional Critical Speeds, Mode Shapes, Interference Diagram, Separation Margins, Tuning of Critical Speeds	Stress levels in shafting for each relevant operating condition, comparison with allowable stress	Cumulative Fatigue Calculations, Determination of Tolerable Events	Lateral Critical Speeds, Mode Shapes, Critical Speed Map, Unbalance Response, Stability, Tuning of Critical Speeds
EM-Reciprocating Compressor Application	**Necessary**	**Necessary**	**Fairly rare, but sometimes done for large flywheels or a driven inertial load approaching motor inertia**	**Almost Never**
EM-Centrifugal Compressor Application	**Necessary**	**Necessary if Train Must Run Near Critical Speed / Likely Excitation Order Coincidence**	**Necessary**	**Necessary**
Gearbox Applications	**Necessary**	**Occasionally Necessary**	**Necessary**	**Necessary**

4.2 Required Input Data for Torsional Rotordynamic Analyses

Various equipment suppliers usually contribute to the torsional rotordynamic analysis input data because the calculations are based on the entire system and must include the motor, VFD or VSHD, coupling(s), gearbox, and compressor(s). It is the responsibility of the packager to review and deliver these components as a system. However, a third party or the end user may perform the torsional rotordynamic analyses. The equipment suppliers must provide the following data related to the equipment they are supplying to the party responsible for the rotordynamic study:

1) Typical Torsional Analysis Input Data:

   - Any available mass-elastic model summaries for the motor, compressor(s) coupling(s), and any gearbox shafting.
   - Any known torsional or lateral critical speeds, along with mode shapes, if available.
   - OEM design limits for allowable vibration limits, torque, or stress.

- Dimensioned drawings of each shaft, indicating lengths, diameters, added inertias of major components (motor core, fans, impellers, pinion, bull, etc), and fillet radius at each major diameter change.
- Shaft material density, elastic modulus, and ultimate tensile strength (highly dependent on the heat treatments used).
- Total weight of all rotating components (e.g., motor core, shaft alone, total rotating assembly weight, etc.).
- Coupling details (hub inertias, torsional stiffness, torque ratings, shaft penetration information).
- Loading conditions and gas composition.
- Motor construction details, including shaft, spider, armature geometry, stress concentration details, etc.
- Motor drive and alternating torque for anticipated transient events as a function of speed (start-up) or time (short circuit).
- Compressor load torque as a function of speed (for transient start-up analysis only).
- Specification of any viscous dampers in the system (inertia of each major component, damping, and connecting stiffness).
- Compressor geometry and operational data: stroke, bore, clearance, and unloading data by cylinder (reciprocating compressors only).
- Reciprocating weights (reciprocating compressors only).
- Counterweight mass and eccentricity data (reciprocating compressors only).

If some of this data is provided as "preliminary," the data should be marked as such and updated in a final version. Incorrect or estimated input data will affect the accuracy of the predicted critical speeds, separation margins, forced response stress/torque, and cumulative fatigue results.

4.3 Torsional Mass Elastic Model

The torsional mass elastic model is the initial starting point for the electric motor rotordynamic analysis. This model must take into account all equipment in the train, including the driver, compressor, couplings, and any gear components. Generally, the model consists of lumped inertia values (representing the major system masses such as the motor core, coupling hubs, etc.) with a series of interconnecting springs (representing the shafting). Any stiffening effects of the rotor core should be taken into account in the torsional model.

The model must be of sufficient fidelity, with enough mass stations and distributed flexibility to characterize the important modes. For example, a common (but not recommended) industry practice is to lump all motor inertia into one value, and utilize one torsional spring to represent the motor drive shaft. This method usually results in significant errors in the predicted torsional critical speeds, especially for the second and higher modes and should, therefore, be avoided. Stress concentration factors should be developed for each element of the model, based upon the geometry involved.

4.4 Torsional Critical Speed and Forced Response Analyses

In terms of critical speeds, the primary torsional design method used for electric motor driven compressors is frequency avoidance. An interference (or Campbell) diagram should be prepared, comparing the predicted critical speeds to the anticipated excitation orders from all equipment in the train over the specified operating speed range. This should be accomplished for both the low-speed and high-speed equipment in trains involving gear ratios.

The mode shapes should also be prepared and compared to the interference diagram in order to assess the likely coupling mechanisms involved. The critical speeds should be tuned, if necessary, to provide an acceptable separation margin from significant excitation orders.

In cases involving reciprocating equipment, or where operation near a critical speed is absolutely necessary, a forced response analysis should be used to determine the stress levels in the train. The analysis should account for all potential sources of excitation from the motor, compressor, and mechanical issues, such as misalignment, during the forced response analysis.

The resultant stresses should be analyzed for each planned operating condition over the anticipated speed range and compared to clearly defined allowable stress values to determine acceptability. Damping may be added to the train (typically with elastomeric couplings or viscous dampers) in order to provide additional damage tolerance, if necessary.

As a last resort, the operating envelope (speeds and/or loading conditions) may need to be changed to avoid situations which cause excessive stress levels in the shafting.

4.5 Transient Torsional Analysis (Start-up and Short Circuit Events)

A transient analysis should be performed, especially in cases involving synchronous motors, large driven inertia loads, critical speeds below the operating speed range, long acceleration times, significant compressor loading during start-up, or large VFD induced alternating torques, to characterize the cumulative fatigue damage which occurs during start-up and any potential short circuit conditions. Typically, excitation torque equations as a function of time are provided by the motor OEM for the startup, 2-phase short circuit, and 3-phase short circuit conditions, and should be utilized as an input to the analysis. The results of the cumulative fatigue analysis should indicate a number of anticipated events that the train can tolerate. This should be compared to the anticipated service life of the train to determine acceptability.

The start-up and short circuit analyses are based on defining an endurance limit for the alternating stress and corresponding torque. Process trips will typically cause a transient torque, which is less than this upper limit. Unloading of the compressor and anti-surge control events are also more difficult to analyze because of the complex thermal variations and compressor transients involved.

4.6 Torsional Damping Levels

For most torsional systems, damping is provided via the coupling or an attached viscous damper. Most modern fixed ratio gearbox designs provide only minimal torsional damping. The estimated damping level can have a major impact on the calculated steady-state dynamic torques predicted in the rotordynamic analysis and should be based on comparable experience with similar systems or direct torsional measurements. Damping levels should account for applied drive torque, expected operating temperature, any internal dissipation mechanisms, and aging and environmental issues associated with time-dependent damping mechanisms (e.g., elastomeric elements). The following damping levels, expressed as either a damping ratio or amplification factor (Q), are recommended:

Table 4-2. Recommended Damping Levels for Rotordynamic Model

System Data	Coupling Data	Recommended Damping
Gearbox used, added system damping available	Viscous or elastomeric type coupling	Q < 30, Damping Ratio > 1.67%
Gearbox used	No viscous or elastomeric damping	Q = 30, Damping Ratio = 1.67%
Variable speed gearbox used	Manufacturer of variable speed hydraulic drive system will recommend these values.	
No gearbox, no effective damping data available	No contribution from viscous or elastomeric damping	Q > 50, Damping Ratio < 1%

4.7 Torsional Analysis Allowable Stress and Torque Criteria

An allowable stress value should be calculated for each section of shafting, for any forced response or transient torsional analysis. This allowable stress value should be based on the effective endurance limit for the shaft material, which is generally developed by applying strength modification factors to the material ultimate tensile strength. These factors should include the tensile to shear energy factor, endurance ratio, size factor, surface finish factor, reliability factor, safety (design) factors, etc. The methodology used to arrive at the allowable stress limit, and any assumptions made regarding the strength modification factors, should be clearly documented. The calculated allowable stress for each section of shafting should be compared to the calculated intensified stress from the forced response or transient torsional analysis to determine acceptability for each anticipated operating condition.

