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958™

IEEE Guide for the Application of AC Adjustable-Speed Drives on 2 400–13 800 V Auxiliary Systems in Electric Power Generating Stations

IEEE Power Engineering Society

Sponsored by the
Energy Development and Power Generation Committee

IEEE

Published by
The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

1 June 2004

Print: SH95138
PDF: SS95138

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IEEE Std 958™-2003

IEEE Guide for the Application of AC Adjustable-Speed Drives on 2400 to 13 800 V Auxiliary Systems in Electric Power Generating Stations

Sponsor

Energy Development and Power Generation Committee
of the
IEEE Power Engineering Society

Approved 12 June 2003

IEEE-SA Standards Board

Approved 17 September 2003

American National Standards Institute

Abstract: A fundamental understanding of the operation, selection, and application of ac adjustable-speed drives on 2400 to 13 800 V auxiliary systems in electric power generation stations are provided in this guide. This guide applies to dc link type, ac adjustable-speed drives (ASDs) and does not address other drive systems such as cycloconverters. Included are overviews of ASD terminology, theory of operation, and a discussion of the factors that can influence equipment selection. Also defined are drive system classifications, design considerations, the interactions between the ASD and the electric supply system and the driven load, economic evaluation approaches, and typical applications. Finally, guidance on ASD specifications and installation are provided.
Keywords: adjustable-speed drive (ASD) systems

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Print: ISBN 0-7381 3708-1 SS95138
PDF: ISBN 0-7381 3709-X SH95138

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Introduction

(This Introduction is not a part of IEEE Std 958-2003, IEEE Guide for the Application of AC Adjustable-Speed Drives on 2400 to 13 800 V Auxiliary Systems in Electric Power Generating Stations.)

When work on this guide started several years ago, electric utilities were somewhat handicapped in efforts to retrofit existing coal, gas, and nuclear-fueled power plant motor-driven processes with adjustable-speed drives (ASDs). The economic rules required that any energy saving dollars produced be passed on to ratepayers, rather than to investors. That picture has changed now with electric utility deregulation. Many utilities are buying and selling the older generating units and are becoming transmission companies, or generation companies using newer and much more efficient combined cycle units. Even business speculators are acquiring standby simple-cycle gas turbine generators for use when the market price for electricity rockets.

Owner investors of older technology coal, gas, and nuclear power plants can now benefit from making their plants more efficient by retrofitting the large fans and pumps, typical for these plants, with ASDs. Thus, with deregulation, this guide is now topical for utilities. The material in this guide is also useful for other industries that have applications of electric motors with large power ratings, such as petroleum refineries, natural gas pipelines, chemical producers, and copper and gold mines. Low-voltage technology generally uses insulated gate bipolar transistor (IGBT) switching devices in the inverter or voltage source applications. Motor insulation problems that may exist at low voltages do not transfer over to medium-voltage motors driven by ASDs. Low-voltage ASDs are now available up to 750 kW. If power plants are to make major gains in efficiency, both low-voltage and medium-voltage ASDs may need to be applied. Some ASD manufacturers are using the low-voltage ASD as a building block to construct medium-voltage ASDs. Hopefully this guide will clarify this concept.

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The work to draft this guide was started in 1990 and has incorporated the evolving electronic configurations of ASDs and power generating station interface issues. Throughout this guide's development, coordination and liaison were conducted with the IEEE Power System Relaying Committee, the IEEE Station Design Subcommittee, and the Industrial Applications Society.

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IEEE Guide for the Application of AC Adjustable-Speed Drives on 2400 to 13 800 V Auxiliary Systems in Electric Power Generating Stations

1. Overview

1.1 Scope

This guide applies to dc link type, ac adjustable-speed drives (ASDs) as illustrated in Figure 1 and does not address other drive systems such as cycloconverters. The guide is intended to cover the application of drive systems for use in electric power generation stations designed for connection to electric service rated between 2400 V and 13 800 V.

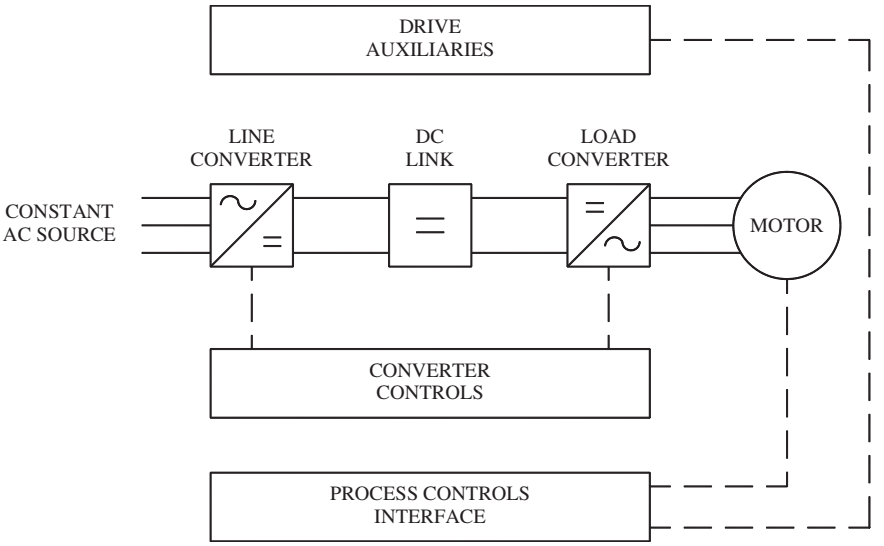


Figure 1—DC linked ac adjustable-speed drive system

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The guide includes ASD terminology, theory of operation, and a discussion of the factors that can influence equipment selection. It also defines drive system classifications and addresses typical applications. Drive system design considerations, the interactions between the ASD and the supply system, and the driven load are also discussed. Finally, guidance on ASD specifications and installation are provided.

1.2 Purpose

The purpose of this guide is to provide a fundamental understanding of the operation, selection, and application of ASDs for use in electric power generation plant motor-driven systems connected to electric service rated at 2400 V to 13 800 V.

2. References

The following standards and guides are from the American National Standards Institute (ANSI), Institute of Electrical and Electronics Engineers, Inc. (IEEE), and the National Electric Manufacturers Association (NEMA). Whenever reference is made to a standard or guide that is superseded by an approved revision, the latest revision shall be used.

ANSI C37.20-1978, American National Standard Switchgear Assemblies and Metal-Enclosed Bus.[1]

ANSI C50.41-2000, American National Standard Polyphase Induction Motors for Power Generating Stations.

IEEE Std 112™-1996, IEEE Standard Test Procedure for Polyphase Induction Motors and Generators.[2,3]

IEEE Std 115™-1995, IEEE Guide: Test Procedures for Synchronous Machines—Part I: Acceptance Performance Testing; Part II: Test Procedures and Parameter Determination for Dynamic Analysis.

IEEE Std 444™-1973(W), IEEE Standard Practices and Requirements for Thyristor Converters for Motor Drives—Part 1: Converters for DC Motor Armature Supplies.[4]

IEEE Std 519™-1992, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.

IEEE Std 995™-1987(W), IEEE Recommended Practice for Efficiency Determination of Alternating-Current Adjustable-Speed Drives—Part I: Load Commutated Inverter Synchronous Motor Drives.[5]

IEEE Std C37.96™-2000, IEEE Guide for AC Motor Protection.

IEEE Std C57.12.00™-2000, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

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[4]IEEE Std 444-1973 has been withdrawn; however, copies can be obtained from Global Engineering Documents, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. +1 303 792 2181 (http://global.ihs.com/).
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IEEE Std C57.12.01™-1998, IEEE Standard General Requirements for Dry-Type Distribution and Power Transformers Including Those with Solid Cast and/or Resin Encapsulated Windings.

IEEE Std C57.110™-1998, IEEE Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents.

NEMA MG-1-1998, Motors and Generators.[6]

3. Definitions

This clause contains definitions used in this guide and are provided to establish a common terminology for ASDs. Many of these terms and other electrical terms used in this guide are defined in *The Authoratative Dictionary of IEEE Standards Terms*, Seventh Edition [B18].[7]

3.1 adjustable-speed drive: An electric drive designed to provide easily operable means for speed adjustment of a motor within a specified speed range.

3.2 base operating point: Base operating point for motors defines a reference operating point at a specified speed, frequency, fundamental voltage or current, and torque.

3.3 base speed: The lowest speed obtained at rated load and rated voltage at the temperature rise specified in the rating.

3.4 channel: A single path for transmitting electric signals, usually in distinction from other parallel paths.

3.5 characteristic harmonic: Those harmonics produced by semiconductor converter equipment in the course of normal operation on the ac input side of the converter. In a six-pulse converter, the characteristic harmonics are the nontriplen odd harmonics, for example, the 5th, 7th, 11th, 13th, and so on. In a twelve-pulse converter, the characteristic harmonics are the 11th, 13th, 17th, 19th, and so on.

3.6 commutation: The transfer of the current from one converter switching branch to another.

3.7 converter: An operative unit for electronic power conversion, comprising one or more electronic switching devices and any associated components, such as transformers, filters, commutation aids, controls, and auxiliaries.

3.8 current limiting: An overload protection mechanism that limits the maximum rms output current to a preset value, and automatically restores the output when the overload is removed.

3.9 displacement power factor: The ratio of the active power of the fundamental wave, in watts, to apparent power of the fundamental wave, in volt-amperes, that is required by the drive at the connection point.

3.10 drive motor: The equipment used for converting available power into mechanical power suitable for the operation of a machine.

3.11 drive system: Combination of the power converter (controller), motor, isolation element, and any motor mounted devices.

3.12 dynamic braking: A system of electric braking in which the excited machine is disconnected from the supply system and connected as a generator, the energy being dissipated in the winding and, if necessary, in a separate resistor.

3.13 efficiency: The ratio of load power to the total line power including the contribution of harmonics and auxiliary equipment.

[6]NEMA publications are available from Global Engineering Documents, 15 Inverness Way East, Englewood, CO 80112-5704, USA (http://global.ihs.com/).
[7]The numbers in brackets correspond to those of the bibliography in Annex A.

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3.14 electric service source: The electrical network to which the drive is connected.

3.15 flexible shaft system: Represents a shaft rotor combination when supported by bearings, an oil film, bearing brackets, or pedestals, housing and installed on a mounting base or foundation of defined stiffness that has a mechanical resonance below the minimum operating speed or within the operating speed range.

3.16 fundamental efficiency: The ratio of the fundamental load power to the fundamental line power.

3.17 harmonic distortion (voltage and current): Nonlinear distortion of a system characterized by the appearance in the output of harmonics other than the fundamental component when the input wave is sinusoidal.

3.18 harmonic distortion factor: The ratio of the root-mean-square (rms) value of all the harmonics to the rms value of the fundamental.

3.19 harmonic filter: A generic term used to describe equipment whose purpose is to reduce the harmonic voltages impressed upon specific parts of an electrical power system.

3.20 harmonics: A sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency.

3.21 interaction: A direct or indirect effect of one device or system upon another.

3.22 inverter: A machine, device, or system that changes direct-current power to alternating-current power.

3.23 motor base rating: When a motor is applied to an inverter, the motor base rating shall be the nameplate power rating, voltage, frequency, speed, and torque.

3.24 noncharacteristic harmonic: Those harmonics that are not produced by semiconductor converter equipment in the course of normal operation. These may be a result of beat frequencies, a demodulation of the characteristic harmonic and the fundamental component, unbalance in the ac power system, or unsymmetrical control of the converter. An inadequately designed dc link filter allows inverter harmonics into the electric service supply.

3.25 power system: The electric power sources, conductors, and equipment required to supply electric power.

3.26 pulse: The number of repetitive similar waveforms in the dc voltage output of the converter per cycle of alternating input voltage.

NOTE—See Kimbark [B20].

3.27 regenerative braking: A form of dynamic braking in which the kinetic energy of the motor and driven machinery is returned to the power supply system by means of the ASD's input converter.

3.28 rigid shaft: A shaft rotor combination when supported by an infinitely stiff support system, results in a primary mechanical resonance above the maximum defined operating speed.

3.29 rigid shaft system: Represents a shaft rotor combination when supported by bearings, an oil film, bearing brackets or pedestals, and housing and installed on a mounting base or foundation of defined stiffness, which has a primary mechanical resonance above the maximum defined operating speed.

3.30 speed range: All the speeds that can be obtained in a stable manner. The speed range is generally expressed as the percent of rated speed for the minimum to maximum operating speed.

3.31 stability: The ability of a drive to operate a motor at constant speed (under varying load), without *hunting* (alternately speeding up and slowing down). It is related to both the characteristics of the load being driven and electrical time constants in drive regulator circuits.

3.32 synchronous speed: The motor speed in r/min defined by frequency and number of poles, $n = 120f/p$, where p is the number of poles.

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4. Overview of ac adjustable-speed drive systems

4.1 Basic adjustable-speed drive system

The basic power electronic adjustable-speed drive system is shown in Figure 1. The drive system consists of line and load converters connected by a dc link with a synchronous or an induction motor. The function of the dc linked converters is to convert the input ac voltage and frequency to an adjustable magnitude and frequency output voltage and current for the connected motor. The application of adjustable frequency voltage to either type of motor will result in adjustable speed and torque operation of the motor.

4.2 Principles of operation

AC machines are designed to operate at some maximum level of flux. The fundamental equation, Equation (1), governing the relationship of magnetic flux (φ), voltage, and frequency is (Fitzgerald et al. [B6]):

$$\varphi = E/(kf) \tag{1}$$

where

E is the per phase rms voltage applied,

f is the frequency of the applied voltage,

k is a constant based on the design of the machine.

To ensure the motor is operated within its designed magnetic flux density, the controls of the ASD are generally designed to limit the voltage to frequency ratio (V/Hz) to rated values or less. This mode of operation is commonly referred to as a *constant volts per hertz* operation.

The following derivation of machine characteristics from a variable voltage and frequency source were based on neglecting saturation, stator resistance, and skin effect.

4.3 Synchronous motors

The derivation for the following expressions for the output torque of a synchronous motor as a function of the source and internal voltages and frequency are presented in Annex B:

$$T = k_{s1}(E_s/f)(E_i/f)\sin\delta \tag{2}$$

where

T is the output torque of the motor (N·m),

E_s is the per phase magnitude of the source voltage (V),

E_i is the per phase magnitude of the self generated EMF produced by field excitation (V),

f is the frequency (Hz),

δ is the power angle (radians),

k_{s1} is a constant based on the motor (see Annex B).

From Equation (2) it is apparent that if the ratios of E_s/f and E_i/f are held constant, the torque output at any frequency (speed) will be the same as for rated voltage and frequency operation.

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For adjustable-speed operation, the line converter dc output establishes the level of load converter output voltage. If the motor field excitation current is held constant, then the motor's self-generated EMF produced by the field current (E_i) will vary directly with motor speed and the ratio of E_i/f will remain relatively constant. Thus, the motor torque output becomes independent of frequency (speed) and is dependent only on the power angle (δ) (see Figure 2).

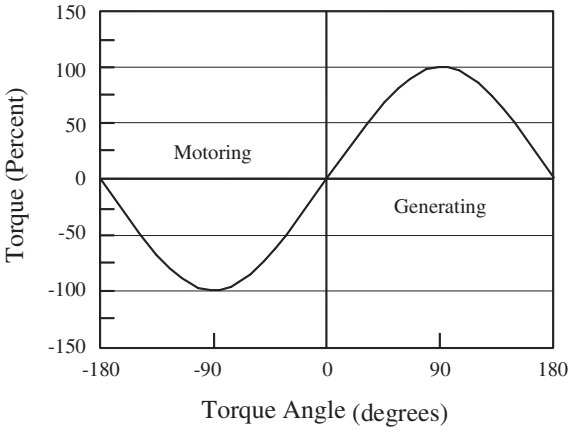


Figure 2—Torque angle characteristic for synchronous machines

If the motor field excitation (E_i) is controlled by varying the magnitude of the field current, then additional control of the motor torque is realized (see Figure 3). In applications requiring high acceleration rates, the excitation can be increased above normal, resulting in considerable accelerating torque. Similarly, rapid deceleration rates can be obtained by decreasing the level of excitation. Another benefit of excitation control is the maximization of motor efficiency, input power factor and optimizing the sizing of the converters (Rosa [B31]).

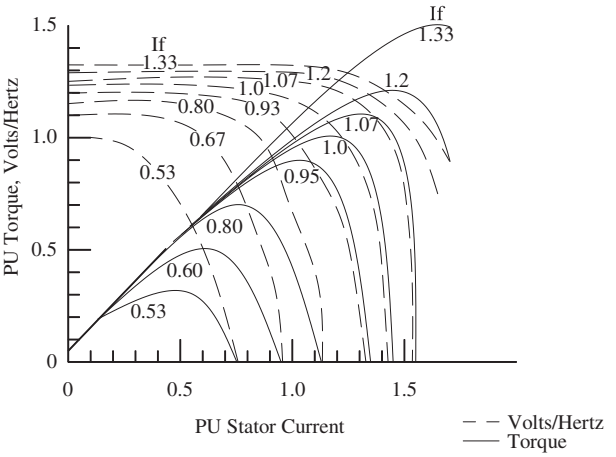


Figure 3—Torque characteristics of synchronous motor supplied from an adjustable-speed drive (Owen and Weiss [B30])

The following expression, Equation (3), for motor output torque as a function of the source V/Hz and the input current is also derived in Annex B:

$$T = k_{s2}(E_s/f)I\cos\beta \tag{3}$$

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where

I is the stator current (A),

β is the angle between the applied voltage and the current,

k_{s2} is constant based on the motor (see Annex B).

In general, when operating a synchronous motor from an ASD, the motor excitation is controlled such that the motor is over-excited at a fairly constant leading power factor (cos β). This mode of operation in conjunction with constant V/Hz results in the output torque varying directly with the input current.

4.4 Induction motors

The derivation for Equation (4) for the output torque of an induction motor as a function of the applied voltage magnitude and frequency is presented in Annex B:

$$T = k_i(V/f)^2(\omega - \omega_r)/r_r \tag{4}$$

where

T is the output torque of the motor (N·m),

V is the magnitude of the source voltage (V),

k_i is a constant based on the motor (see Annex B),

r_r is the rotor resistance (Ω),

f is the frequency (Hz),

ω_r is the speed of the rotor (radians/s),

ω is the synchronous speed of the motor (radians/s) defined by Equation (5):

$$\omega = 4\pi f/p \tag{5}$$

where p is the number of poles of the motor.

Equation (4) shows that the output torque of an induction motor is proportional to the square of the ratio of supply voltage to supply frequency, and the difference between synchronous speed and actual rotor speed ($\omega - \omega_r$) at the operating frequency. If the source V/f is equal to the rated value the familiar torque–speed curve of the induction motor is obtained (see Figure 4). However, by utilizing other values of source frequencies an infinite number of torque–speed curves can be produced. Figure 4 shows several examples. When operating an induction motor from an ASD, the objective is to control the output V/Hz such that the steady-state output torque produced by the motor is to the right of the maximum torque. This region offers the most efficient operation and maximizes the torque per ampere input of the motor (Finney [B5]). Thus, through varying the voltage and frequency at the terminals of the motor, the torque output can be varied to match the requirements of the load (see Figure 4).

5. Motivation for applying adjustable-speed drives

5.1 Process efficiency

Often, the best method of controlling a process is by controlling the speed of the motor. For example, Figure 5 shows how the flow of a typical centrifugal pump or fan varies linearly with speed. The corresponding torque and power required by the fan vary approximately with the square and cube of

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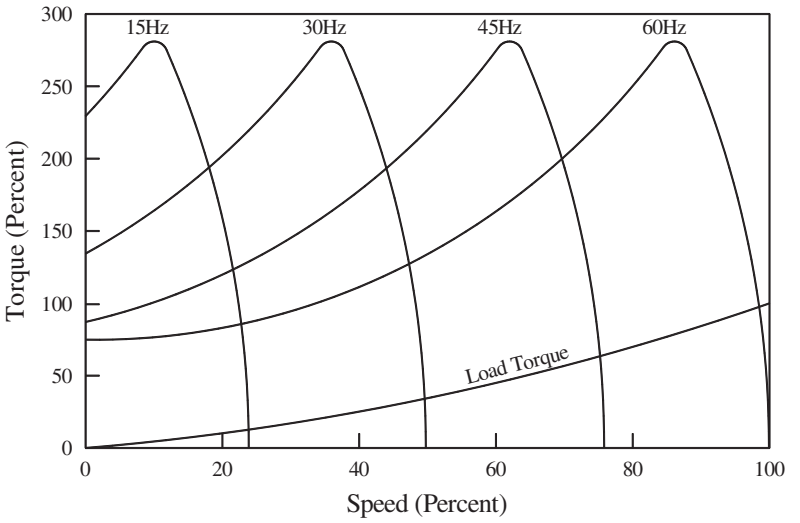


Figure 4—Torque–speed characteristics for induction motor supplied from a variable voltage and variable frequency source (Note that the effects of stator resistance are neglected.)

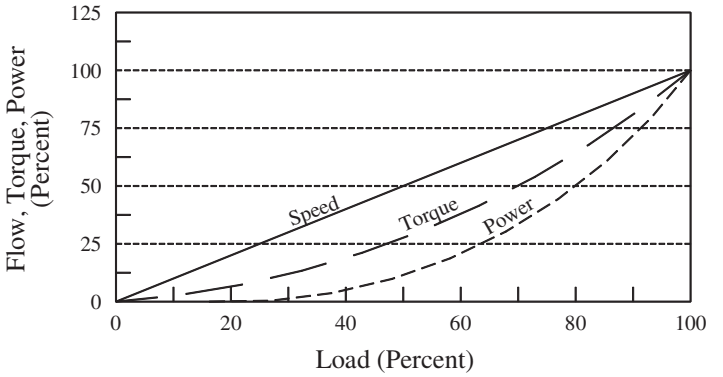


Figure 5—Typical centrifugal pump or fan flow, torque, and power characteristics as a function of speed

speed, respectively. Thus, if the speed of the fan can be controlled directly, a considerable power saving can be realized at reduced fan load over other methods of flow control such as mechanical throttling. The net result is an improvement in overall process efficiency. Figure 6 provides a comparison of the efficiency for the more common methods of controlling the outputs of large centrifugal fans typically found in generating stations (Gripp [B7]). The ASD provides the best overall efficiency over the broadest operating range. A pulse-width modulated (PWM) type drive will have a higher efficiency at low fan loads than a load commutated inverter (LCI) type drive. The potential gains in process efficiency and the corresponding saving in energy consumption and operating cost are the dominant motivating factors for applying ASDs. The following provide common examples of these savings.

5.1.1 Boiler draft fans

Boiler draft fans and thus the drive motors are typically oversized. The fan commonly has two ratings; test block (TB) and maximum continuous rating (MCR). The power demand for the TB rating

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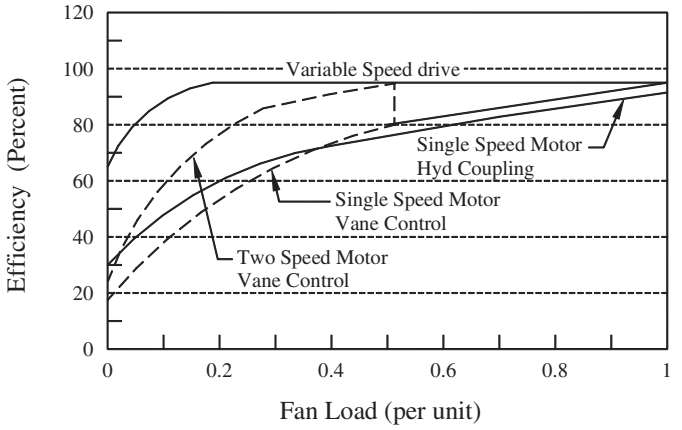


Figure 6—Comparison of common fan drive system efficiencies as a function of fan load (Gripp [B7])

is significantly larger than for the MCR with the MCR rating being between 60 and 75 percent of the TB rating. The TB rating is based on various contingency factors such as derivation of air or gas density especially during unit start up when the air or gas is colder than normal, draft system leakage, deviations in draft system resistance, and abnormal operation due to pluggage of draft system components. The MCR rating is based on normal full load operation of the draft system. As a result the excess fan capacity normally has to be reduced. This reduction can be accomplished by the following:

a) Constant speed motor with fan inlet vane or damper (throttling) controls
b) Two speed motors with fan inlet vane or damper controls
c) Adjustable-speed with a hydraulic coupling
d) Adjustable-speed with an ASD

Significant power savings can result from applying an ASD and eliminating the inefficiencies of the other options (see Figure 6). Additional saving can be realized when the plant and draft system loads are reduced. In fact the most significant efficiency gains are at the lower end of the load range.

5.1.2 Plant water and other pumping systems

The application of ASDs can also be beneficial to plant water, ash, and other pumping systems. Many of these pumping systems are designed based on a two out of three operating schemes. With the pumps in good working order and normal flow demand the pumps are sized such that two pumps can supply the process flow requirements. The third pump serves as a back-up for pump outages and peak flow periods. Pump wear and degradation of the system over extended periods of operation can result in insufficient flow with two pumps. When this occurs, all three pumps must be placed in service but with each operating at less than rated load. Since the flow is commonly modulated by partially closing the process low control valve considerable throttling losses are incurred in the pressure drop across the valve. ASDs can be applied in one of two ways to control system flow and improve system efficiency. The first option is to operate all three pumps at reduced speed and power to achieve the required flow. The second option is to run two pumps and motors slightly above rated speed to produce the desired flow. The second option may require operating the pumps and motors above rated speed, the potential for exceeding the capabilities of the pumps and motors may exist. The equipment manufacturers should be consulted when considering this option.

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5.2 Other benefits of ASDs

There are a variety of other benefits that ASDs offer. A brief discussion of some of the more popular examples is provided in 5.2.1, 5.2.2, 5.2.3, and 5.2.4.

5.2.1 Plant retrofits that increase auxiliary load

Many fossil fuel generating plant boilers are undergoing changes to address environmental requirements. With the addition of electrostatic precipitators to remove particulates and the addition of flue gas conditioning systems to remove sulfur from the boiler effluent (selective catalytic reduction system for NOX control), it is often necessary to increase the size of the boiler induced draft (ID) fans and forced draft (FD) fans to overcome the increased pressure drops caused by the addition of these new systems. Another boiler modification, which can result in added load on auxiliary busses, is the conversion from pressurized boiler operation to balanced draft operation. In the past, the large ID and FD fans were commonly driven by large constant speed or dual speed induction motors. In many retrofit cases it may not be feasible to add new or larger boiler fan drive motors for one or more of the reasons listed in 5.2.1.1, 5.2.1.2, and 5.2.1.3.

5.2.1.1 Motor starting

In older plants, the starting current and acceleration time of the larger across-the-line start fan motors can exceed the short-time rating of the auxiliary buswork and/or auxiliary transformers, but also can cause unacceptable voltage dips throughout the electrical distribution system. These effects can be minimized by utilizing the current limiting or *soft start* feature inherent with ASDs. Since the output torque and input current can be controlled by an ASD, the starting and acceleration currents can be significantly reduced (see Figure 7) (Higgins et al. [B10]). A secondary benefit of this *soft start* feature is the reduction of thermal and mechanical stresses on the motor windings resulting from full voltage across-the-line starting. The reduction of these stresses can extend the life of motors in plants with frequent startups.

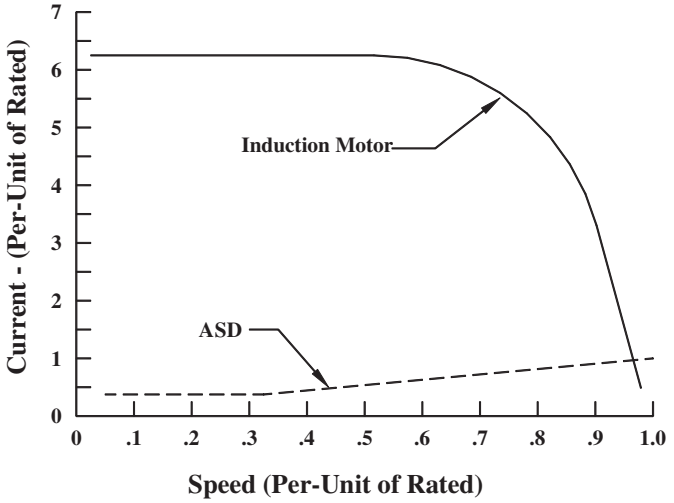


Figure 7—Comparison of current-speed curve for starting of a typical induction motor and ASD system (Higgins et al. [B10])

5.2.1.2 Short circuit

The additional fault current contribution from new larger fan motors can exceed the momentary or interrupting capability of switching equipment under short circuit conditions. This impact can be

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minimized by the application of an ASD for the new fan drives. The current limiting feature of an ASD is such that it will limit short circuit current (nonregenerating mode) to the auxiliary system (Urano and Appiarius [B34]).

5.2.1.3 Motor inertia

For large draft fans the motor cost may be much lower since a motor with constant WK^2 may be used rather than a special motor with high inertia or WK^2.

5.2.2 High-speed ASDs

There is an additional characteristic of an ASD that lends itself to certain load applications. This characteristic is high-speed operation. This feature is particularly applicable to motor driven boiler feed pumps. Boiler feed pumps are often designed to operate substantially above 3600 r/min. On motor driven pumps, speed increasers are often required to provide the higher operating speed since the maximum speeds of constant speed motors are frequently limited to 3600 r/min for 60 Hz systems with two pole motors (3000 r/min for 50 Hz systems). However, since the output of an ASD is not constrained to system input frequency, the application of an ASD can eliminate the need for the speed increaser.

There are a number of high-speed systems in industrial service worldwide, operating pumps and compressors in power ranges from 6000 to 21 000 kW with speeds of 6000 to 10 000 r/min (Oliver et al. [B27]). These ASDs are often referred to as *super synchronous* since they run at speeds higher than those obtainable with standard motors and fixed supply voltage frequencies. The introduction of high-speed motors with magnetic bearings makes speeds of 20 000 r/min feasible.

5.2.3 Other benefits for fans and pumps

There are other benefits besides improved efficiency with the application of ASDs to fans and pumps. For example, for boiler draft fans using constant speed motors and vane or damper controls, ASD operation reduces the wear on vanes and dampers and their associated linkages and drives by minimizing the amount and frequency of mechanical movement of these components. ASD operation also presents the opportunity to enhance the limits of the existing damper control range and in some cases to eliminate the control vanes altogether. Operating the fan at reduced speeds can also reduce the amount of erosion experienced on the fan blades. Both of these features will result in reduced fan maintenance cost. Finally, the ability to operate the fans at low speeds gives more stable control of fan flow during low load, off line, start up and boiler purge conditions as compared to using inlet vanes. An ASD controlled fan has the capability of better draft control compared to an inlet vane controlled fan during boiler upsets, thereby possibly eliminating a boiler trip.

In certain cases, pumps can experience cavitation problems. Pump cavitation can cause significant damage to the pump impeller requiring costly repairs and/or replacement (Oliver [B26]). An ASD can be used to modify pump operation at the flow conditions that cause the cavitation, thereby potentially eliminating the damage to the pump.