The calculated steady-state and dynamic torque values should also be compared to the maximum limits given by the coupling manufacturer and (if applicable) the gearbox manufacturer. The value should also be used in assessing any bolted joint connections on the shaft where the maximum dynamic torque can be transmitted (e.g., between flywheels and shafts).

4.8 Transient Torsional Cumulative Fatigue Analysis

Transient torsional stress developed during start-up or short circuit events can cause cumulative fatigue damage, depending on the absolute stress level as compared to the endurance limit, and the number and frequency of cycles experienced during the event. The damage tolerance of each shaft section in the model should be evaluated during this type of analysis, and stress criteria and stress intensification effects should be considered in a manner consistent with the forced response analysis.

Stress calculations are accomplished by first translating each of the torque values for the section in question to a stress by normal strength and material relationships, and taking the outside and inside diameters into account. The stress variation can be very complex for these events and should be well documented in the transient torsional analysis. Usually, one or more of the torsional critical speeds are excited at some point during the transient events.

The cumulative fatigue analysis is accomplished using Miner's linear damage rule, as implemented in the "rain flow" cycle counting algorithm. This algorithm extracts from the complex stress variation a count of the number of cycles as a function of stress range. For each of these stress ranges, the SN diagram of the material in question is queried to establish the number of cycles to failure at this stress range. The fractional damage is calculated as the ratio of actual number of cycles at this stress range divided by the number of cycles to fail at the stress range. Cumulative damage at each stress range for the entire cycle is totaled to give cumulative damage per transient event. The allowed number of events is then the inverse of this damage per event.

4.9 Synchronous Motor Slip Frequency Excitation

Synchronous motors (including permanent magnet types) produce a very large excitation torque during the start-up event. The frequency of this excitation typically varies from two times the line frequency at zero speed, to zero at full speed (motor synchronized), and is commonly referred to as the "2x slip frequency." This excitation should be included in the transient torsional start-up analysis.

4.10 Torsional Excitations Due to Variable Frequency Drives

VFD harmonic excitation tends to occur in many discrete frequencies, as opposed to the variable frequency excitation (due to multiples of the slip frequency) typically found with synchronous motors. The VFD harmonic content must be included in the transient torsional analysis, particularly for the start-up event.

The variations in the type of VFDs and the topologies will affect the torsional excitation orders produced by the drive train. Output filters may be used to reduce high frequency harmonics entering the motor for both current and voltage source types of VFDs. In a pulse width modulation VFD, if the application does not require high switching frequencies, the harmonics may be reduced by changing the angles of the modulated pulses as the VFD is designed.

The primary factors affecting the amount of torsional excitation due to VFD interference are the following:

1) The use of voltage source or current source topology may determine the amplitude of harmonic fluctuations although other factors can influence the harmonic amplitudes as well.

2) The type of power semiconductor.

3) The modulation scheme used will influence the frequencies of the harmonics.

4) The amount of filtration used between the inverter and the motor.

4.11 Motor, Centrifugal Compressor, and Gearbox Lateral Critical Speeds

The lateral critical speeds of motors, centrifugal compressors, and gearbox shafts should be evaluated with undamped critical speed maps, mode shapes, damped unbalance response, and bearing coefficient (stiffness and damping) calculations.

For large industrial motors, experience has shown that the stiffening effects of the rotor core and related structures (bars, ribs, and laminations), along with the coupling hub weight/inertia properties and bearing stiffness and damping coefficients, can have a significant affect on the lateral critical speeds for certain motor geometries.

Most centrifugal compressors should also be evaluated with respect to the potential for subsynchronous excitation of critical speeds. The lateral rotordynamic behavior of gearbox shafting is significantly influenced by the loads induced on the bearings as torque is transmitted through the assembly. These bearing loads are largely a function of the compressor operating conditions. Therefore, gearbox shafting should be evaluated for partially loaded conditions in addition to full load.

5.0 STARTING OF THE ELECTRIC MOTOR

To determine the starting method for the motor, the electric utility or electricity provider should be consulted to determine the maximum short circuit ratio for the power system and its associated MVA capability. When a large electric motor is started, the current drawn by the motor to accelerate the rotor with its full load can be 500-700% of the full load current. The electric utility system will react to the initial current demand with a corresponding voltage drop. Across–the-line starts should always be evaluated as a first consideration because of the reduced cost and simplicity of this option, but in many instances, this method will not be possible because the electric system cannot tolerate the voltage drop.

The start-up method for the electric motor drive system will affect the amount of current drawn by the electric motor and the amount of torque imposed on the coupling and shaft during the start. If the motor can be unloaded or the load can be reduced (either through the use of suction throttling, recycling, clutch arrangements, etc.), the motor can be brought online with a lower start-up torque.

The starting method of the motor drive train system will influence many other factors in the compressor installation and should be addressed in the beginning stages of an electric motor drive project. The basic start-up methods are discussed below and summarized in Table 5-1.

Table 5-1. Summary Table of Start-up Methods

Start-up Method	Advantages	Disadvantages
Across-the-Line Start, Loaded Drive Train	Least costly, least complex method.	May not be possible given fault current ratio of system and current draw. Will impose higher torsional load on shaft.
Across-the-Line Start, Unloaded Drive Train	Also fairly inexpensive option. Requires method of unloading drive train, which may add expense or reduce operational efficiency.	Will still impose some voltage drop on power system. Requires some method of unloading compressor, running in bypass or suction throttle.
Soft-Start with a VFD (either full size or selected for starting only)	Least severe option for torsional load and current demand by motor upon start-up. Almost guarantees motor can be started in any electrical grid.	VFD cost may be high. Harmonics imposed by some VFD types can be excessive.
Helper Motor to Start with Reduced Load	May be less costly than adding VFD, helper motor can add some redundancy and back-up for peak periods.	Requires some method of unloading compressor, running in bypass or suction throttle. Helper motor required for each individual unit. Less efficient operation during start-up.
Helper Motor to Start with Torque Converter	Helper motor can add some redundancy and back-up for peak periods. Torque converter will be more efficient method of starting than reduced load.	Requires added cost of torque converter. Helper motor required for each individual unit.
Low Voltage Options for Starting	Reduced torsional loads on shaft, ensures low voltage draw on power system.	Requires added cost of voltage reducing transformers and some method of unloading compressor, running in bypass or suction throttle.

5.1 Method 1: Across-the-Line Start

Starting the motor across-the-line is the first option to consider. For small motors (7,000 hp or lower) this may be possible for typical electrical utility supply characteristics. For power generated onsite, an across-the-line start may not be possible due to capacity limitations. The utility or operating company must be involved in the evaluation of an across-the-line start. If the power is being generated on site, then the across-the-line start may trip the local power source, if the short circuit ratio is not properly evaluated.

Synchronous motors will normally be started in a reduced load start because the torque at start-up will not support the full load. The starting case should be considered in the overall system design. The induction motor can be started more easily across-the-line because more torque is available in this start-up mode.

One other notable disadvantage of the across-the-line start method is that the transient torque levels imposed on the system are generally greater than those applied with the other starting methods and may adversely affect the fatigue life of the train components.

5.2 Method 2: Soft-Start with Full Size VFD

If the application already requires a VFD, the station full-size VFD can easily be programmed to accommodate a “soft-start”. This is done by controlling the volts/Hertz ratio of the motor input power. By starting the motor at a low effective frequency and then ramping up the speed, motor current and torque can be limited to close to full load values. A full-size VFD can provide a motor soft-start while providing full load torque. This control technique can also be used to control the motor so that less power is delivered when the load is smaller. Different VFD types and systems implement this technique differently.