Another example where an ASD can be beneficial is in the matching of the operating speed of the fan or pump and the motor. In the case of a constant speed motor, the operating speed of the equipment is limited to that of the motor. In many cases, this speed does not correspond to the optimum speed of the fan or pump resulting in compromised system performance or requires the selection of a larger fan

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or pump at the expense of system efficiency. An ASD can be used to compensate for the mismatch in the design speed for a standard fan or pump and its application requirements.

5.2.4 Environmental and site-specific benefits

There are also a number of environmental, good neighbor, and other site-specific benefits for applying ASDs when retrofitting systems in generating stations.

5.2.4.1 Audible noise reduction

At least one utility (Oliver [B26]) applied ASDs to ID fans when residents near a newly commissioned plant complained about noise from the plant during certain periods of operation. The noise level increased significantly with the original operating speed of the ID fans because of resonance of the fan blade passing frequency with the stack. The application of ASDs permitted operation of the fans at speeds off resonance minimizing the level of noise pollution.

5.2.4.2 Fish kill

Another utility (Oliver [B26]) applied ASDs to their circulating water pump systems in order to reduce the number of fish killed by circulating water pumps. Water flow velocity was reduced at partial plant loads to minimize the number of fish pulled into the circulating water pump intake system.

6. Drive sytem economic evaluations

Many of the potential benefits of ASDs over other drive options have been discussed in Clause 5. Usually, the economics of the various options considered is the deciding factor in the selection of a particular drive system. As illustrated in Figure 6, ASDs can be more efficient than other drive options. The projected energy savings must be evaluated considering the difference in equipment, procurement, installation, and design engineering costs between the various options.

Information needed to calculate the power and energy savings for power plant generating unit pumps and fans with ASDs is as follows:

a) Annual load curve
b) Heat rate versus net generator output
c) Motor output versus net generator output, and pump and fan curves for both
    1) Fixed-speed operation
    2) Adjustable-speed operation

An example of an annual load curve is shown in Figure 8. Heat rate versus load is shown in Figure 9. Motor kW output versus unit load is shown in Figure 10. It is necessary to calculate the motor kW output versus unit load curve for adjustable speed operation. This requires the use of pump or fan characteristic curves, Figure 11 and the system resistance for the circuit under study. A typical set of data is provided in Figure 11. For pumps, any existing static head requirements are needed. The difference in motor power for fixed speed and adjustable speed is evaluated over the expected life of the plant, and is compared to the installed cost of the ASD equipment for the same time period, as shown in Figure 12.

The value of the energy savings can be conservatively valued as the fuel cost savings, or more realistically, the value of the energy, if sold on the open market.

Results of an economic calculation are shown in Table 1.

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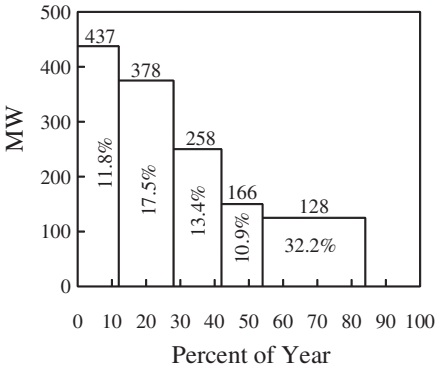


Figure 8—Load duration curve

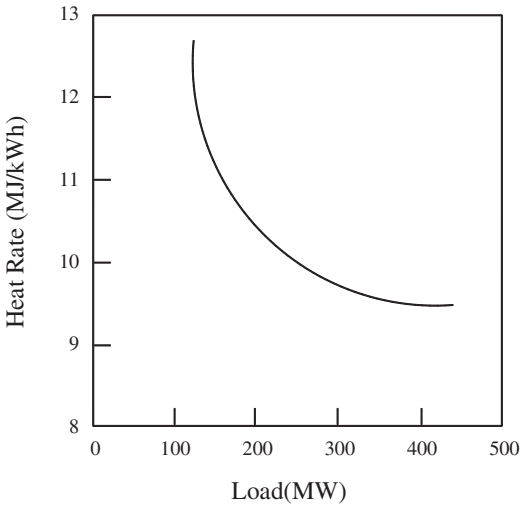


Figure 9—Heat rate versus load

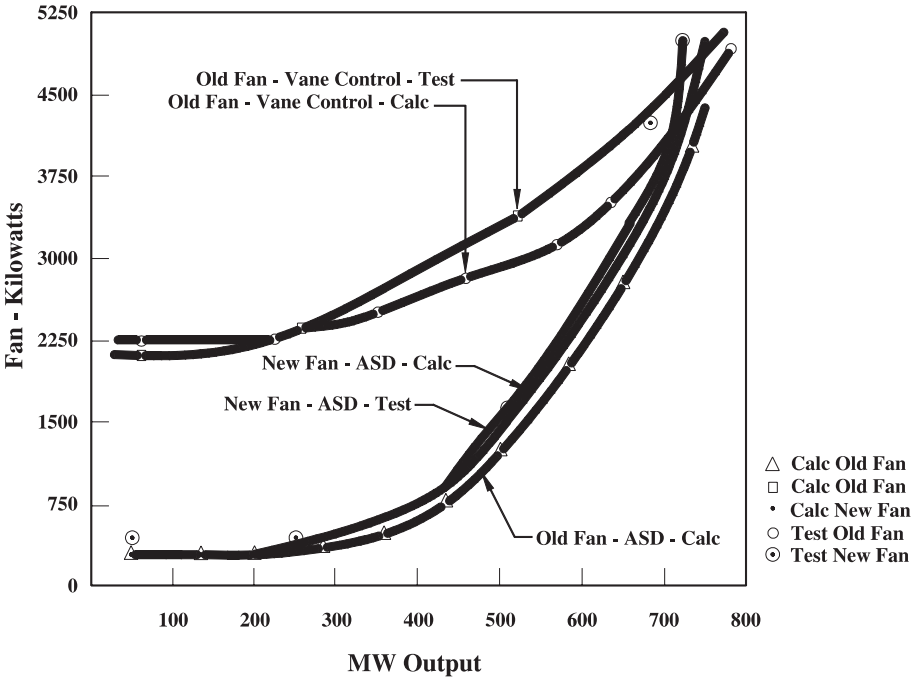


Figure 10—Typical plant FD fans/ASDs motor output power versus unit gross MW

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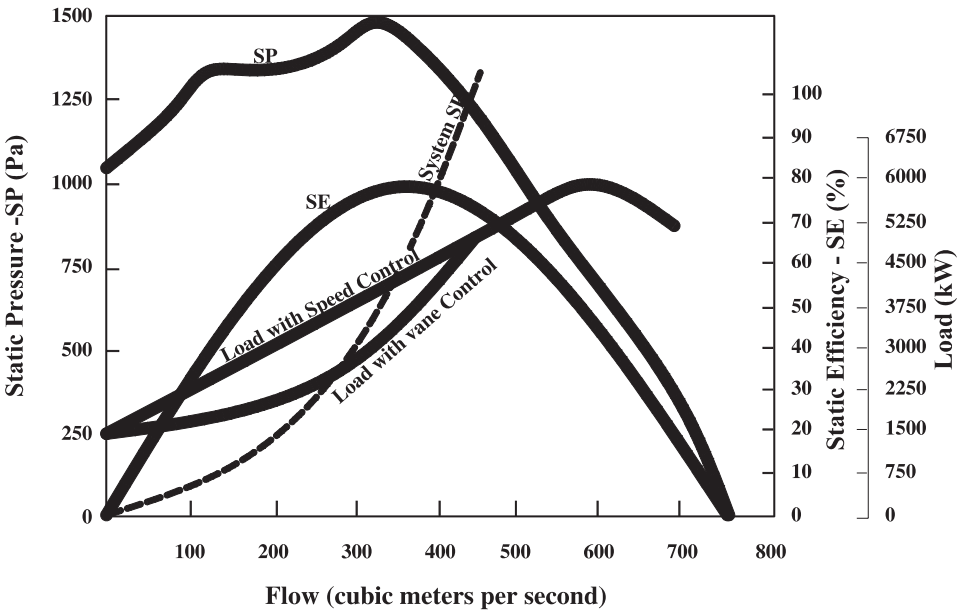


Figure 11—Forced-draft fan performance curve

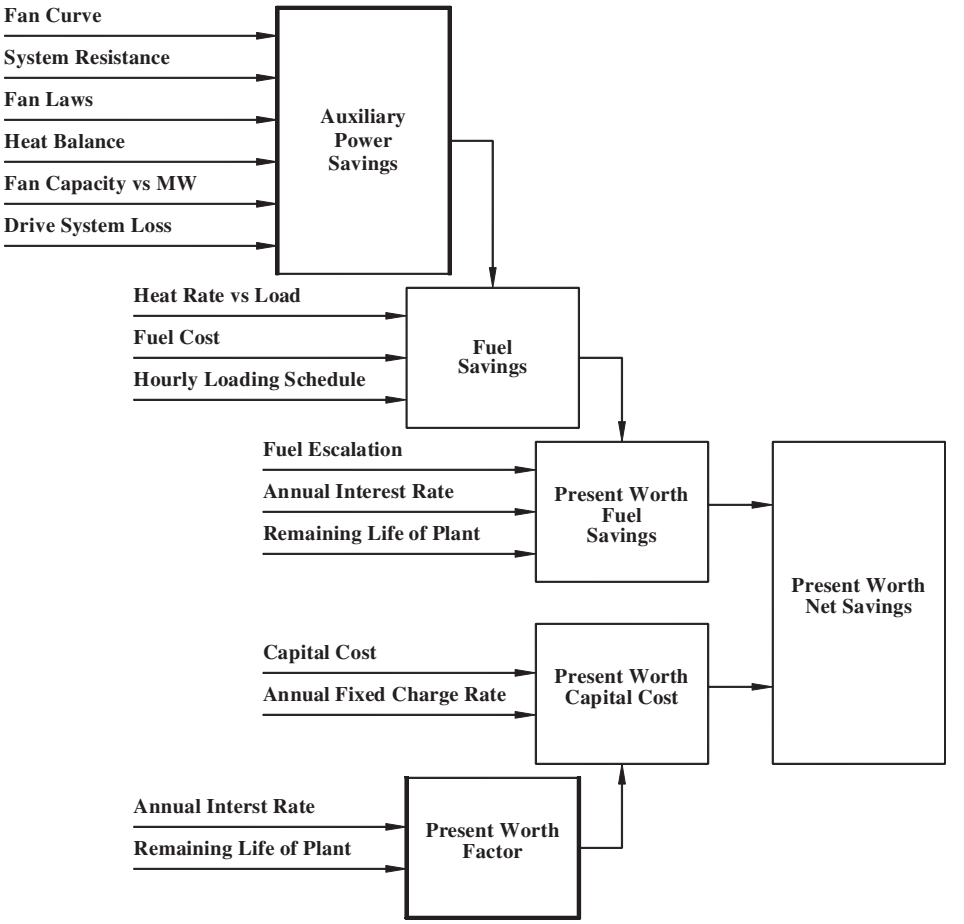


Figure 12—Present worth of energy savings flow chart

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Table 1—Energy and fuel savings for conversion of an existing induction motor to ASD operation

Unit load (MW)	Hours at load	Heat rate (MJ/kWh)	Pump capacity (m^3/s)	Motor speed (r/min)	Motor eff (%)	ASD eff (%)	Power-fixed speed (kW)	Power-ASD (kW)	Power savings-two drives (MWh)	Fuel cost savings ($1000)[a]
400	30	12.6	1490	693	0.855	0.97	4314	394	235	6.37
500	30	11.9	1535	696	0.855	0.97	4330	411	235	6.01
600	30	11.2	1885	724	0.860	0.97	4439	483	237	5.71
700	30	11.0	2945	1086	0.897	0.97	4812	1576	194	4.59
800	30	10.8	3000	1099	0.898	0.97	4827	1636	192	4.44
900	30	10.6	3540	1312	0.900	0.97	5711	2771	176	4.00
1000	30	10.3	4130	1523	0.901	0.97	6509	4333	131	2.89
1090	7830	10.34	4560	1683	0.903	0.97	6650	5832	12812	284.71

[a]Total annual fuel cost savings = $0.319 million.

Because of the importance of the economic evaluation, the following provides a general discussion of many of the factors that should be considered in an ASD evaluation. In addition, a sample economic evaluation is provided in Annex C.

6.1 Data required for economic analysis

The data listed in 6.1.1, 6.1.2, 6.1.3, 6.1.4, 6.1.5, 6.1.6, 6.1.7, 6.1.8, and 6.1.9 are required to perform an economic analysis.

6.1.1 Life expectancy

The expected life or remaining life of the plant must be determined.

6.1.2 Interest rate or rate of return and taxes

If the new ASD option involves a capital investment, the interest rate on the equipment cost and subsequent taxes based on investment is determined. In some cases the evaluation is performed using a required rate of return on the investment.

6.1.3 Load projection

The capacity factor of the plant and the projected hours of operation at various plant loadings are necessary.

6.1.4 Drive option efficiencies and power consumption

The system efficiencies and projected operations for the ASD system and the other drive system options under consideration are used to project the energy consumption of the various options.

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The energy usage may also factor into other benefits such as unit heat rate, and station service usage. These items are annual benefits.

6.1.5 Equipment cost

The installed cost of the various drive options. This cost includes the first cost of the equipment, design engineering, installation, and check-out. If a new system is being compared to an existing system any cost associated with returning the existing system back to a level of satisfactory performance should also be included.

6.1.6 Operating and maintenance (O&M) cost

Estimates of operating (excluding power consumption) and maintenance cost for the various options are necessary. These estimates should include any mechanical components and electrical auxiliaries that wear out and/or need adjusting, calibrating, or maintaining periodically. Include estimated maintenance cost (time and materials) for potentially high maintenance components that one or more of the options include that another would eliminate. In the case of evaluating a new drive option against an existing system, include the difference in estimated maintenance costs between the existing system accounting for any system components that may be added or eliminated by the new drive option. In general, these O&M costs are recurring or occur annually. However, in cases where experience has shown that certain system components require periodic rebuilds, these costs should be factored in over the life expectancy of the various options.

6.1.7 Reliability

In many cases, the degradation in the reliability of an existing system prompts the consideration of new drive options. Thus, estimates of the reliability factors between the various options should be made and the cost impacts evaluated using plant replacement energy costs where drive system operability impacts plant output.

6.1.8 Plant capacity

Any incremental capacity benefit, if the drive options provide an increase in unit capacity, and the capacity can be utilized to replace higher cost generating capacity, capacity purchased from outside sources, or serve to meet new capacity requirements.

6.1.9 Environmental

Potential environmental impact benefits including *emission allowance credits* realized as a result of the retrofit activity should be factored into the analysis.

6.2 Evaluation procedure

In order to simplify the evaluation, projections about plant operations can be divided into bands with band center operating points; for example, 50% load, 70% load, 90% load, and 100% load.

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The energy used (E_u) by the various drive options can then be computed for each operating band based on the center point [$E_{u1}(50)$, $E_{u2}(70)$, $E_{u3}(90)$, and $E_{u4}(100)$]. The annual usage is then equal to the summation of the energy used for each band multiplied by the number of hours (H) of operation for each operating band as shown in Equation (6):

$$E_{yr} = \sum_{i=1}^{n} (E_{ui})(H_i) \tag{6}$$

If plant operations are expected to change appreciably in future years a new set of bands should be developed and new energy usages computed for the corresponding time period. Other factors can be computed in similar fashion.

6.3 Evaluation methods

In order to make an economic decision on whether or not to install a particular drive option, a comparison must be made between the cost of doing the project and the benefits to be realized.

To take into account the time value of money, classical economic techniques employ compound interest rates in applying present worth factors. Some of the more common evaluation techniques are Payback Period, Net Present Value and Profitability Index (see Annex C). In general, each utility will have a preferred method of economic analysis including what factors should be included in the analysis.

A sample economic evaluation is presented in Annex C.

7. Typical ASD applications

7.1 Equipment applications

The following are typical applications of ASDs in power generating stations:

a) Forced draft fans, induced draft fans, primary air fans, and gas recirculating fans.
b) Circulating water pumps, condensate pumps, boiler feed pumps, house service water pumps, ash sluice pumps, pulverizer mills, scrubber spray and scrubber absorber pumps, and fuel oil pumps.
c) Conveyors and crushers for coal and lime handling systems.

7.2 Selection

Selection of the ASD is based on the following:

a) Application (fan, pump, conveyor, etc.)
b) Output power requirements under all modes of operation, including base speed.
c) Operating speed range.
d) Load speed–torque characteristics and inertia referred to the motor shaft speed.
e) Motor/load shaft dynamics (rigid or flexible shaft system).
f) Motor/load foundation resonance.
g) Acceleration and deceleration requirements.
h) Environmental conditions and any special considerations.

Generally, knowledge of the process dynamics and steady-state characteristics are required to determine the ASD speed–torque curves and acceleration and deceleration requirements.

Subclauses 7.3 and 7.4 discuss these characteristics for some of the most common loads.

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7.3 Fans and pumps

The fans and pumps typically used in power generating stations (see 7.1a) are either the centrifugal or axial flow type, except for the fuel oil pumps, which can be of the positive displacement type. Centrifugal and axial flow fans and pumps have essentially the same torque–speed characteristics. The torque varies as the square of the operating speed (see Figure 5). In general, the processes associated with such fans, pumps, and compressors do not require unique acceleration or deceleration characteristics. Variable torque ASDs having an adjustable speed range of 20–100% of base speed are commonly used for driving centrifugal or axial flow fans, pumps, and compressors.

Induced draft fans applied in balanced draft boiler applications sometimes require controlled deceleration to avoid boiler implosion following a flame collapse. For this reason, an ASD with forced breaking may be required.

An ASD for a large boiler fan is normally sized at the fan test block rating (maximum design loading for the fan). However, during normal operation, the drive generally operates at, or below, the fan maximum continuous rating (MCR), which can be as low as 60% of the test block rating. This characteristic may make the use of a dual channel ASD attractive. By sizing each channel for 60% of the fan test block, the fan can be continuously operated at or near MCR with the failure of one channel. See Clause 9 for further discussion on drive configurations.

For all types of displacement pumps, the flow varies directly with the speed regardless of the head pumped against. Displacement pumps used for pumping heavy fuel oil operate at essentially constant head and require practically constant driving torque at all speeds. This application does not require unique acceleration or deceleration characteristics. A constant torque ASD without regeneration capability may be used for driving a positive displacement fuel oil pump at variable speeds for energy saving.

Fans typically have high inertias on the order of 10 to 20 times standard values (Smeaton [B33]). Pumps on the other hand generally have low inertias less than or equal to standard values.

7.4 Conveyors and crushers

In general, both of these loads have similar speed–torque characteristics. The torque demand varies significantly if they are started loaded or unloaded.

Figure 13 shows a typical speed–torque curve for a loaded and unloaded conveyor. This load variance results from the amount of material on the belt. If the conveyor is loaded during starting, the ASD must provide high starting torques to overcome the static forces and accelerate the loaded conveyor to running speed within the time limits imposed by the motor thermal capability. Conversely, the accelerating torque must be limited such that the conveyor belt is not subjected to excessive tension stresses that may break the belt during starting and acceleration. Also, braking means are required to quickly stop the loaded conveyor in the event of an emergency. When the belt is a part of a system where one or more belts can coast a greater distance than others, special stopping features are required to prevent flooding of transfer points. These characteristics make an ASD with constant speed–torque characteristics and controlled regenerative capability preferred for driving belt conveyors.

Crushers are normally started unloaded and do not require a high starting torque. However, abnormal events such as a power failure or trips due to overload can result in a shut down of a fully loaded crusher (see Figure 14). To reduce the need for removing material from the crusher upon subsequent starting, a high starting torque motor is normally used. These characteristics make an ASD with high starting torque capability and constant speed–torque capability the preferred application.

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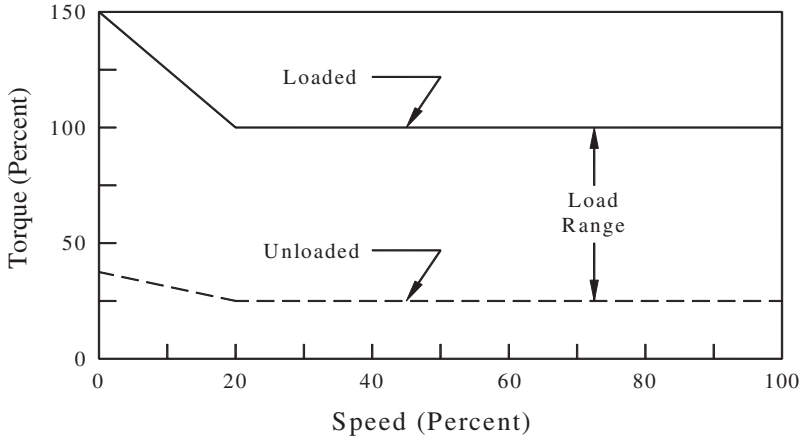


Figure 13—Typical speed–torque curve for conveyor

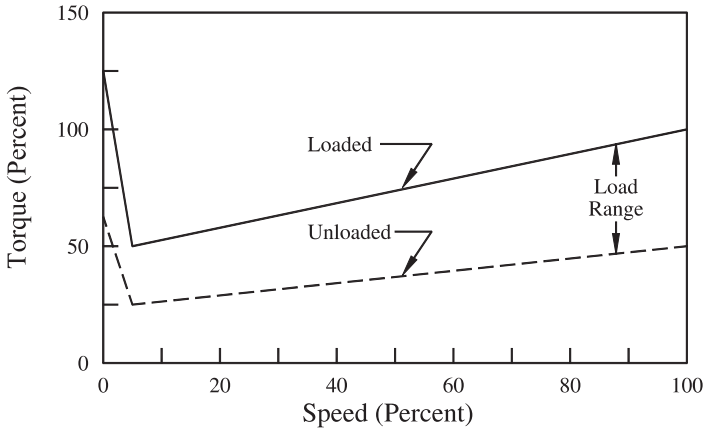


Figure 14—Typical speed–torque curves for crusher

The inertia of these loads can range from three to ten times the nominal NEMA load inertia. The value for the conveyor is generally on the lower end of the range with the crusher up near the top of the range (Smeaton [B33]).

8. Types of adjustable-speed drives

8.1 DC linked converters

Figure 15 depicts the two most popular dc linked converters, the voltage source, and current source types. Each consist of the basic functions, namely, a converter section, an inverter section, and a dc link connecting the two. The converter section changes ac 60 Hz power into dc power. The dc circuit is called the *dc link*. The inverter section is used to change the dc power into adjustable frequency ac power for the motor circuit. Their differences are in the configuration of their respective dc links. The voltage source inverter (VSI) is shown in Figure 15a) with its dc link capacitor, which behaves as a fairly stiff and controlled voltage supply to the connected inverter. The current source inverter (CSI) is shown in Figure 15b) with its dc link inductor, which behaves as a well regulated current supply to its connected inverter. In both ASDs, the input converter is sometimes called the *front-end* and consists of

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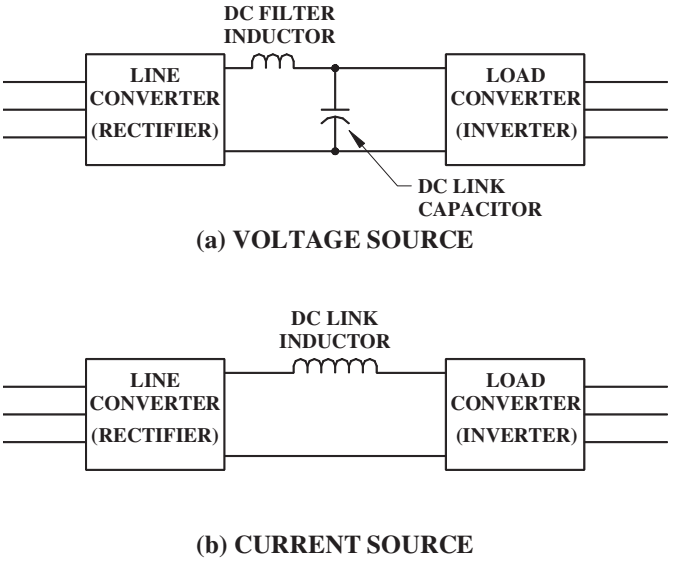


Figure 15—Types of dc linked converters (Hassan [B9])

power switching devices and logic controls. In medium-voltage ASDs the converter is used to control the voltage and/or current to the inverter section to maintain the proper V/Hz ratio from the inverter.

8.2 Line converter circuits

8.2.1 Uncontrolled line converters

Figure 16 shows an uncontrolled line converter. In this type of converter, the primary power semiconducting devices are rectifier diodes. The basic three-phase uncontrolled converter consists of six sets of diodes connected to a three-phase source and produces a dc output voltage proportional to the magnitude of the ac input source phase voltages. The magnitude of the average dc output voltage neglecting voltage drops and commutation effects is shown in Equation (7) (Lipo and Novotny [B21]):

$$V_{d0} = 1.35V_{L-L} \tag{7}$$

where V_{L-L} is the line to line rms voltage of the source.

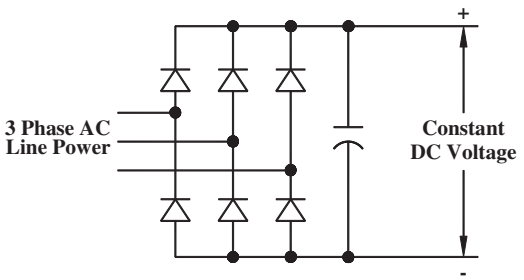


Figure 16—Uncontrolled line converter (Oliver [B26])

The uncontrolled line converter develops a constant dc output voltage. When this type of converter is utilized in an ASD, the load side converter must produce for the variable voltage or current requirements of the motor (Oliver [B26]).

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A sample converter output voltage is shown in Figure 17. When supplying a load, the no-load voltage is reduced by the current dependent voltage drops across the source resistance, the source reactance, the two conducting diodes, and commutation overlap (Finney [B5]). The dc output voltage contains a ripple voltage with a frequency of six times the source frequency and is caused by the natural switching (commutating) of the diodes between pairs of source phase voltages. As a result, the three-phase ac to dc converter is commonly referred to as a *six-step* or *six-pulse converter* (Kimbark [B20]).

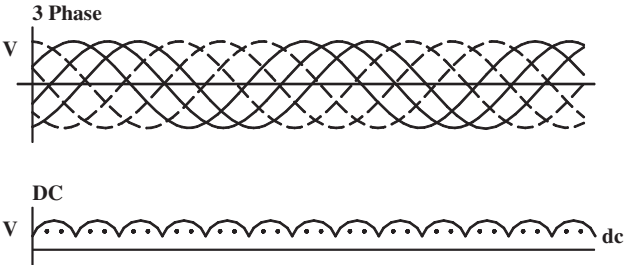


Figure 17—Sample average uncontrolled line converter output voltage (Oliver [B26])

The switching or commutation of the diodes occurs naturally as the relative instantaneous phase voltage magnitudes across the diodes change with time. Thus, commutation is controlled by the source or line voltages and the converter is said to be line commutated.

The uncontrolled line converter is not capable of supplying energy from the dc link to the source, which is desirable in applications requiring dynamic load braking through regeneration. An uncontrolled line converter is capable of supplying energy only in one direction; from the line to the dc link. The current flows from the source to the dc link, with no ability to reverse the polarity of the dc link voltage. Uncontrolled line converters are commonly utilized in ASD applications where regenerative capability is not required. If regeneration is needed, various circuit modifiers exist that permit regeneration.

8.2.2 Phase controlled line converters

Figure 18 shows a phase controlled line converter. The primary power semiconducting devices are power thyristors or silicon controlled rectifiers (SCR). The three-phase controlled converter consist of six thyristors connected to a three-phase source and produces a dc output voltage dependent on the magnitude of the ac source phase voltages and the timing of the gating signal of each thyristor. The delay in the gating signal is commonly expressed as the electrical angle α. The angle α is called the *delay angle* or firing angle and is the delay in gating of the thyristor beyond the point on the input ac

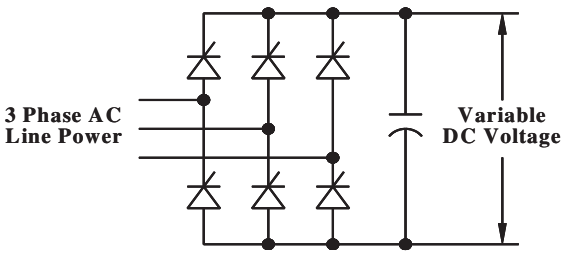


Figure 18—Phase controlled line converter (Oliver [B26])

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waveforms where a diode would naturally conduct. The magnitude of the average dc output voltage neglecting commutation effects is shown in Equation (8) (Lipo and Novotny [B21]):

$$V_{d0} = 1.35V_{L-L} \cos \alpha \quad (8)$$

Unlike the uncontrolled line side converter, the controlled line converter will develop an adjustable dc output voltage. In fact, when α ranges from 90° to 180°, the output voltage goes from 0 V to $-1.35V_{L-L}$. This feature permits regeneration from the dc link to the source from positive current and negative voltage causing a reversal in power flow from the load to the source. Typically, α is limited to a maximum delay of approximately 150° to ensure proper commutation of the thyristors. Figure 19 shows sample no-load dc output voltages for different values of α. These waveforms neglect source reactance effects. When supplying load, the average dc voltage is reduced by the current dependent voltage drops across the source resistance, the source reactance, the two conducting thyristors, and commutation overlap (Finney [B5]).

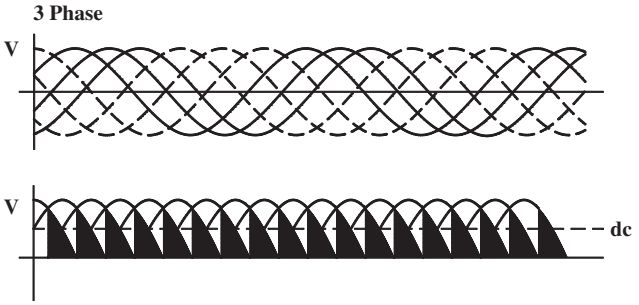


Figure 19—Sample no-load output voltage for phase controlled line converter

As with the uncontrolled line converter, phase controlled line converters are referred to as a *six-step* or *six-pulse converter*. Commutation is also controlled by the source or line voltages and the converter is line commutated.

8.2.3 Effects of line side converters on the ac source

The conversion process from ac to dc by means of solid-state rectification can cause two potential adverse effects on the ac source. These effects are distortion of the ac source voltage by the injection of harmonic currents into the ac source network and a lagging power factor. The harmonic influence on the line, particularly voltage notching resulting from commutation, is generally lower for an uncontrolled line converter than a phase controlled line converter. This difference occurs when the delay angle (α) is greater than zero, which results in commutation occurring at a higher phase-to-phase voltage (Oliver [B26]). The voltage distortion and harmonic current characteristics of ASDs and their effects on the ac source are discussed in more detail in IEEE Std 519-1992.[8]

The displacement power factor is also generally better for an uncontrolled line converter than a phase controlled line converter. This again is due to the delay angle of the controlled line converter. The input power factor for a phase controlled line converter varies linearly with the relationship of the level of the supplied dc link voltage to rated dc link voltage (see Figure 20).