5.3 Method 3: Small VFD for Soft-Start

Use of a smaller VFD can help to reduce the motor current requirements for start-up. If the motor is only required to support a constant speed for the compressor, then a full-size VFD may not be necessary. A smaller VFD could be used to assist in controlling the volts/Hertz ratio to the motor during start-up and then to shut off afterwards (once the electric motor has reached full speed.) The drive may also be arranged with a bypass once the motor is at full speed. The full-voltage in-rush will not be realized by the motor or the power system source using the small VFD. Using a small VFD for soft-start will require the compressor to be unloaded during start until the motor reaches full speed.

5.4 Method 4: Smaller Starter Motor at Reduced Load

In some instances, when a VFD or variable speed hydraulic drive is not intended to be used in the application, a starter motor may be sized for less than the full load, with the intention of reducing the initial current demands on the primary motor during start. This adds some complexity to the system but provides additional reliability. Once the primary motor is up to its full speed, the starter motor may be turned off and the full load can be assumed by the primary motor. This technique also requires the compressor to be unloaded during start. This approach is not as cost-effective for multiple motor-driven compressors at a single station which would require a separate starter motor for each.

5.5 Method 5: Smaller Starter Motor with Torque Converter

Another option is to use a starter motor with a torque converter if the compressor load cannot be reduced sufficiently. Some coupling designs permit the motor drive to be uncoupled from the compressor. If this type of coupling is available, a smaller starter motor may be added to the installation that can be started with an across-the-line start. The smaller motor is used to start the primary motor rotating. Once this occurs, the prime electric motor can be fully engaged with the clutch on the torque converter.

5.6 Method 6: Low Voltage Options for Reduced Load

Reactors, autotransformers, or power semiconductor technology may also be used to reduce the motor voltage at start-up if the motor torque requirement may be relieved through a reduced load. Reducing voltage to the motor at start-up will reduce the start-up torque and help to reduce the current drawn by the motor during start-up. Motor torque will decrease at a rate proportional to the square of the voltage decrease. Voltage may be reduced to as low as 65% of the nameplate rated voltage in some cases.

Most commonly, autotransformers or capacitor assisted starts are used to minimize current draw while the motor is brought up to full speed. Autotransformer techniques used for low voltage starting will affect the power distribution system differently. Capacitor assisted starts allow the motor to be brought up to speed on large capacitance and then switched over to line power. Motors designed for low voltage starting may have higher than standard in-rush currents if started across-the-line.

5.7 Evaluation Process for Start-up Method

For all of these options, the designer must evaluate the motor starting torque and determine if the compressor drive can tolerate these levels during start. A major consideration for evaluating which starting technique is used is the ability to unload or decouple the compressor from the motor drive.

API 546 and 541 motor standards limit the number of consecutive motor starts in a certain time period because the starting capabilities of the motor affect the long-term reliability and performance of the motor due to the possible torque limits imposed. For constant speed applications, a specific start-up case may need to be developed by the operator and accommodated by the motor/compressor/coupling manufacturers. Starting torque loads are typically limited to 30-50% of full load torque.

The following evaluation process flow chart outlines the rationale governing the start-up method process selection.

Evaluation Process for Determining Start-up Method for Compressor with Electric Motor Drive

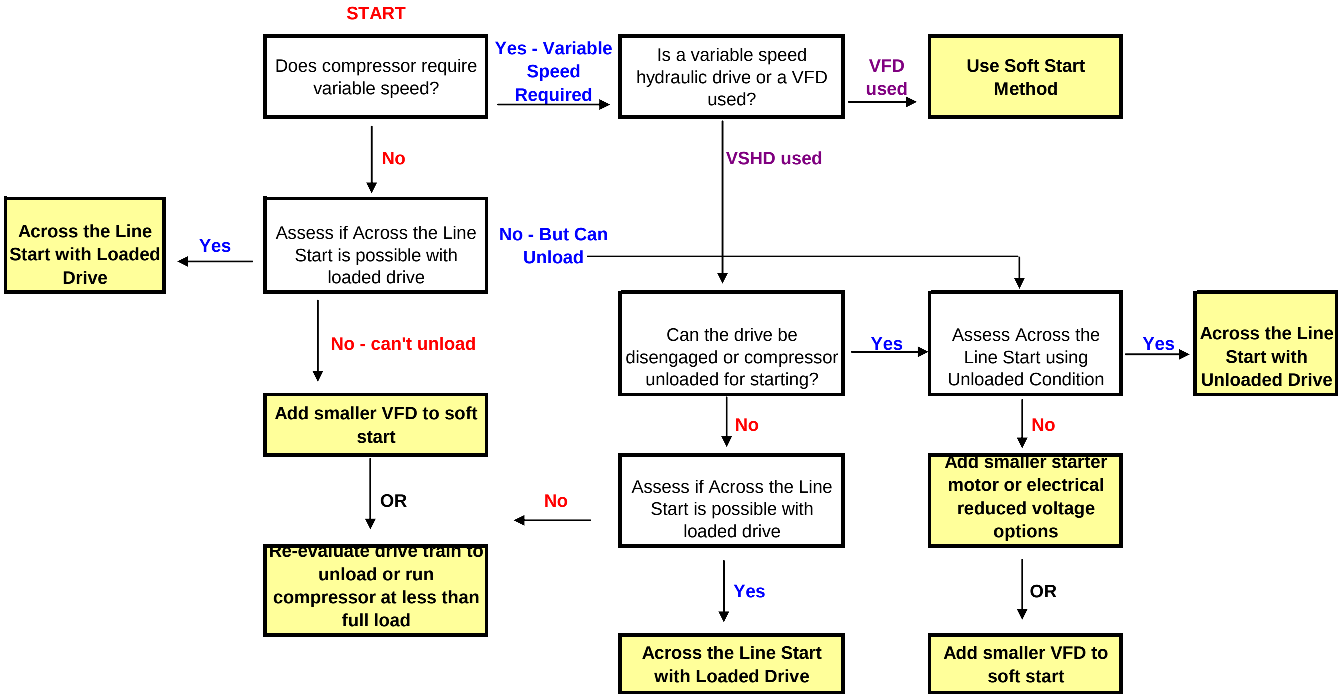

Figure 5-1. Start-up Method Evaluation Process Diagram

6.0 CENTRIFUGAL COMPRESSOR APPLICATIONS

Centrifugal compressors are usually driven by gas turbines, steam turbines, and electric motors. There are three basic types of electric motor drives for centrifugal compressors:

- Variable frequency drive (VFD) with electric motor driving the compressor at motor speed or though a fixed ratio gearbox.
- Constant speed motor operating across-the-line with a variable ratio gearbox, using a variable speed hydraulic drive.
- Constant speed motor operating across-the-line driving the compressor at motor speed or through a fixed ratio gearbox.

Unlike reciprocating compressors, the electric motor output speeds tend to be lower than the typical range of centrifugal compressor speeds. This mismatch in speed range typically requires some combination of a gearbox, VFD, or VSHD to increase the electric motor rotational speed to match that required by the centrifugal compressor. Direct drive systems may be devised for high-speed motor applications up to 20,000 RPM – although these are not used on a widespread basis.

Gearboxes are used with variable frequency drives and constant speed electric motor drive applications to match the motor shaft speed to the compressor speed. In some cases, it may be possible to match the motor speed range using a VFD to the compressor speed range without a gearbox. For VSHD, a gearbox is always required as the VSHD gearbox provides the variable speed capability.

The most common and most efficient type of process control with a centrifugal compressor is speed variation. Multi-shaft gas turbines, variable frequency drives, and variable speed hydraulic drives are well suited to this method of process control. Constant speed drivers, such as constant-speed electric motors, will need to use another type of process control, such as suction and/or discharge throttling valves, variable compressor inlet guide vanes, or bypass valves to provide the required variable process control. This type of process control is less efficient than speed control due to the throttling losses or excess flow losses.