The highest power factor occurs when the converter is supplying rated dc link voltage where the delay angle α equals 0° (Lipo and Novotny [B21]). Since no phase control exists with the uncontrolled line converter, the displacement power factor presented to the line is nearly constant across the design speed range of the drive.

[8]Information on references can be found in Clause 2.

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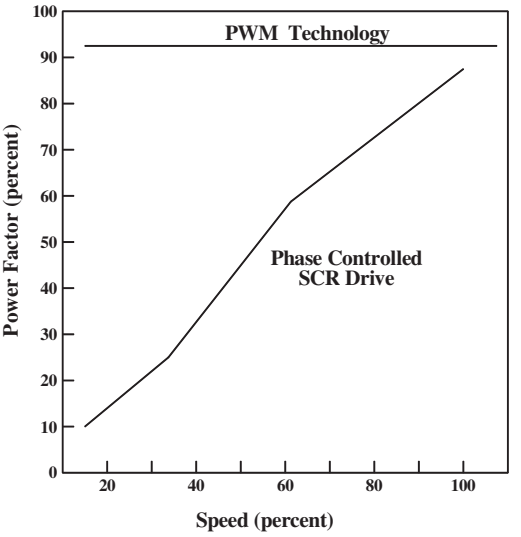


Figure 20—Comparison of power factor on line converters (Hammond [B8])

8.3 Load side converters

A variety of load side converters (inverters) are used in ASDs. The selection is dependent on the type of source side converter utilized, whether the dc linked converters are voltage source inverter (VSI) or current source inverter (CSI) configured, and the type of load to be operated. For the motor sizes included in the scope of this guide and the motor types typically applied in power generating stations, VSI drives are generally restricted to induction motors. Both induction and synchronous motors are used with a CSI ASD (Lipo and Novotny [B21]). Because of this interdependence, discussions of load side converters is included in the description of the different types of ASDs.

8.4 Voltage source inverter drive systems

8.4.1 Six-step voltage source inverter drive system

The basic six-step voltage source inverter system is shown in Figure 21, it powers an induction motor. A phase controlled line converter is used to control the voltage across the large dc link capacitor,

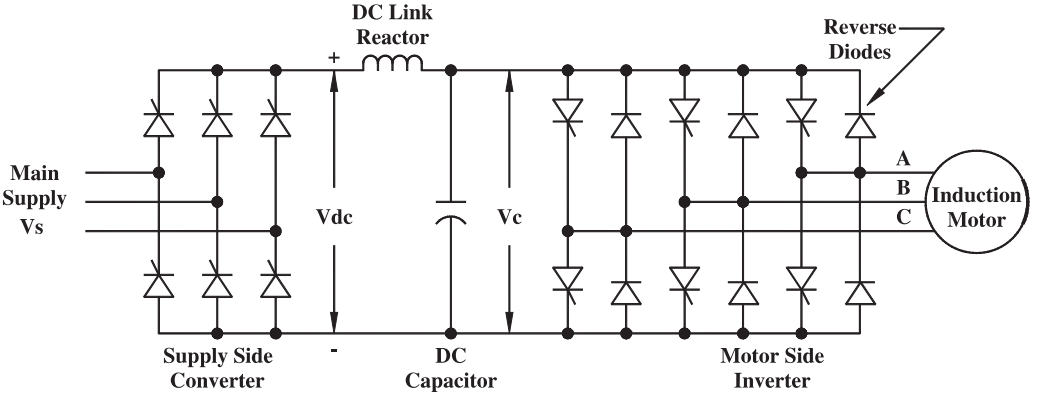


Figure 21—Basic six-step voltage source inverter (VSI) drive system (Finney [B5])

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which appears to the inverter as a stiff but controllable voltage source. The inverter is self (forced) commutated and may utilize power transistors, self commutating thyristors, or gate turn off thyristors (GTOs). Inverse parallel diodes are applied across each inverter semiconductor device to permit continuous current flow to the motor during the interval a semiconducting device is in the off state (Finney [B5]). The fundamental component of the output voltage is proportional to the regulated dc link capacitor voltage. The dc link voltage and the inverter output voltages are controlled by the input line converter and the output frequency is controlled by the timing of the inverter gating signals.

The inverter impresses a stepped voltage wave on the motor stator windings with the order of the harmonic voltages and currents typical of a six-step power converter. See Figure 22 for typical motor voltage and motor current waveforms.

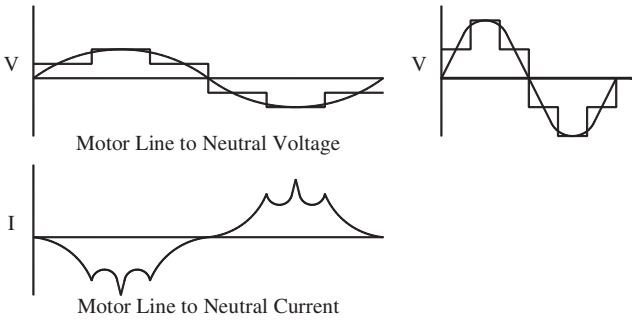


Figure 22—Motor voltages and currents for six-step VSI drive (Oliver [B26])

The voltage harmonics from the ASD are imposed on the leakage inductance of the motor. Thus, the characteristic of the harmonic currents that flow are a function of the inverter output and the machine leakage reactance (Finney [B5]). In general, motors designed for application with a VSI drive are provided with fairly high values of leakage reactance resulting in low values of harmonic current. For this case the ASD output current would be fairly sinusoidal. Since the motor torque is a function of the current and the internal voltage which are both fairly sinusoidal, motor torque pulsations are low, provided the speed range is limited. Torque pulsation become appreciable at low speed from the stepping action of the stator MMF at low frequencies and operation at low speed is generally avoided (Finney [B5]). This ASD was used only in the smaller kW ratings and has been replaced with PWM-VSI drive systems. For additional details on this drive, see Finney [B5] and Lipo and Novotny [B21].

8.4.2 Pulse-width modulated (PWM) voltage source inverter (VSI) drive system

The basic configuration of the PWM voltage source inverter drive system is shown in Figure 23. An uncontrolled line converter maintains a constant voltage across the dc link capacitor, and appears to the inverter as a stiff voltage source. The inverter is self (forced) commutated and may utilize power transistors, IGBTs, IGCTs, or GTOs (Finney [B5]). A typical voltage source PWM system operates in the sinusoidal PWM mode (Lipo and Novotny [B21]) converting to a square wave voltage similar to the six-step voltage source inverter drive near base speed (Finney [B5]). Thus, the inverter operation is responsible for controlling the V/Hz impressed on the motor. The sinusoidal PWM mode yields motor terminal voltages waveforms with low harmonic content in the low-frequency operating range (Finney [B5]). Sample output waveforms are shown in Figure 24. The voltage may or may not require a motor filter capacitor. The use of a filter capacitor depends on whether the reactive power demands of the motor are provided by the dc link capacitor through load side converter design. A motor filter may

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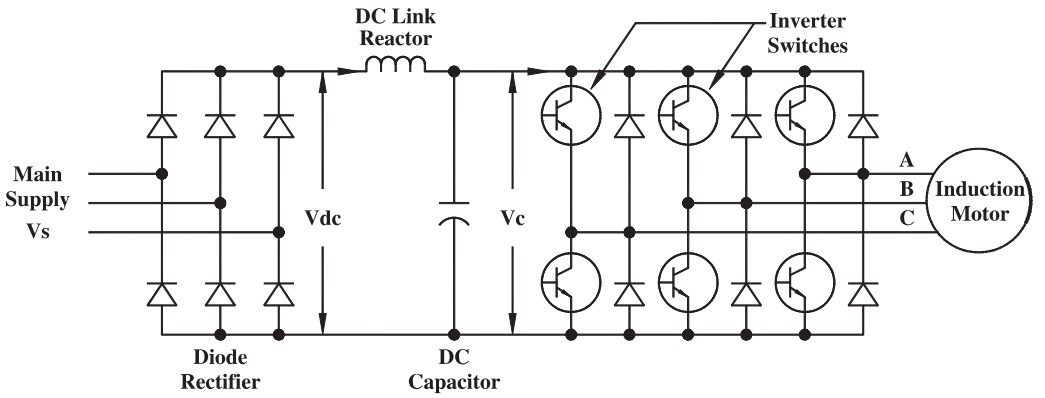


Figure 23—Diagram of PWM-VSI drive system (Finney [B5])

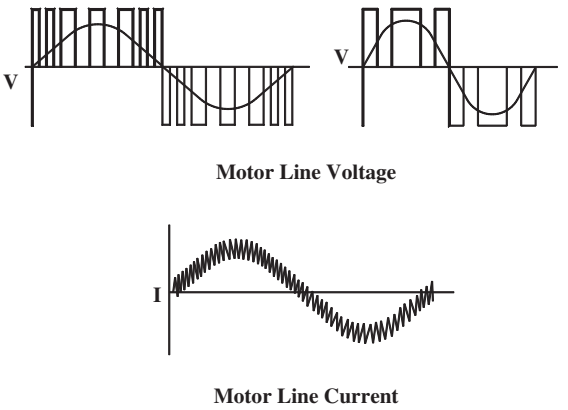


Figure 24—Motor voltage and current PWM-VSI drive (Oliver [B26])

also be required to limit ASD produced rapid *dv*/*dt* across the motor windings. This will also be a factor in reducing capacitance transmitted shaft voltages to protect the bearings from shaft currents.

If the switching rate of the PWM inverter is appreciably higher than the fundamental operating frequency, the output voltage is effectively sinusoidal and results in a sinusoidal current to the motor. Since both the internal voltage induced in the motor and the input current are basically sinusoidal (see Figure 24) motor torque pulsations are very low (Finney [B5]). When operating in the square wave voltage mode (at and above base speed) the speed oscillations are low. For additional details on this drive, see Finney [B5], Huffman [B11], and Lipo and Novotny [B21].

8.4.3 Multilevel PWM-VSI drives

The basic PWM-VSI drive in Figure 23 is sometimes referred to as a *two-level PWM*. The voltage output of each inverter leg is limited to either the positive or negative dc bus voltage. Multilevel PWM-VSI drives have been developed to improve the output wave forms impressed on the motor (Bose [B1]). Figure 25 (Bose [B1]) shows a three-level PWM-VSI drive. The single dc link capacitor of the two-level PWM is replaced by two capacitors with a common neutral. As such this arrangement is also called a *neutral point clamped inverter* (Bose [B1] and Oliver [B26]). With this configuration the output voltage waveform becomes more sinusoidal than the two level controller as shown in Figure 26 (Oliver [B26], and Bose [B1]). Additional benefits over the two level PWM are a reduction in the

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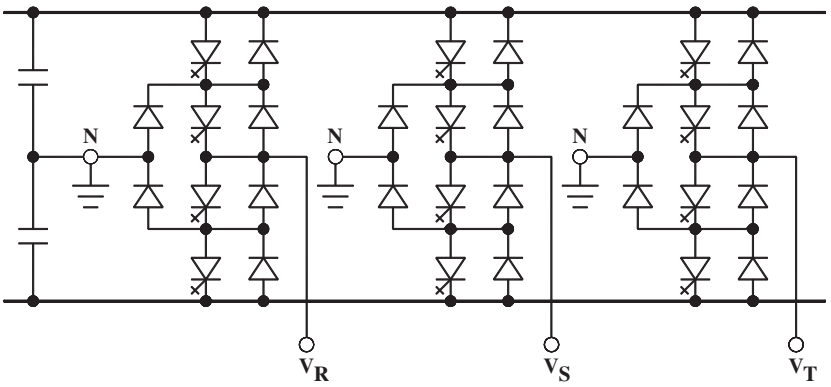


Figure 25—Three-level PWM-VSI drive (Bose [B1])

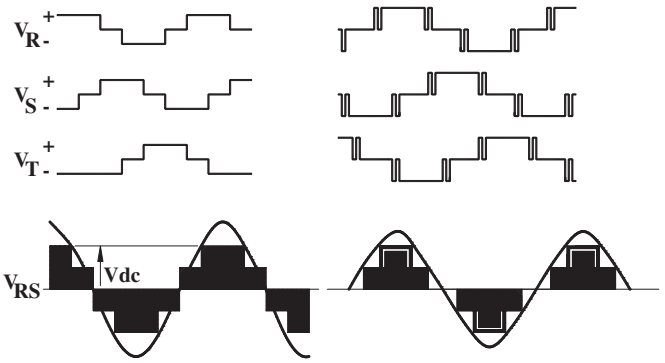


Figure 26—Comparison of output voltages for two- and three-level PWM-VSI drives (Oliver [B26])

voltage stress to the main inverter components in proportion to the dc link voltage (50% of that of the two-level inverter) and clamping of the neutral point also facilitates the ability to monitor the neutral voltage and detect ground faults throughout the converter. These benefits are partially offset by an increase in complexity of the inverter switching (Hassan [B9] and Oliver [B26]).

8.5 Current source inverter ASD systems

8.5.1 Load commutated current source inverter induction motor ASDs

This ASD is sometimes referred to as the *modified load commutated inverter* and has been used for high speed, 10 000 r/min and higher applications. In contrast to the synchronous motor, the induction motor receives excitation from the source and exhibits a lagging power factor. Thus, the use of an induction motor will not result in natural inverter commutation. To compensate, an output filter, consisting of shunt capacitors, is connected between the load side converter and the motor. The effect of the output filter is to raise the level of commutation energy available from the induction motor to a level that allows the load side converter to be load commutated (leading power factor). The kvar rating of the filter is typically around 1.25 times the full load kVA of the motor. As the motor speed is reduced, a point is reached where sufficient energy is not available from the capacitor to commutate the inverter. The speed at which this occurs depends on the load torque characteristic. For a load

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torque that varies with the square of speed, this point is between 50% and 60% of rated speed. Below this speed range there is no longer sufficient energy available from the motor to continue the load commutation process. For operation below this speed an alternate method of commutation of the load side converter must be provided. This also implies that an alternate method of commutation is required when starting the drive.

The diverter commutation method has been applied on modified LCI induction motor ASDs at speeds below 50% and 60%. The diverter increases the operating speed control range of the ASD, and allows the converter to accelerate the motor from the minimum operating speed. The switching off of the load side converter power devices is accomplished by effectively shorting or diverting the dc link current from the load converter. Thus, the name diverter. To accomplish the diverter switching, an auxiliary circuit is applied in the dc link.

The diverter imposes a square wave current to the filter capacitor and motor combination. The magnitude of harmonic current to the machine stator winding is dependent on the relative value of impedance of the two components at the operating frequency, as shown in Equation (9):

$$I_h(\text{motor}) = I_h(\text{inverter})[X_c/(X_m + X_c)] \tag{9}$$

where

I_h is the current harmonic of order h

X_m is the reactance of the machine at the converter frequency times the harmonic number (h)

X_c is the corresponding capacitive reactance of the filter

From the above, the harmonic currents in the motor are lowest at maximum frequency (speed). The harmonic voltages impressed on the machine terminals are a function of the harmonic current and in the corresponding impedance of the machine, thus they are also lowest at maximum speed.

For normal operating frequencies, the harmonic currents from the modified LCI converter flow primarily in the filter. As a result, the net current flow in the motor is fairly sinusoidal (Finney [B5]) and the harmonic effects on the motor torque, heating, and voltage stress are reduced as compared to those of a CSI synchronous motor drive.

During low-speed operation (low frequency) the effect of the capacitance is negligible and the current to the motor is a square wave (Finney [B5]). Thus, for this mode of operation the modified LCI induction motor drive has similar characteristics to the LCI synchronous motor ASD in regards to pulsating torques, harmonic heating, and voltage notching.