Of primary importance to this application of the electric motor, process control variations, such as suction and discharge pressures, suction temperatures, gas compositions, and flow rates will have a large effect on the required speed and power at the compressor shaft. These variables need to be defined by the operating company and specified so that a suitable motor drive system can be sized and selected, which covers the entire operating range of the unit.

While centrifugal compressors tend to follow the “fan law” of power versus speed for a specific set of process conditions, changes in process conditions will yield a multitude of fan law curves that need to be considered when selecting and sizing the power drive system. Assuming a single fan law curve is not sufficient for a compressor with a wider range of process conditions, this assumption can result in an electric motor undersized for the application, in terms of torque or power.

6.1 Output Power as a Function of Driver Output Speed

Each electric motor drive type has a specific operating envelope of torque and speed combinations or capability. The electric motor drive capability is used in determining how much of the compressor’s capability or operating envelope is available for use. Some electric motor drives will cover more of the compressor operating maps than other drives. The basic output power versus output speed capabilities of several compressor drives are shown in Figure 6-1.

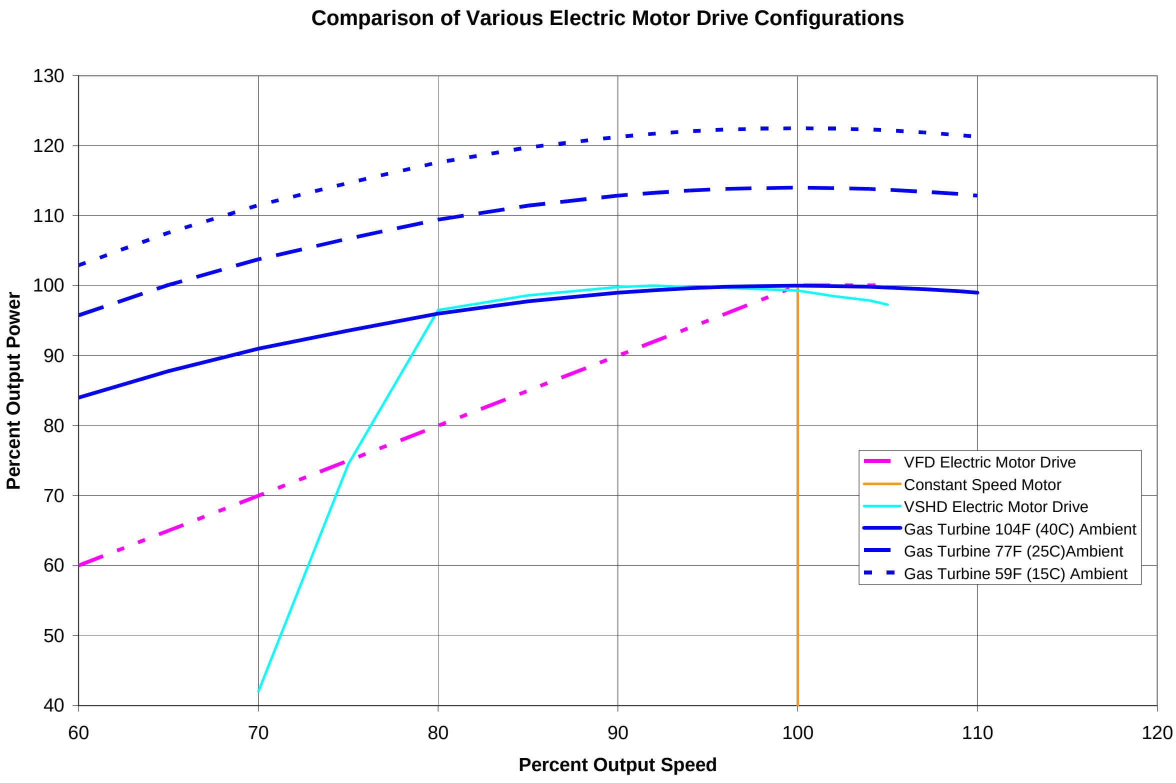

Figure 6-1. Comparison of Operating Window for VFD, VSHD and Constant Speed Motor

The VFD and electric motor drive system will operate in one of three different modes. These different modes are a result of the design limitations of the electric motor and are used in different parts of the speed/power operating envelope. The VFD modes include:

- Constant power versus speed
- Constant torque versus speed
- Variable torque versus speed

Depending on the VFD mode of operation, the available motor torque or power may be limited at different motor speeds. This is reflected in the power curve shown in Figure 6-1 where at motor speeds below synchronous speed the motor operates at constant torque with reduced power. For speeds above synchronous speed, the motor operates at constant power with reduced torque.

Variable speed hydraulic drives will have a nearly constant output power versus output speed characteristics, as shown in Figure 6-1, over a certain part of the speed range. The electric drive motor power rating, efficiency of the variable ratio gearbox over the operating speed range, and the VSHD cooler size will determine the VSHD/electric motor drive operating envelope.

Constant speed electric motors have a variable power capability at a constant speed (synchronous motors) or a near constant speed (induction motors). This provides a range of power outputs for a compressor operating at a less power intensive condition, but only one speed output. The efficiency of the drive train stays fairly constant in this configuration because of the ability of the motor to reduce power output based on the compressor load requirement.

Electric motors can be sized based on API 617 requirements or a customer specified power rating or service factor. All of the components in the power drive system - transformers, switch gear, cabling, motors, drives, gearboxes, couplings, coolers, etc., must be sized for the specified power rating or service factor. API 617 requires that electric motor drives have a minimum rating that is at least 110% of the highest power required (including gear and coupling losses) for any of the specified operating conditions. Customer defined power ratings or service factors may be smaller or larger than the API 617 specification.

Motors and power drive systems must be selected to meet the site conditions - elevation, ambient temperature range, motor and drive coolant temperature range, hazardous location requirements, etc. The power rating of a motor and power drive system will not increase at lower ambient temperatures. Motor nameplate and power drive system ratings for a compressor application will not be identical for different driver options due to the different power/speed requirements for the different driver options.

Most electric motor driven compression trains use a speed increasing or speed reduction gearbox to match the motor operating speed range to the compressor operating speed range. Due to gearbox losses, the use of a gearbox will increase the compression train power requirements slightly but will also provide a means to change the operating speed range of the compressor if future process conditions change. The use of a gearbox may be avoided if there is sufficient overlap of the motor operating speed range and the compressor operating speed range.

6.2 Electric Motor with Variable Frequency Drive for Centrifugal Compressors

Based on the three basic output capability options for a VFD and electric motor drive system (constant power versus speed, constant torque versus speed, or variable torque versus speed), the motor package can be sized for the operating conditions required.

Figure 6-2 shows the output power versus output speed characteristics for the three types of VFD electric motor drive systems. Note that the output power at rated motor speed is the same for all three types and that the nameplate power rating for all three types of variable frequency drives can be the same. The available power at off-design conditions for the three output options is distinctly different. It is important that the output power versus output speed capability of the proposed drive system be understood so that the proper VFD and motor combination can be selected for an application.

Some applications may be able to use a variable torque VFD motor system if the process conditions and gas compositions are fairly constant (such as a refinery type application). Larger variations in process conditions will require a constant torque capable VFD/EMD or a constant power VFD/EMD. Constant power packages tend to be the most costly based on the overall size of the motor required in this output capability option.