With the combination of the filter capacitance and the inductive reactance of the motor, a resonance will occur between them at some frequency and cause a large circulating 5th harmonic current. Based on typical circuit values, the resonant frequency is approximately 2.5 times rated frequency. Based on the characteristic harmonics of a square wave current, the dominant exciting frequencies are 5, 7, 11 and 13 times output frequency for a six-pulse drive. The approximate resonant speeds are (Bose [B1]) 40% for the 5th harmonic; 30% for the 7th; 20% for the 11th; and 15% for the 13th harmonic. When the filter and motor are in resonance, high currents circulate between them. The frequency of these currents are at the resonant frequency and will cause additional harmonic heating in the motor and harmonic shaft torque will be produced.

Several methods can be used to avoid these resonant conditions. One method is to restrict the operating speed to ranges above resonance. Another method is to add inductors between the converter and the filter. The final method is through inverter control, which selectively eliminates the appropriate harmonic at the desired operating speed (Bose [B1]). In the first case, the controls of the drive are designed to accelerate through the resonant speed range. In the second case, the resonant point is

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shifted down to allow a lower operating speed range and starting handled as with the first case. In the final case, the offending 5th harmonic is eliminated.

Another consideration for interaction between the filter capacitor and the motor, is the potential for motor self-excitation during drive shutdown or the loss of load side converter output. If the filter capacitance kVAr rating exceeds 20% of the kVA rating of the induction motor, the system may become self-excited and cause motor overvoltage. Appropriate means should be provided to automatically disconnect the filter from the motor for this condition.

8.5.2 Load commutated inverter synchronous motor drive

The load commutated current source inverter synchronous motor drive is commonly referred to as an *LCI synchronous motor drive*. It consists of controlled current dc linked converters and a synchronous motor (see Figure 27). An important characteristic of the synchronous motor is that it can be operated at a leading power factor. This operating characteristic makes it possible to use a simple thyristor inverter. Operating the synchronous motor at a leading power factor ensures that the motor phase current changes direction before the phase voltage changes polarity. As a result, the synchronous motor, which is the load, causes the inverter commutation and hence the term load commutated inverter or LCI and the inverter frequency follows the motor speed.

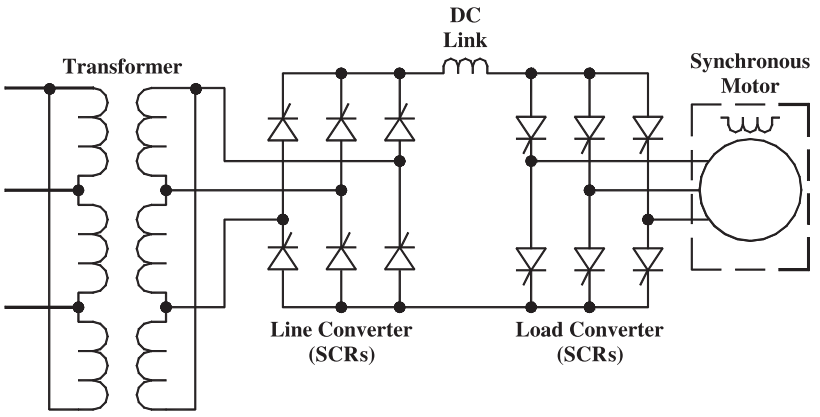


Figure 27—Load commutated current source inverter synchronous motor drive system

The field voltage of the synchronous motor is controlled to ensure leading power factor operation. Additional field voltage control can be employed for increasing the acceleration or deceleration of the load. By utilizing a separate controllable power supply for field excitation, the LCI synchronous motor drive is capable of operating in a load commutated mode across a full 10 to 1 speed range. Once the speed drops below a certain value (generally around 10–20% of base speed), the motor does not generate sufficient voltage to commutate the inverter. In this region, self-commutation is provided by modulating (turning on and off) the dc link current, which is accomplished with the line side converter. Current is provided to the motor by sequentially gating a pair of load side thyristors to direct current through the corresponding pair of motor stator windings to produce torque in the correct rotation for the load. This method of commutation is limited from 0 to around 5–6 Hz because of the time constant of the dc link inductor. At this point, the ASD must convert to LCI operation. The amount of torque the ASD can produce for this mode of operation is generally less than rated. However, since the majority of drive applications are pumps and fans, which require only a fraction of rated torque at the lower speeds, this method of commutation for starting is acceptable for most ASD applications (Lipo and Novotny [B21]). Drive start up is handled in a similar manner.

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The stiff current source of the LCI provides a square wave current to the motor stator windings with the order of the harmonic currents typical of a six-step power converter. The current harmonics cause additional heating in the motor, particularly the rotor, resulting in elevated temperatures.

Since the internal voltage of the motor is basically sinusoidal (Finney [B5]), the product of the square wave stator current and the internal voltage produce significant torque pulsations that may be objectionable to the driven load. These torque pulsations may stimulate resonance frequencies of the mechanical system (motor rotor, shaft, and connected load) and cause excessive lateral and torsional vibrations. The frequencies of these torques are a function of the operating frequency (speed) and the converter pulse number. For example, on a six-pulse converter, the largest torque pulsation is at six times the operating frequency. Thus, on current source drives, torsional vibration studies are necessary and damping coupling designed to limit objectionable torques may be required (Higgins et al. [B10]).

The machine stator winding is included in the inverter commutation circuit and voltage *notches* are generated during the commutation (see Figure 28) (it is noteworthy to mention that this figure's notches are expanded on the time scale drawn and in reality may look more like notches). These notches impose voltage stress (dv/dt) on the winding of the motor and the motor has to be designed for this stress. In general, machines designed for LCI operation are supplied with a low leakage reactance to improve commutation (Finney [B5]).

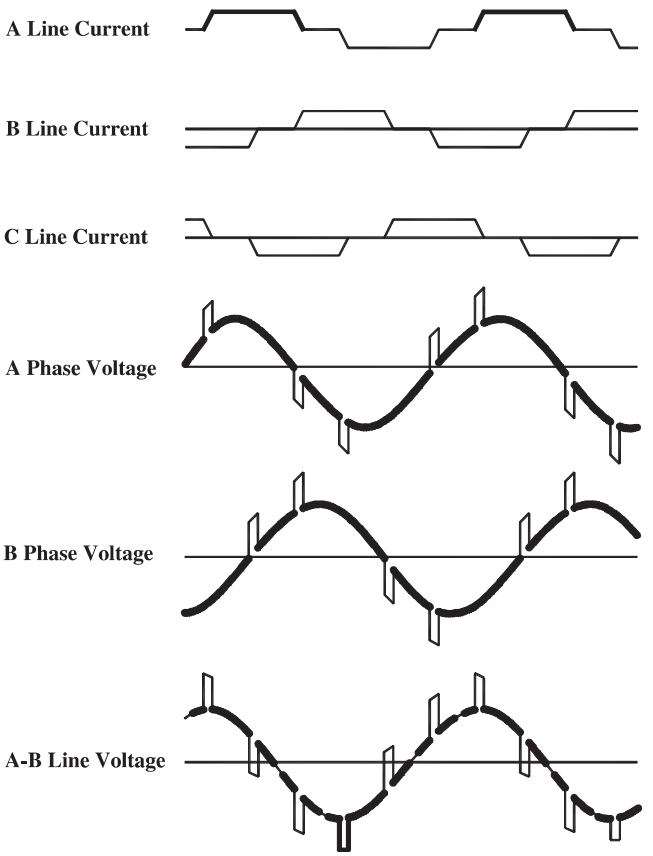


Figure 28—Current source LCI synchronous motor waveform showing voltage notches (Finney [B5])

To minimize harmonics to the supply system, and to significantly reduce the additional motor heating from inverter harmonics and the corresponding torque pulsations, a twelve-pulse ASD system is

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usually used for large synchronous motors. The motor is fitted with two stator windings, separated from each other by 60° mechanical degrees inside the stator. Each of these windings is fed with the square wave of current from the inverter, but a harmonic cancellation takes place within the stator core magnetic flux, such that rotor pole face harmonic rotor heating is significantly reduced (Figure 29).

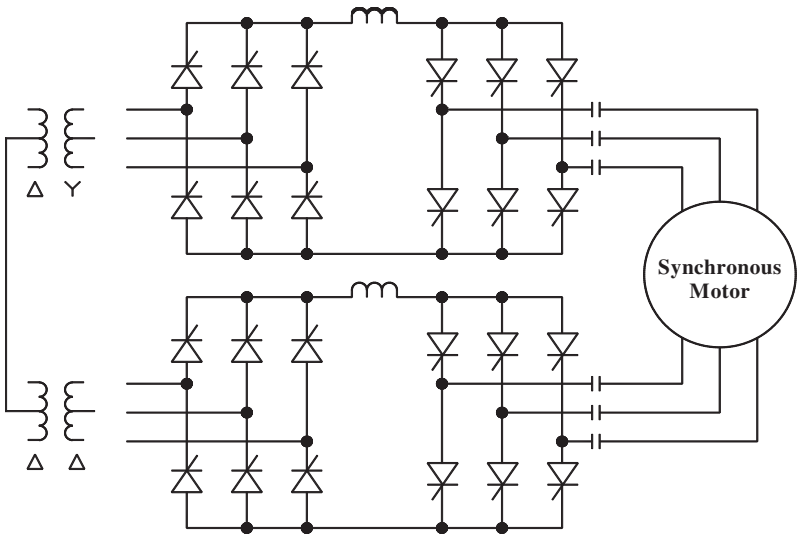


Figure 29—Diagram of twelve-pulse dual-channel LCI drive system with two-winding synchronous motor

For additional details on this ASD see Finney [B5], Huffman [B11], and Lipo and Novotny [B21].

8.5.3 Alternate commutated methods for current source inverter induction motor drive systems

There are two types of self-commutated current source inverter designs. The first utilizes forced commutation of the thyristors. The thyristor turn off is controlled by auxiliary capacitive commutation circuits (Finney [B5]). The second type utilizes gate turn-off (GTO) thyristors. With this inverter, the load side converter firing is modified to a PWM mode as load and speed are reduced. With the PWM inverter, the motor filter capacitor size can be reduced as its primary role changes from compensation to commutation (Bose [B1]). Typically, the kVAr rating of the filter capacitor is about 0.8 times the full load kVA of the motor.

Both the GTO-PWM and the diverter inverters can be designed for selective harmonic elimination. For further details on alternative methods of commutation for IMD see Finney [B5] and Bose [B1].

8.5.4 Current-source GTO-PWM inverter induction motor ASD

This ASD is sometimes referred to as the *induction motor drive* (IMD). This ASD uses a controlled rectifier for the converter to establish dc link and motor voltage (see Figure 30). It has a dc link inductor and no diverter circuit. It uses a full GTO bridge in the inverter to establish motor frequency. The specific inverter output configuration depends on the particular manufacturer. One manufacturer using this concept has no output filter capacitor. The size of the output filter capacitor is

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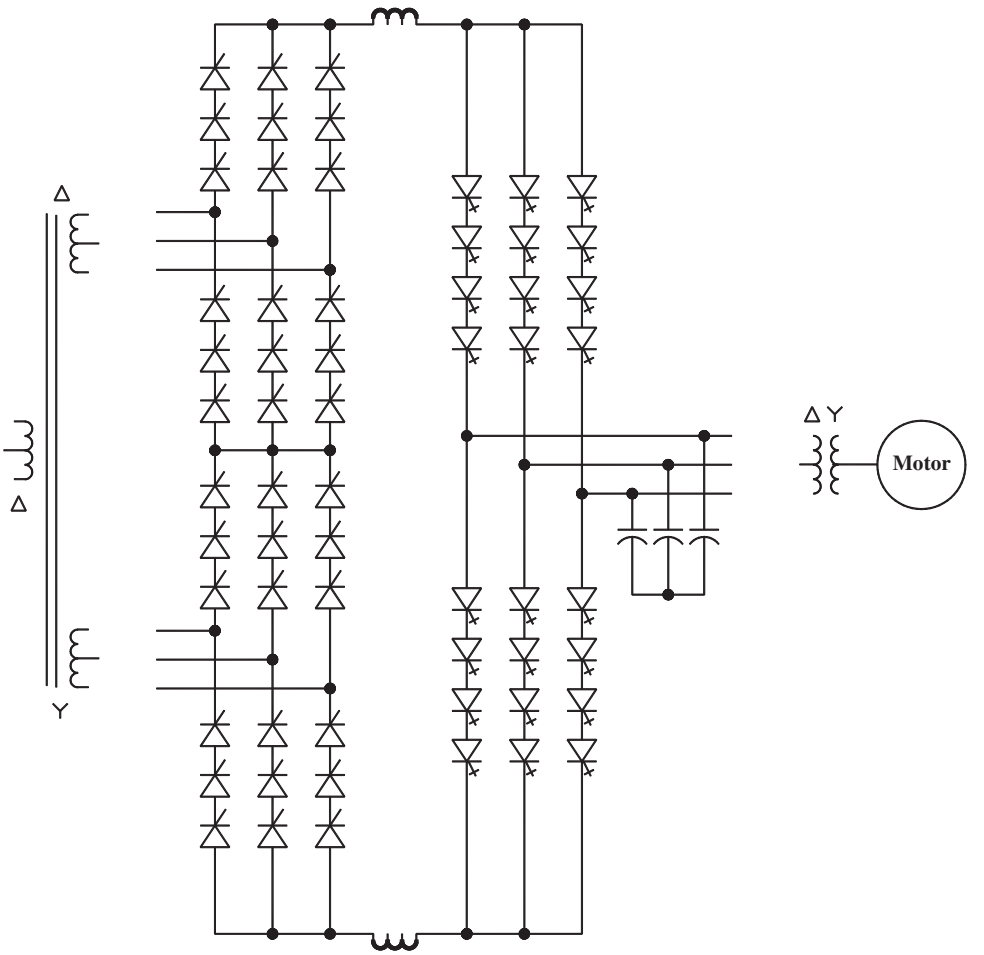


Figure 30—Power converter circuit for IMD

a function of the extent of PWM chopping that is applied to the output current wave, and the amount of reactive kVA fed to the motor through the dc link ripple voltage. For instance, the 80% capacitor filter design has no PWM chopping above 80% speed, and the 40% filter capacitor design uses PWM chopping at all speeds.

These current-source GTO-PWM inverters, with output capacitor filters, all use selective harmonic elimination to eliminate any harmonics in the output voltage and current that might cause resonance between the output filter and the motor windings. These ASDs are generally limited to 5% or 10% overspeed.

8.6 Comparison of ASD characteristics

The controls strategy of the ASD may have an impact on the harmonics injected into the ac source and into the motor. For the ac source, the potential for harmonic reduction depends on the type of ASD employed. The harmonic reduction is obtained by maximizing the power factor presented to the ac source and thus resulting in the minimum line currents for a given operating condition of the ASD. With non-phase controlled line converters no control action occurs or is required to maximize the input power factor. For phase controlled converters, the control system can be designed to optimize the operation of the line and load converters such that the line side power factor is at the maximum feasible for a given load.