The three basic power-versus-speed capabilities available with VFD motor system determine how the power changes as a function of motor speed. The VFD provides a constant volts/Hz output over the operating speed range of the motor, up to the rated or synchronous speed of the motor. At motor speeds above the synchronous or rated motor speed, the voltage is held constant at the higher VFD output frequencies and the motor power capability is relatively constant over this above synchronous speed range. Constant power versus speed capable VFD/EMDs require the use of larger VFDs and motors as the current will increase with a decrease in motor speed in order to maintain a constant power output. Constant torque versus speed capable VFD/EMDs will operate at a constant current over the speed range to produce a constant torque. Variable torque versus speed capable VFD/EMDs will operate with a reduced current capability at lower motor speeds.

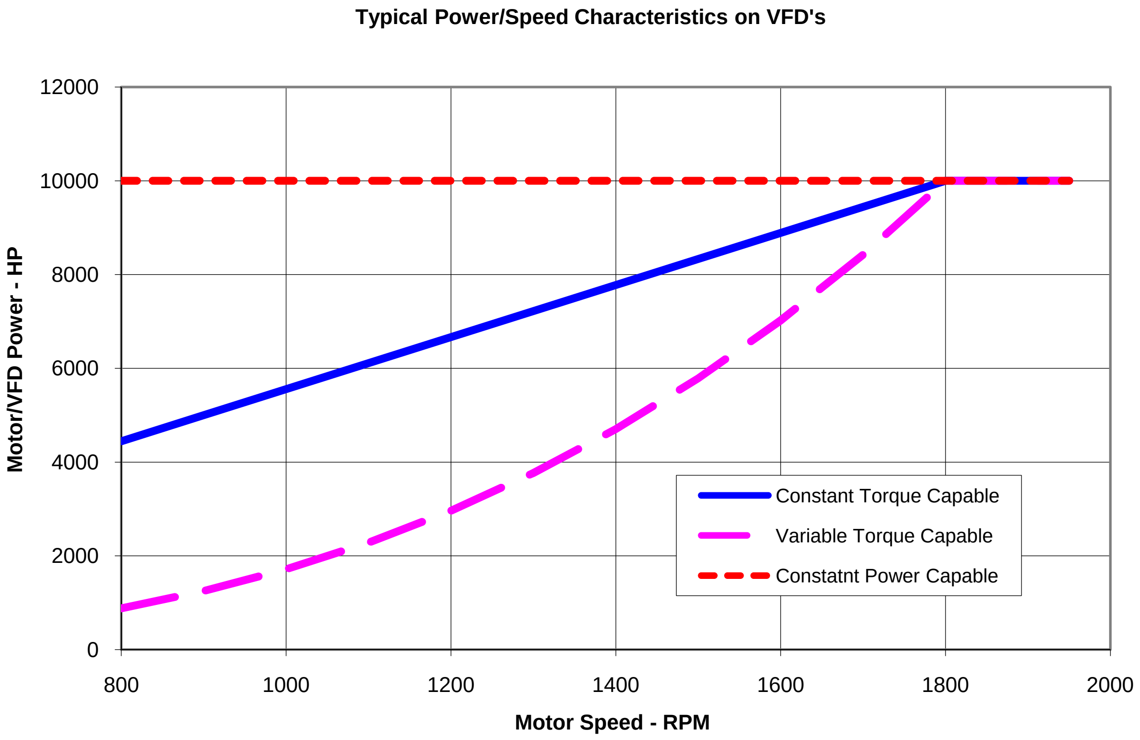

Figure 6-2. Power/Speed Characteristics for Three VFD Types

Proper VFD motor drive selection will require the selection of the appropriate power versus speed capability and the determination of the maximum and minimum VFD motor drive operating speeds.

API 617 requires that variable speed centrifugal compressors have a maximum continuous operating speed (MCOS) of 105% of the highest predicted operating speed of any of the given operating conditions. If a gearbox between the compressor and drive motor is required, the gearbox ratio is usually selected to operate the compressor at its MCOS when the motor is operating at its MCOS. Speed margins other than +5% may be required based on customer or project specific requirements. The minimum compressor train operating speed is determined either by the minimum allowable compressor operating speed or the VFD motor drive minimum allowable operating speed. Most VFD motor drives can operate down to at least 50% of base speed and sometimes lower.

VFD motor drives have an inherent soft start capability and are typically the easiest electric motor drive configuration to start up. The main mode of process control for VFD motor drive driven compression trains is speed variation. The unit control panel (UCP) varies the speed setpoint to the VFD to achieve the process setpoint. The maximum current to the motor from the VFD is typically controlled internal to the

VFD. The maximum current limit will override the speed setpoint so the VFD and motor are not operated in an overloaded condition. Centrifugal compressor anti-surge control is also required.

VFD motor drives generate harmonics on the power supply input and on the output to the motor. The harmonics reflected back to the power supply are of prime interest to the utility and plant. The harmonics on the power supply to the motor are of prime interest in proper coupling selection and lateral and torsional vibration.

Some VFD systems will use mixed control modes and combine the three characteristics shown in Figure 6-2. This can help to improve the operating envelope of the system. It is important to know the characteristics of the various VFD motor drives and the options available to select the most appropriate VFD motor drive for the application.

6.3 Electric Motor with VSHD for Centrifugal Compressors

The power versus speed capability of a VSHD depends on the electric motor power rating and the efficiency of the VSHD over the speed range. The gearbox is selected to operate the compressor at an MCOS of 105% speed if the requirements of API 617 are used. Project or customer specific requirements may dictate another compressor MCOS. The minimum compressor train operating speed is determined either by the minimum allowable compressor operating speed or the VSHD minimum allowable operating speed. Most VSHD’s have a minimum operating speed in the 60% to 70% range of base speed.

Start-up of a VSHD compression train requires more evaluation as the electric motor is started and operated as a constant speed motor with or without any soft-start capability. Some VSHD units have an option for a clutch and hydraulic coupling so that the VSHD and compression train can be decoupled from the drive motor during drive motor start-up.

Once the drive motor is up to speed, the hydraulic coupling is filled, the compression train comes up to speed, the clutch is engaged, and the hydraulic coupling is drained. This can allow the use of a soft-start system to reduce the impact of starting a large drive motor. It may be possible to use a soft-start system on a smaller power VSHD without decoupling the compression train. A start-up study using the compression train and VSHD speed/torque requirements during start-up and the available motor speed torque values must be done to determine this.

The main mode of process control for VSHD driven compression trains is speed variation. The unit control panel varies the speed setpoint to the VSHD to achieve the process setpoint. Instrumentation must be included to monitor the current draw of the drive motor so that the UCP can override the speed setpoint and not overload the drive motor.

6.4 Constant Speed Electric Motor Drives for Centrifugal Compressors

Constant speed electric motor drives have a variable power over a constant or nearly constant (induction motors) speed characteristic. The gearbox must be selected to account for any required compressor speed tolerance to meet given operating conditions (unless the impellers can be trimmed) and the impact of using an induction motor with slip.

Constant speed electric motor drives are usually better suited to smaller power applications with minimal variation of process conditions. Motor starting requirements can make these challenging applications, especially in the larger motor power sizes as the motors are started across–the-line or must use one of a variety of motor soft-start approaches.

Process control is achieved by the use of suction and/or discharge throttling valves, variable compressor inlet guide vanes, or bypass valves. The UCP will vary the commands to the throttling valves, compressor inlet guide vanes, or bypass valves to control the process. The throttling pressure losses and bypass flow rates involved with this type of process control must be included in the compressor and drive selection. Instrumentation must be included to monitor the current draw of the drive motor so that the UCP can override the process control setpoint and not overload the drive motor.

7.0 RECIPROCATING COMPRESSOR APPLICATIONS

The most typical methods of capacity control for reciprocating compressors use unloaders or fixed-volume clearance pockets to control flow and power output. These capacity control adjustments are performed with the train running at a fixed speed. If variable speed is not required, it may be possible to run the reciprocating compressor at the same speed as the electric motor by picking a motor synchronous speed given by the number of motor poles.

Occasionally, reciprocating compressor electric motor drives will utilize a VFD to control the speed range of the compressor because of the relative simplicity of this drive train configuration. Speed control will permit a wider range of flow rates than simple volume pockets. However, the pulsation control aspects of a variable speed reciprocating compressor are more difficult because the higher orders of the compressor begin to overlap. The pulsation filter must be designed for the lowest possible speed of the compressor and it is typically not possible to place higher order nozzle response frequencies in a “window” between the operating speeds.

A speed increasing gearbox is not normally required because of the good agreement between motor speed and reciprocating compressor speeds. In rare cases, VHSDs are used for speed control, but these drive systems are difficult to justify for reciprocating compressor application.

7.1 Reciprocating Compressor Drive Train Design

The operating company and reciprocating compressor manufacturer should work together to determine the specific limits on torque, pulsation levels, and stress based on the known characteristics of the reciprocating compressor. The following specifications should be adhered to in the design of the compressor drive train.

7.1.1 Preliminary Design Stage Considerations

The motor manufacturer and VFD (if separate parties) should be advised that the driven compressor will be a reciprocating compressor, which generates typical pulsation levels in the range of 0-120 Hz.

A torsional analysis should be performed as soon as possible in the drive train design process, even if certain input data is preliminary. The torsional analysis should follow the applicable recommendations of Section 4.0 for reciprocating compressors and assume a specific reciprocating compressor model. The analysis should result in determining the proper flywheel inertia, coupling stiffness, and estimated stress on the shaft.

The vibratory torque limit is typically prescribed by the compressor OEM and given to the motor manufacturer to assess the motor robustness. This limit is given as a percentage of the motor nameplate torque. It should account for the additional torques present on the motor due to the presence of the reciprocating compressor.

7.1.2 Sizing of the Motor/Drive Train

The motor power output over the compressor speed range should include an allowance of ±3% to support full load operation of the unit at different load levels. The minimum and maximum power requirement for the reciprocating compressor over the compressor speed range should be included in the motor size selection to ensure adequate power and torque at all operating points.

Breakaway torque requirements for the motor should be determined based on inertia data supplied by the reciprocating compressor manufacturer. The inertia values should represent conservative estimates of the maximum inertia for any given frame.

7.1.3 API Design Guidelines for Reciprocating Compressor Operation

According to API 618, the electric motor should be sized to provide 105% of the power required for the full flow operation at the design conditions. The motor should also be capable of providing 110% of the maximum power over all of the specified operating conditions. The 5% margin at design conditions and 10% margin at maximum power conditions accounts for the uncertainty in the power calculation for the compressor and additional inefficiency in the electric motor.

Motor starting torque should match requirements for compressor starting torque, at a reduced voltage of 80% of normal voltage. This allows for a 20% voltage drop. The motor starting torque should be capable of starting the reciprocating compressor with all head ends unloaded or with all stages operating in 100% bypass. Allowable acceleration time for the motor is recommended at 15 seconds.

The API standard requires a 20% difference between any compressor excitation order and the torsional frequency of the motor rotor oscillation. This applies to synchronous motors based on the API standard but an induction motor application should have at least a 5% margin between the torsional frequency and any compressor order.

It should be noted that high-efficiency induction motors will behave differently than standard induction motor designs. Due to the lower slip factor of these motor designs, higher current pulsations may be induced into the flow. The higher current pulsations will cause higher average current and power consumption than standard efficiency motors. Design of the high efficiency motor systems should account for an additional power penalty and higher average current draw. The API standard suggests that these high efficiency induction motors be used for steady-state loads, such as fans or blowers because of the characteristic higher current pulsations.

7.2 Torque Pulsations

The electric motor will generate current pulsations due to the motor and/or VFD distortions of the input current waveforms and the conversion process in the motor/VFD system. The current pulsations can aggravate the torsional loads and cause higher stresses on the shaft, often termed torque pulsations. The electric motor output pulsation limit is defined by API 618.

The API standard recommends that current pulsations from a synchronous motor not exceed 66% of the full load current value, which is consistent with NEMA MG-1 and IEC 60034. Induction motors are required to have current pulsations not exceeding 40% of the full load current value. In general, induction motors will tend to produce higher current pulsations that need to be closely evaluated under variable torque loads to assure that the resultant pulsations do not cause excessive torque on the shaft or inefficient operation.

The OEM of the reciprocating compressor or the packager should supply the operating crank effort to the motor manufacturer in order to determine the current pulsation levels produced by the motor as a function of operating speed and the minimum flywheel inertia requirement.

The motor torque output and torque pulsation levels should be provided by the motor manufacturer along with any assumptions used to specify the motor/VFD package efficiencies and current pulsation levels.

7.3 Motor Drive Specifications

API 618 requires that the purchaser of an electric motor specify the following characteristics and accessories on a motor design specification. An example specification sheet for the motor/reciprocating compressor application is provided in Appendix A-2. The required motor drive specifications for a reciprocating compressor application are:

7.3.1 Purchaser Side Specifications

- Type of motor (synchronous or induction)
- Bearing arrangement
- Electrical characteristics
- Starting conditions or planned starting method, include voltage drop expected for starting
- Type of enclosure
- Full range of expected operating conditions
- Sound pressure level requirement
- Area classification
- Insulation class and maximum temperature rise
- Required service factor
- Ambient temperature and elevation above sea level
- Electrical transmission losses
- Instrumentation planned for motor
- Auxiliary equipment
- Vibration acceptance criteria
- Use of variable frequency drive or other speed control method
- Power factor requirements
- Applicability of the IEC 60034 standard, API 541 standard, API 546 standard, or IEEE 841

7.3.2 Compressor Vendor Data – Required Data

- Required motor rotor inertia to satisfy flywheel requirements at specified operating conditions
- Starting torque requirements
- Mounting or coupling details
- Operating crank effort to the motor manufacturer in order to determine the current pulsation levels produced by the motor as a function of operating speed and the minimum flywheel inertia requirement.

8.0 APPLICATION ASSESSMENT, MAINTENANCE AND RELIABILITY

8.1 Application Assessment Requirements

In addition to the selection of the appropriate motor drive system to match the operational needs of the centrifugal compressor, several additional parameters should be assessed in the initial planning stages of the project. These include unit monitoring, utility system provisions, site conditions and interfacing with the utility or power generation system.

8.1.1 Unit Control and Monitoring

The need for balance of plant control and monitoring, historical data logging, and system communication should be reviewed and implemented as necessary.

8.1.2 Interface with Utility or Power Generation System

Understanding and compliance of the entire requirements of the utility or power generation system need to be evaluated and planned for during the planning/pre-order phase. Electric motor drives will also require safety devices, such as overload trip, switch gear, under voltage trip, loss of phase trip, etc. An external transformer to drop site voltage to drive input voltage is often required.

8.1.3 Site Conditions

The site conditions, enclosure requirements, and regulatory/certification requirements need to be understood and specified during the planning/pre-order phase. Sites above 1,000 m or with ambient or cooling temperatures above 40ºC will require additional engineering and scope, as the standard rating for most electric motors and variable frequency drives is 1,000 m and 40ºC. If the compression trains will be installed offshore with marine motions and shock loads, those requirements should be part of the project requirements and the equipment design should support those requirements. This may require thrust bearings for electric motors, ability to handle deck/foundation flexing and distortion, increased slope on lube oil drain lines and lube oil tank modifications for pitch and roll conditions, higher levels of third party certification, etc.

8.1.4 Utility Requirements

The utility requirements (power drive system main power, auxiliary power, cooling loads, air/water/gas requirements) and responsibility of supply need to be determined and installed.