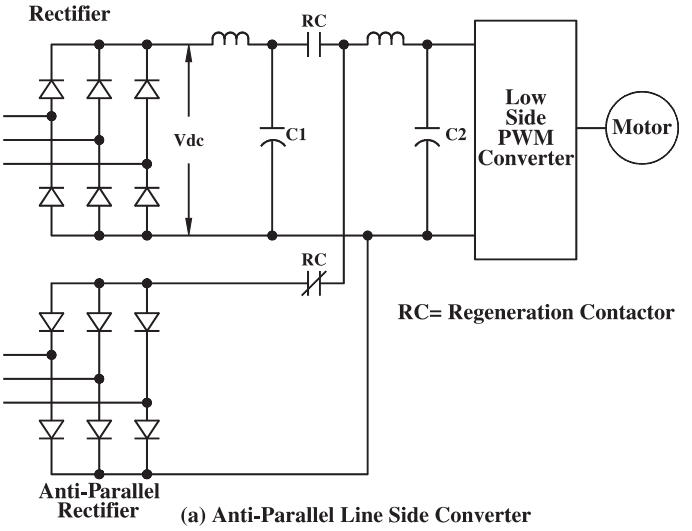
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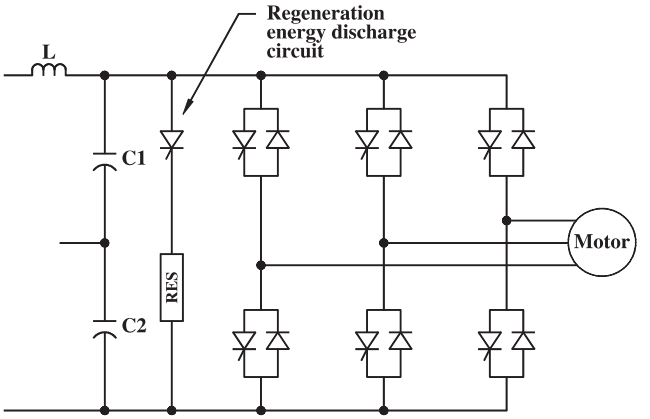
8.6.1 Regenerative capabilities of ASD systems

Most of the ASDs discussed above can be designed with regenerative capabilities. Regeneration is the ability of the drive system to convert the stored energy in the rotating equipment (motor and load inertia) and return it to the power system supplying the drive. To have regenerative capability with a CSI synchronous or induction motor drive system only requires the inclusion of this feature in the control scheme. The roles of the line and load side converters are reversed thus inverting the dc link voltage. The flow of power in the dc link reverses with positive current and negative voltage. Similar effects are obtained with VSI drives using a phase controlled line converter. VSI drives using an uncontrolled line converter will not regenerate without augmented circuit. Two possible circuit modifiers are the following:

a) Addition of an anti-parallel source side converter (see Figure 31a).
b) Addition of a discharge resistor circuit in the dc link (see Figure 31b) (dynamic braking).



(a) Anti-Parallel Line Side Converter



(b) DC Link Discharge Resistor (Finney [B5])

Figure 31—Circuit modifiers for providing regeneration with uncontrolled line side converters

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Additional switching, gating circuitry, and/or drive control scheme modification are required to implement either.

8.6.2 Speed regulation and field oriented control

The standard ASD is suitable for most applications where control tolerances and fast speed of response are far below the level of vector or field oriented control. Field orientation or vector control allow induction motors to be used in place of dc motors in applications that formerly could only be met by dc motor systems. The benefits of control system determination of motor torque and flux producing components, and the monitoring and control of the relationship between these two flux elements is key to controlling shaft torsional stresses and process production quality. Control design should, therefore, strive to achieve true vector control capability unless shaft speed rather than shaft position is the important parameter.

8.6.3 Protection and control

The controls of the ASD are basically designed to accomplish the following:

a) Provide protection and control functions
b) Respond to line and load disturbances
c) Improve control of the motor shaft speed or position

The controls used in ASDs are microprocessor based and provide protection and control functions for the ASD. The controls supplied with the ASD must respond to changes in process demand. Typically process demand signals are generated external to the ASD by the main control system for the generating station. Depending on the vintage of the plant control system it may be analog or digital. Thus, the ASD controls should have sufficient flexibility to interface with either type. The ASD control system must translate the external process demand signal into control actions. It generates the required converter control signals to produce the necessary voltages or currents to cause the ASD to operate at the desired speed.

ASD controls can be complex. The degree of complexity varies with the type of ASD and the dynamic and steady-state process requirements. The control design system should permit field adjustment or tuning of critical protective and control parameters, without necessitating changes in physical hardware. The control system should allow for either keypad or standard computer interface directly to the control system to allow parameter adjustments. Programming should be in English text and should follow a logical block programming sequence.

9. Adjustable-speed drive configurations

This clause describes the various drive configurations commonly employed in power generating stations, highlighting the performance features and limitations of each.

9.1 Choice of ASD

The choice of ASD for a power plant application derives from consideration of the following factors:

a) Economics
b) Reliability

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c) Load torque characteristic
d) Speed of response
e) Maximum speed and speed range
f) Output power requirements
g) Harmonics (including electric service interactions, i.e., transient voltages and momentary voltage sags, etc.)

All of these are interrelated, and all are essential to a successful ASD application. Once management is sold on the economic cost/benefit of the ASD installation and reliability of the ASD technology is not an issue, then the engineering inputs and decisions can be made on the technical choice of ASD technology.

As a practical matter, the ASD technologies to be considered for medium-voltage motors in power plant are as follows:

1) Low-voltage IGBT PWM-VSI with input and output transformers
2) Current-source GTO-PWM
3) Voltage-source IGCT PWM
4) Voltage-source IGBT PWM twenty-four-pulse input
5) Current-source modified LCI

Each of these technologies use input transformers in power plant medium-voltage motor applications. The low-voltage IGBT PWM ASD is available in power ratings up to 375 kW for six-pulse ratings or 750 kW in twelve-pulse ratings. The current-source GTO-PWM ASD is available up to 6500 kW in six-pulse ratings, or 13 000 kW on twelve-pulse ratings. The voltage-source IGCT PWM ASD is available up to 5500 kW in six-pulse ratings or 11 000 kW in twelve-pulse ratings. The voltage source IGBT PWM ASD is available up to 6000 kW ratings. The current-source modified LCI ASD is available in 6000 kW six-pulse ratings, or 12 000 kW in twelve-pulse ratings.

Some of these technologies have inherently lower cost in the 350 kW to 1000 kW range than others. The number of switching devices in series is a factor; the low-voltage ASD has only one switching device in series. The cost of each switching device is a factor, since some are much more expensive than others. Air cooling or liquid cooling affects the price in the lower power ratings. Air cooling provides a lower price, but other means, with offsetting costs, may be needed to remove the air heated by ASD losses from the region of the ASD to prevent recirculation of heated air back to the cooling air inlet to the ASD.

9.1.1 Harmonics

The level of harmonic current(s) to be injected into the electric service system by the ASD should be one of the first considerations in selecting an ASD technology. Because a six-pulse or twelve-pulse ASD configuration effects the magnitudes of specific harmonic currents and the costs of six-pulse versus twelve-pulse are significantly different, the ASD input converter pulse number needs to be addressed. The resulting electric service harmonic voltage distortion is directly related to the ASD configuration chosen. This voltage distortion, or distortion factor *DF*, is defined as the percent of the rms of the amplitudes of all the individual harmonic voltages, E_n, divided by the amplitude of the fundamental voltage, E_1, as shown in Equation (10):

$$DF\% = \frac{\left(\sum E_n^2\right)^{1/2}}{E_1} \times 100 \tag{10}$$

The distortion factor is dependent on the ASD power rating as related to the kVA capacity of the electric service bus or transformer supplying the ASD. A voltage distortion factor of less than 5% is

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usually adequate for power plant applications, although it is not unusual to specify a value of 3% or less. This value of voltage distortion is specified for the auxiliary power bus supplying the ASD as opposed to a point of common coupling as discussed in IEEE Std 519-1992. Nevertheless, IEEE Std 519-1992 can be used as a guideline to estimate the resulting voltage distortion for a particular power plant ASD application.

As a first approximation, if the ratio of the output power of the ASD to the kVA capacity of the supply system is less than 0.5, the voltage distortion should not be a problem. Another approximation is shown in Oliver [B26, Figure 10-1]. The (Oliver [B26]) reference curves show the estimated voltage distortion on the bus supplying the ASD for six-pulse and twelve-pulse systems as a function of the ratio of the supply system kVA to the output power of the motors controlled by ASDs. If there is any question about the level of harmonics to the electric service system, if there are power factor correction capacitors in the neighborhood of the ASD, or if harmonic filters are present, a harmonic study should be made before selecting the ASD.

Once the harmonic study is completed, the decision of six-pulse or twelve-pulse input can be made. It is better to use an ASD with a twelve-pulse or higher pulse input than one with a six-pulse input with harmonic filter, because of possible complications of the filter becoming resonant with other harmonic sources.

9.1.2 Reliability

Reliability of ASDs for power plant applications has been a concern of many power plant managers. The concern seems to be centered around two things. First, a number of plant managers have a mechanical engineering background in steam boiler or steam turbine technology. Their primary training is in mechanical valve control or vane control systems. This personal experience background coupled with the fact that many of the early ASDs had a poor record of reliability and possible confusion from the wide-spread publication of some recent experiences with low-voltage ASDs that caused motor failures, has led to these reliability concerns. The motor failures associated with low-voltage ASDs, in general, bear no relation to medium-voltage ASD applications.

Now, ASDs can be considered to be as reliable as any other power plant equipment. This is the result of several generations of improvements in ASD technology, much simpler and more reliable switching devices, and the experience gained with many high output power ASDs installed in critical applications in several different industries, including the electric power generation industry.

When selecting an ASD manufacturer it is prudent to establish a qualified bidders list, with bidder evaluations supported by interviews with other users. It should be noted that some types of ASDs are classified as *high-performance/response* ASDs capable of being used, for example, in steel manufacturing rolling mills that require high rates of acceleration, deceleration, and fast forward and reverse actions. Other *general purpose* ASDs do not have this capability, but can be suitable for power plant pump and fan applications. It is noteworthy to mention, that the high-performance/response ASD capability can be a benefit in restoring motor-system stability during power plant boiler control transient upsets.

ASD reliability has been studied (Nailen [B23]), and mean time before failure (MTBF) and mean time to repair (MTTR) statistics have been developed for ASD components. The MTBF has been determined to be about 45 000 h. Means considered to increase MTBF are as follows:

a) Redundant cooling systems
b) Redundant thyristors ($N - 1$)
c) Redundant control system
d) Dual train ASD

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e) Flying spare
f) Bypass switch
g) UPS for ASD controls
h) Control of EMI

9.2 Reliability enhancements for six-pulse systems

There have been several modifications applied to the basic six-pulse systems (see Figure 32) as a means to enhance their reliability. The more common modifiers are discussed in 9.2.1, 9.2.2, and 9.2.3.

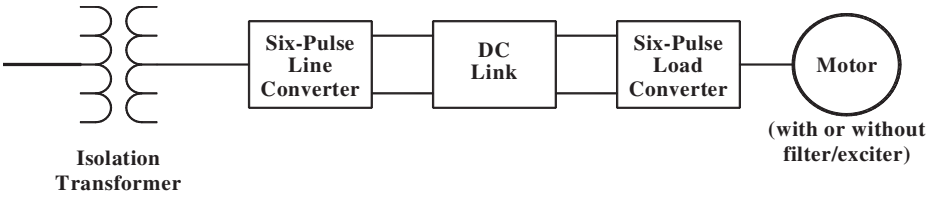


Figure 32—Basic six-pulse adjustable-speed drive

9.2.1 Bypass scheme

Figure 33 shows the fundamental bypass scheme. For this configuration, a switch is provided that can bypass the drive system in the event it fails. In this scheme, the motor is connected directly to the line and the motor must be capable of across-the-line starting or have some other starting scheme in addition to the ASD. In the bypass mode of operation, the motor operates at constant speed and will no longer control the process through variable speed. Thus, another method of controlling the process is required, or the process must be capable of tolerating constant speed operation. In processes where several loads operate in parallel to meet the overall process demand, it may be possible to vary the load on the other loads to satisfy the overall demand. Relay protection in the bypass mode should be equivalent to relay protection with the ASD operating in the normal mode.

9.2.2 Standby ASD

Figure 34 shows another scheme used to enhance the reliability of the basic six-pulse drive. In this scheme a spare power unit consisting of an input transformer, a line converter, dc link, and load converter is provided. These components are sized to carry the same load as the primary systems. The scheme can be applied where transfer from any primary power unit to the standby unit is accomplished with both units de-energized or with both energized. The latter scheme has also been referred to as a *flying spare* (Gripp [B7]). From Figure 34 one can observe that several power isolation devices are required. In the case where the transfer is between de-energized units, the power isolation devices can be manually operated and designed for no-load operation. If the transfer takes place between energized units the power isolation devices must be electrically operated load break devices such as circuit breakers or contactors. To implement the flying spare scheme, the standby unit must monitor the condition of the other units it is intended to be a spare for and the standby unit must initiate a transfer prior to shut down of the defective unit (Nilsson [B25]).

9.2.3 Redundant converter power semiconducting devices

Converters designed for medium-voltage applications (line to line voltage of 2300 V are higher) generally require multiple power semiconductor devices in series in each leg of the converter due to the voltage limits of the individual solid-state devices. Since the primary failure mode of these devices

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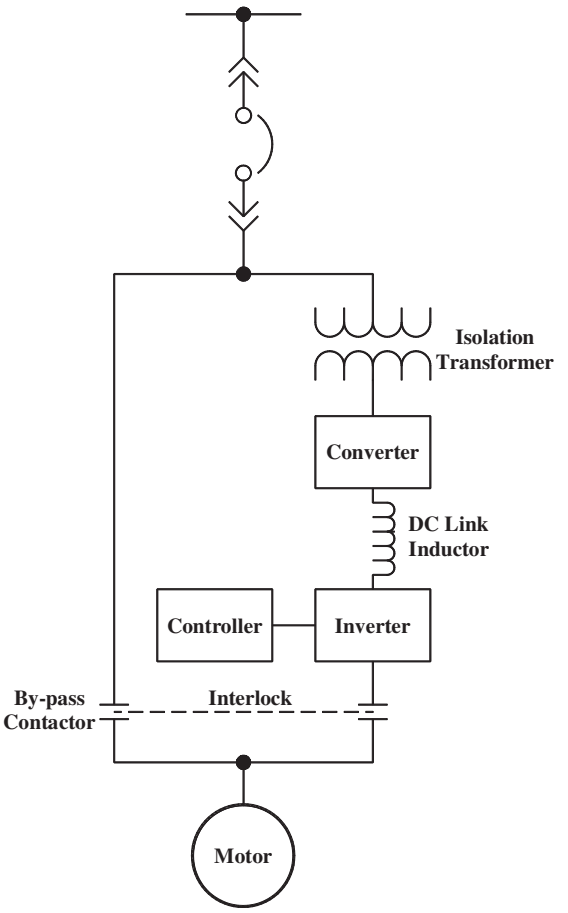


Figure 33—Simplified bypass scheme

is to short out, the voltage capability of the effected leg is reduced if any one of the series solid-state devices fails. This reduction in voltage capability requires the converter to be shut down to prevent additional damage. Thus, in a single channel ASD, the entire drive is shut down. Most ASD suppliers have converter designs, which permit an extra power semiconductor device, over the minimum required for the rated voltage of the converter, to be installed in each leg. This feature is directed at improving the reliability of the converters. If one of the power semiconducting devices fails shorted, the ASD can continue to operate with adequate voltage margin and the failed device can be replaced at a more opportune time.

This design feature is commonly referred to as $N-1$ *capability* where N is the total number of power semiconductor devices in each leg and $N-1$ is the minimum required for the operating voltage.

9.3 Twelve-pulse ASDs

Subclauses 9.3.1, 9.3.2, 9.3.3, and 9.3.4 describe the twelve-pulse ASD configurations.