8.2 Maintenance

Maintenance items for the electric motor system typically fall under the following categories:

- *Bearing lubrication system:* Proper selection of the appropriate lubricant and frequent changing of the oil will help to prolong bearing life. Frequency of oil change depends on the oil type, ambient temperature, bearing total temperature, and the cleanliness of the motor environment.

- *Bearings:* Beyond the lubrication system, the bearings are a common failure item because of the wide range of load conditions, bearing types and susceptibility to induced currents and corrosion. The potential for bearing induced current loads can be assessed by measuring shaft voltage. Shaft voltage results from an alternating flux linkage across the shaft or asymmetries in the air cap magnetic field.

- *Motor dirt/corrosion:* Keeping the motor clean will help to prevent corrosion and overheating of the motor. The enclosure and operating environment play a large role in the level of dirt build-up on the motor.

- *Windings:* Windings should be inspected periodically to protect against excessive dirt, oil and moisture build-up. Winding inspection can be combined with winding insulation checks. Windings may also be serviced to vacuum out excessive dirt and re-varnish the motor. Winding tests have been developed by NEMA and standard resistance levels have been developed.

- *Insulation:* Dirty or damaged insulation will result in excessive heating and limiting the life of the motor. Overheating may be caused by other factors as well. If the winding electrical insulation resistance falls below acceptable values excessive stray currents will be induced in the motor frame. The induced current will be a definite cause of bearing wear and deterioration.

8.2.1 Insulation Resistance

Insulation resistance is a useful indication of the electrical insulation protection. Insulation resistance should be checked to avoid potential damage to parts with low insulation resistance. Resistance of the material will vary with moisture on its surface, surface condition, age, test potential, and insulation temperature. Test data should be interpreted with these factors in mind. Insulation resistance should be checked regularly, at a rate of once every 2-5 years. For higher voltage fixed speed applications, a useful online test may be done to continuously monitor Partial Discharge of the winding and predict insulation problems (IEEE Standard 1434).

For insulated bearings, the insulation resistance should be tested and corrected if it measures less than 20,000 ohms. The shaft insulation can be checked by measuring insulation resistance of each insulated bearing. Windings should also be checked for insulation resistance. If the resistance is low, windings should be cleaned and dried properly and re-measured.

8.3 Reliability

Reliability of the electric motor system can vary greatly depending on the amount of components in the drive train, the service environment, and the operating conditions (frequent starts/stops, off-design conditions, etc.). The primary causes of failure of the drive train are typically associated with defective components, inadequate maintenance, motor drive mismatch and outages from the power utility. The reliability of the entire system can be defined as:

Mean Time Between Failures = Total Operating Time/Number of Failures

For large electric motor installations involving many factors and options for the drive train, starting method and variable speed options, a formal Reliability, Availability and Maintenance (RAM) study is recommended. This type of analysis should consider all of the components and alternative options for the motor type, use of gearboxes, variable frequency drives, and variable hydraulic drives. The study should also include the auxiliary equipment required to support the electric motor drive system (cooling systems, lubrication systems for bearings, gearboxes, etc., couplings, and bearings). Smaller installations may justify reducing the scope of the RAM study.

This analysis will provide another view of the electric motor system that addresses long-term operational expenses. The application may not be a long-term operation of the motor, in which case longer term maintenance items are not as important as the capitol cost and shorter life items. In other instances, the electric motor may need to support longer term service. In these cases, frequent inspections to reduce wear and greater reliability are justified.

In assessing the VFD technologies and the variable speed gearbox options, the current state-of-the-art is constantly changing. The availability and reliability of these new technologies may be difficult to characterize.

APPENDIX A-1: ELECTRIC MOTOR DEFINITIONS AND PRIMARY EQUATIONS

Definitions

1. **Synchronous Speed:** Synchronous speed is the speed of rotation of the magnetic field of an AC motor. Synchronous motors operate at synchronous speed. Induction motors operate at a speed less than synchronous speed. Synchronous speed is defined as *Nsyn = 120*Hz / n-poles*. Common Measurement Unit = RPM

2. **Voltage:** The unit of electrical pressure or force which is defined electrically as the difference in potential. For AC circuits, the effective voltage is expressed as the root-mean-square. For a sine wave, *(RMS) voltage = 0.707*(max-voltage)*. Common Measurement Unit = volts

3. **Current:** The rate of electron flow, typically expressed in effective amperes. Common Measurement Unit = amps

4. **Resistance:** The amount of resistance to steady flow direct current in a circuit. Fundamentally, the current, voltage and resistance are related by Ohm's law: $V=I^2R$. Common Measurement Unit = ohms

5. **Inductance:** A property of an electric circuit where a change in the current flowing though that circuit induces an EMF that opposes the change in current. In an AC circuit, the inductance will cause a phase shift between the voltage and current waveforms. For a zero resistance (ideal) circuit, the 100% inductive circuit will have a current that lags the voltage by exactly 90 electrical degrees. Common Measurement Unit = henry

6. **Capacitance:** A measure of the electrical charge stored for a given electric potential. In an AC circuit, the capacitance will cause a phase shift between the voltage and current waveforms. For a zero resistance (ideal) circuit, the 100% inductive circuit will have a current that leads the voltage by exactly 90 electrical degrees. Common Measurement Unit = farad

7. **Impedance:** Total resistance to current flow expressed in terms of resistance, inductance and capacitance as: $Z = (R^2 + (XL-XC)^2)^{0.5}$. In many AC circuits, the inductive reactance is much larger than the resistive and capacitive contributions to the overall impedance and can be considered equivalent to the impedance. Common Measurement Unit = ohms

8. **Inductive Reactance:** Analogous to mass inertia, defined as magnetic inertia by which an electromagnetic device causes a delay in current flow. This causes the resultant current to lag behind the instantaneous voltage change in an AC circuit. Common Measurement Unit = ohms

9. **Power Factor:** The ratio of the real power to apparent power flowing into an AC load. The power factor and is a number between 0 and 1. Real power is a measure of the capacity to perform work. Apparent power is the product of voltage and current of the circuit. The power factor is used in AC power circuits to quantify how much reactive power is required by a load. Common Measurement Unit = none

10. **Single Phase A-C:** An AC voltage that alternates between two values regularly, following the basic sine wave.

11. **Polyphase A-C:** When electrical power is supplied over two circuits and the two circuits have voltage values that are 90 degrees out of phase, the circuit is defined as two phase. The more common three phase AC corresponds to three circuits that are 120 degrees out of phase from each other.

12. **Motor Stator:** The outside stationary coils or windings of an AC motor. The stator includes the magnetic core and windings. When connected to an AC supply, the stator produces the motor rotating magnetic field.

13. **Motor Rotor:** The non-stationary part of an electric motor.

14. **Motor Exciter:** In a synchronous motor, a DC supply that supplies the magnetized current to the rotor field winding.

15. **Synchronous Motor:** A polyphase ac motor with separately supplied DC field and an auxiliary amortisseur winding for starting and damping purposes. The operating speed is fixed by the frequency (f) of the system and the number of poles (p) of the motor. (Synchronous speed (r/min) = 120f/p). Thus the speed of the motor can be varied by varying the frequency of the power source. The synchronous motor generally operates at unity or slightly leading power factor and can be used to improve the system power factor. The current is supplied directly to the rotor and links to the rotating magnetic field in the stator to cause the rotor to turn. The physical rotation of the rotor is synchronous with the magnetic field rotation.

16. **Induction Motor**: An asynchronous motor where a secondary current is induced onto the rotor by the stator windings. A polyphase AC current is used to create a rotating magnetic field pattern and induce current in the rotor conductors. Physical rotor rotation is not synchronous with the rotating magnetic field. The induction motor operates at less than unity (i.e., lagging) power factor. Typically, for medium power industrial applications, a squirrel cage design is used to connect the rotor at both ends using connection rings.

17. **Permanent Magnet Motor:** A synchronous motor in which the field system consists of one or more permanent magnets. A synchronous motor similar in construction to an induction motor in which the member carrying the secondary laminations and windings also carries permanent-magnet field poles that are shielded from the alternating flux by the laminations. It starts as an induction motor but operates normally at synchronous speed.

18. **Slip:** The difference in speed between the rotating stator magnetic field and the rotor shaft rotation for an induction motor. Slip is normally expressed as a fraction of synchronous speed.

19. **Torque:** The turning force of an electric motor which is transferred to the rotation of the compressor. The amount of torque supplied by an electric motor is a function of the current density (J) and the strength of the magnetic field (B).

20. **Commutation:** Transition between on- or off-states of a particular solid state device (diode, thyristors, transistor, etc.) in a variable frequency drive.

List of Variables

f = frequency, in Hz
HP = horsepower
I = current, in Amps
k = K-factor utilized to correct voltage
LRA = locked rotor current, in amps
N = running speed, in rpm
Na = actual speed, in rpm
Ns = synchronous speed, in rpm
p = number of poles
Pa = Apparent Power, in volt amps
P_{real} *= Real Power, in watts*
PF = power factor
S = slip speed
SCR = short circuit ratio
T = torque, in ft-lbs
V = voltage
X = reactive impedance
Z = total impedance

Primary Equations

Short circuit ratio is given by:

$$SCR = \frac{Fault\_current}{Load\_current} \tag{1}$$

Transformer impedance:

$$Z\%) = \frac{Voltage\_rise*}{Voltage\_primary} \tag{2}$$

* Voltage rise required to give 100% full load current in a short circuited secondary.

Apparent Power is the defined input power provided to the electric motor or motor drive system in terms of supply voltage and current:

For a single phase system, $Pa = V \cdot I$ For 3 phase $Pa = 1.732V.I$ (3)

Apparent Power is composed of reactive power (non-working power) and real power (power supplied to motor) and may be computed as:

$$Pa = \sqrt{P_{real}{}^{2} + X^{2}} \tag{4}$$

Power Factor is the ratio of real power to apparent power. Power Factor is computed as:

$$PF = \frac{P_{real}}{Pa} = \frac{Watts - in}{k \cdot V_{line} \cdot Amps_{line}} \tag{5}$$

The *k* factor equals 1.732 for three-phase motors and 1.0 for single-phase motors (not as common for gas compressor applications).

The rotational speed of all AC motors is determined by the supply frequency and the number of poles. For induction motors, the slip speed also influences the actual speed:

$$N_a = \frac{120 f}{p} \cdot (1 - S) \tag{6}$$

Where *S* = slip speed ratio is defined as:

$$S = \frac{(N_s - N_a)}{N_s} \tag{7}$$

For synchronous motors, slip speed is equal to zero and the speed is determined by the supply power frequency and the number of poles on the motor:

$$N_{syn} = N_a = \frac{120 f}{p} \tag{8}$$

For three-phase AC systems, the power factor is computed as:

$$PF_{3-phase} = \frac{P_{in}(Watts)}{\sqrt{3} \cdot V \cdot I} \tag{9}$$

The motor torque is a function of both the compression power required and the speed of rotation given by:

$$T = \frac{HP * 5250}{rpm} \tag{10}$$

The motor efficiency can be defined in terms of the actual power delivered by the shaft divided by the real power supplied to the motor:

$$n = \frac{shaftpower}{realpower} \tag{11}$$

The locked rotor current may be calculated based on the allowable Locked Rotor *kVA*/*hp* value, the motor voltage and the horsepower rating as follows:

$$LRA = \frac{1000 \cdot P \cdot LR - kVA / hp}{\sqrt{3} x V} \tag{12}$$

The cross product defines the force of the magnetic field:

$$F = J \times B \tag{13}$$

Torque is commonly expressed in inch-lb:

$$T = HP * \frac{63{,}024}{N} \tag{14}$$

Torque expressed in ft-lb is calculated as:

$$T = HP * \frac{5{,}252}{N} \tag{15}$$

APPENDIX A-2: CHECKLIST FOR ELECTRIC MOTOR DRIVE DESIGN

Electric Motor Drive Equipment: Guideline Checklist

Operating company to fill in all blue cells

1. Primary Drive Train Components

	← **Other Primary Components** →			
Motor Type: ↓	**VFD LCI type**	**VFD PWM type**	**VSHD**	**Gearbox**
Synchronous Wound				
Synchronous PM				
Induction				
High Speed Induction				
		Expected Speed Ratio(s):		
		Lube Oil Requirements?		
Harmonic Frequencies and Amplitudes provided for speed range?				
Output Filter Required?				
Guideline comments:	** Not recommended for reciprocating compressors. Output filter may be required for centrifugals.*	*Output filter may be required.*		

2. Compressor Application:

	Centrifugal	**Reciprocating**	**Other:**
Select EM Application:			
Speed Range:			
Power Range:	*(Provide Power vs. Speed Curves and Motor Capability)*		
Torque Range:	*(Provide Torque vs. Speed Curves and Motor Capability)*		
Expected % variation in power based on operating conditions			
Unloading / Capacity Control Method(s)			
Typical capacity control methods:	*1= Speed Variation,* *2= IGV's*	*1= Speed Variation,* *2= Pockets,* *3= Active valve control,* *4= Cyl unloader*	
EM power / torque sufficient over speed range?	See Section 6.0	See Section 7.0	

3. Select Start-up Method (See Section 5.0)

	Selection	Guideline Reminders
Method 1: Across the Line Start		Assure minimum SCR okay. Induction motors will be more easily started ATL.
Method 2: Soft Start with Full Size VFD		Different VFD types will implement soft starts according to hardware available.
Method 3: Small VFD Sized for Starting		Consider when motor runs fixed speed.
Method 4: Smaller Starter Motor at Reduced Load		Assure unloading method available.
Method 5: Smaller Starter Motor with Torque Converter		
Method 6: Lower Voltage Options at Reduced Load		Assure unloading method available.

4. Electrical Power System Considerations:

	Specification	Guideline Reference
Minimum Short Circuit Ratio		See Section 2.1.1
Transformer Impedance at Substation		See Section 2.1.2
Power Factor Penalty?		See Section 2.2.3
Estimated Startup SCR		
Voltage Drop estimated at start-up		
Startup Method Acceptable?		

5. Required Rotordynamic Analyses: ***(Recommended analyses are marked with X.)***

	Torsional Steady State Analysis	Torsional Forced Response Analysis	Transient Torsional Analysis (Start-up, Short Circuit Events)	Lateral Analysis
EM-Reciprocating Compressor Application	X	X	See Section 4.1	See Section 4.1
EM-Centrifugal Compressor Application	X	See Section 4.1	X	X
Gearbox Applications	X	See Section 4.1	X	X

6. Other Drive Train Components:

	Specification	Guideline Reference
Bearings		See Section 2.3.2 - choose from fluid film, tilting pad, rolling element or magnetic
Added thrust bearing?		See Section 2.3.2.5
Coupling		See Section 2.3.3 - choose from flanged, disc pack, elastomeric, belt drive
Lube oil system		See Section 2.7.1

7. Other Selection Factors:

	Specification	Guideline Reference
Service Factor		See Section 2.2.1
Service Conditions		See Section 2.2.2
Ambient Temperature Range		
Insulation Class		See Section 2.2.10
Enclosure Type		See Section 2.2.8
Skid-mounted?		
Frame Size		

APPENDIX A-3: LIST OF REFERENCES

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