9.3.1 Dual channel twelve-pulse ASDs

Figure 35 shows a dual channel ASD. The ASD consists of two six-pulse channels with a 30 electrical degree phase shift between the two channels (supplied by the input transformers). The introduction of this phase shift results in the dual channel ASD exhibiting the characteristics of a twelve-pulse

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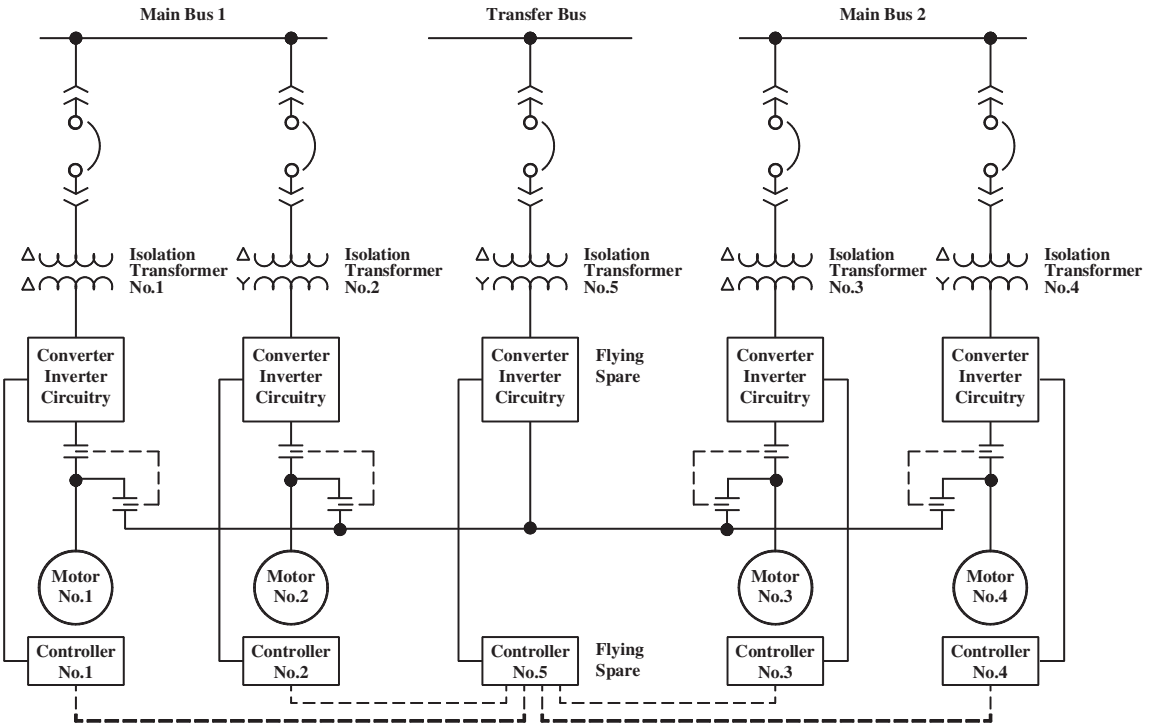


Figure 34—Stand-by ASD (flying spare) (Nilsson [B25])

converter. The characteristic harmonics injected into the source for a twelve-pulse converter are the 11th, 13th, 23rd, 25th and higher order harmonics.

The source side phase shift is accomplished by selecting the two input transformers with different phase relationships. A delta–delta connected transformer is used in one channel with a delta-wye or wye-delta connected transformer utilized in the other channel. A single three-winding transformer can also be used. The primary winding is connected in delta with one secondary winding connected in delta and the other connected in wye. The use of a three-winding transformer generally results in some cost and space savings over the two transformer arrangement. However, the use of a single three-winding transformer tends to reduce the overall reliability of the ASD since a single failure in the transformer results in complete ASD failure.

The phase shift for the motor can be accomplished two ways. The first approach is to utilize a specially designed motor that has two sets of stator winding shifted 30 electrical degrees. The motor is sometimes referred to as a *six-phase motor*, but this terminology is fundamentally incorrect. *Dual winding* motor is the preferred terminology. This arrangement reduces the harmonic torques generated by the motor but does not reduce the harmonic content of the motor currents. The specially designed motor limits this approach to new installations where the motor can be properly designed.

The second approach is shown in Figure 36 and utilizes a three-winding output transformer similar to the three-winding source side transformer discussed above and a motor with one set of three-phase stator windings. The primary windings of three-winding transformers are normally connected with one set in wye and the other set in delta with the secondary windings commonly connected in delta. Two separate load side transformers could be used but adds cost to the installation. When an output transformer is used, both the harmonic currents injected into the motor and the harmonic torques generated by the motor are reduced. The reduction in motor harmonic currents reduces motor heating. Since the load transformer must operate over a wide frequency range it must be properly designed for low-frequency excitation without excessive saturation.

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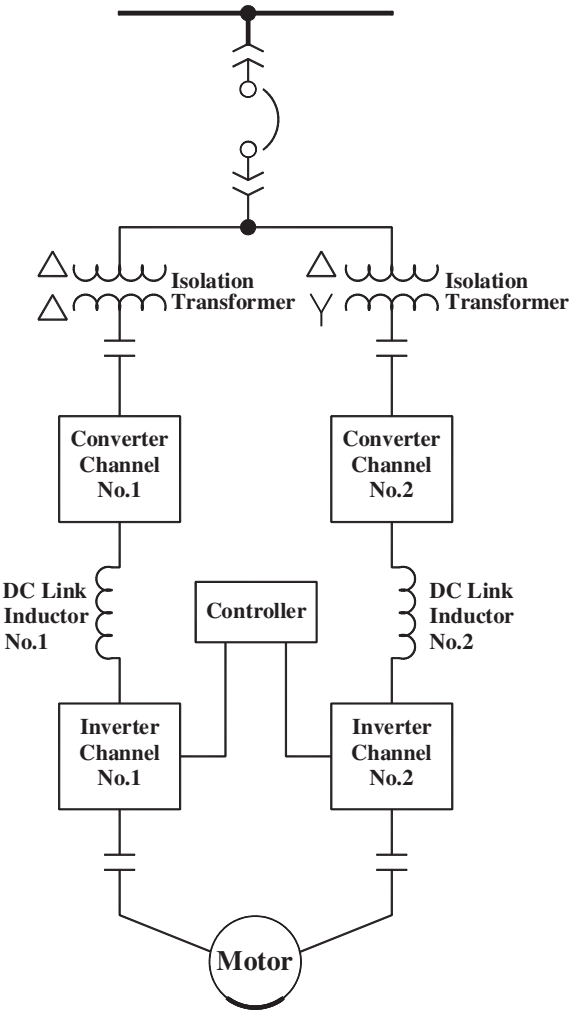


Figure 35—Dual channel twelve-pulse ASD with dual winding motor

9.3.2 Hybrid twelve-pulse ASDs

Another arrangement used where the motor has only one set of three-phase stator windings is illustrated in Figure 37. The source side converters are connected in a single channel twelve-pulse configuration with a six-pulse converter on the load side. This ASD configuration generates characteristic harmonics of a twelve-pulse system at the source but generates the characteristic harmonics of a six-pulse system at the motor.

9.3.3 Capability of twelve-pulse ASDs

The dual channel twelve-pulse ASD has almost twice the motor output power capability of the single channel six-pulse drive. The maximum motor power capability of the hybrid twelve-pulse system is comparable to that of the six-pulse ASD since both are limited by the current capability of the six-pulse converters found in both drives. As with the six-pulse ASD, the output power capability of the hybrid twelve-pulse system could be expanded by paralleling solid-state power semiconductor devices or paralleling converters. However, this practice is generally not used with the dual channel twelve-pulse ASDs being preferred.

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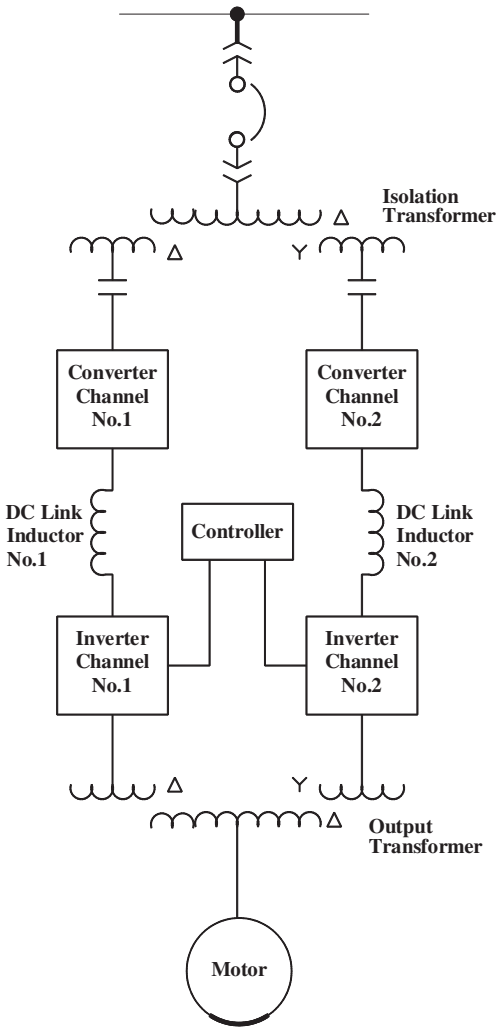


Figure 36—Dual channel twelve-pulse ASD with single winding motor

9.3.4 Reliability enhancements for twelve-pulse systems

The reliability enhancements available for the twelve-pulse systems depend on whether the ASD is a dual or single channel design. The bypass scheme, previously discussed, as applied to the six-pulse system can be applied to both the hybrid twelve-pulse system and the dual channel twelve-pulse system utilizing a motor with only one set of stator windings. The standby power unit can be applied to any of the twelve-pulse systems. However, single channel operation as discussed below is a more widely used reliability enhancement scheme for the dual channel system. The application of $N-1$ converter designs can be used with any of twelve-pulse configurations.

9.3.4.1 Operation of dual channel ASD in single channel mode

A reliability improvement can be realized with the dual channel twelve-pulse ASD of Figure 35, by designing the ASD such that continued operation is permissible with one channel out-of-service. This feature typically includes electrical isolation of each channel so repairs can be made to the faulty channel without shutting down the functional channel. Without further modification the ASD can operate at approximately half-load. However, with one channel out-of-service, the ASD becomes a six-pulse system and exhibits the associated characteristics. This feature is not practical with the hybrid twelve-pulse ASD since it is a single channel design.

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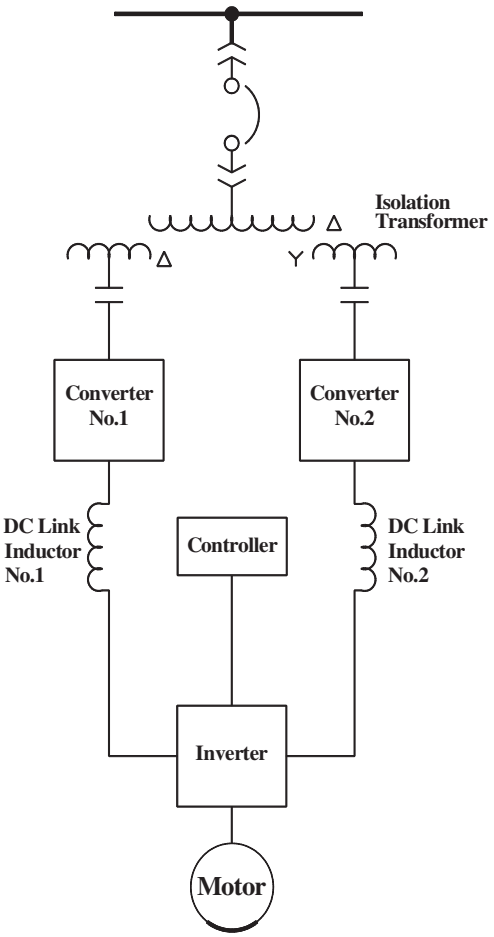


Figure 37—Hybrid twelve-pulse ASD

It should be noted for the dual winding motor arrangement, that when one channel is out-of-service, the idle set of motor windings are still energized by the induced voltage caused by the current in the other set of motor windings. A similar condition exists in the case of source and/or load side three-winding transformers.

9.3.4.2 Oversized dual channel drive

The oversized dual channel drive is an extension of the single channel operating mode discussed above. In this arrangement each channel is oversized to carry more than rated load. The other features are the same as for the single channel operation arrangement. Oversizing both channels allows more than half-load to be carried in the event one channel is out-of-service. This arrangement is ideal for cases where the normal load demand is of the order 60–75% of the maximum rating of the load. One example is a typical boiler fan where the normal load point called *MCR* (*maximum continuous rating*) is approximately 60% of the peak capability of the fan or the test block (TB) rating. Thus, with only a modest increase in the capability of each channel, the ASD can carry MCR load with one channel out-of-service.

9.4 ASDs with higher pulse numbers

The primary motivation to use ASDs with higher pulse numbers than the six- and twelve-pulse systems is reduction of harmonic current distortion. As the size of the load increases the harmonic currents and

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subsequent electric service voltage distortion created can increase. Six-pulse converters generally can be used in the lower power ratings without the addition of harmonic filters to reduce the harmonic impact on the source. Twelve-pulse systems can be used for larger loads without harmonic filters. However, if other ASDs and/or rectifier loads are connected to the same source, harmonic distortion levels can quickly exceed acceptable limits. In these cases, ASDs with higher pulse numbers provide a viable alternative to the addition of harmonic filters.

These higher pulse number ASDs are derived using multiple six-pulse converters. Figure 38 and Figure 39 show conventional 18- and 24-pulse systems, respectively. These arrangements are obtained by using different transformer connections to produce the necessary phase shifts of each channel (20° and 15° electrical degrees, respectively). These ASDs can be provided with either CSI or VSI converters.

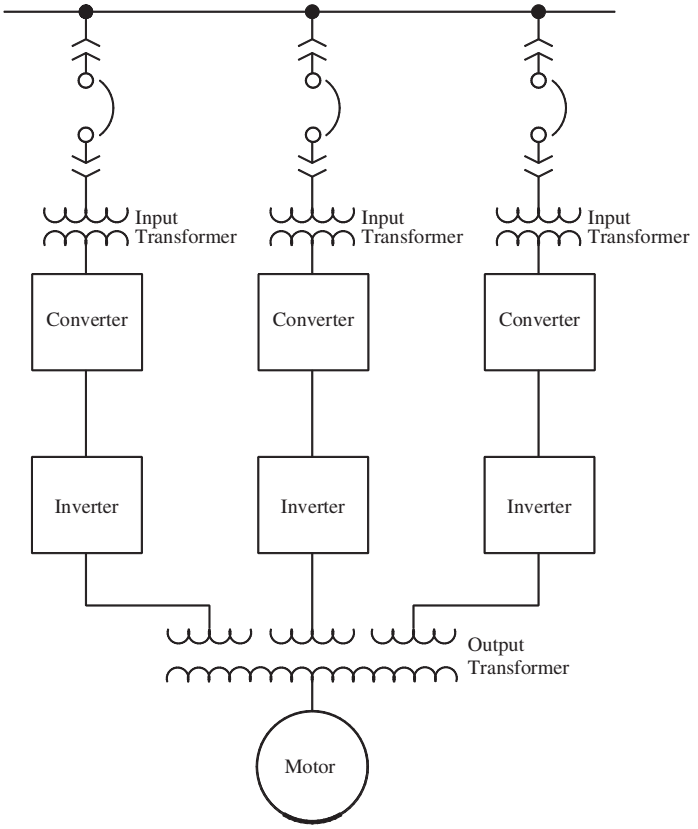


Figure 38—Conventional 18-pulse ASD

Figure 40 shows a different ASD topology for an 18-pulse system available for VSI-PWM converters. This ASD uses a transformer with one primary winding and nine secondary windings. Each winding supplies a power cell typically rated for 480 V. The outputs of the power cells for each phase are connected in series to produce the output voltage for the motor (see Figure 41). Thus, the pulse number of the ASD and the rated output voltage are interrelated. The 18-pulse system shown is designed for a nominally rated 2300 V motor ($3 \times 480\,\text{V} = 1440\,\text{V}_{\text{LN}}$, which is approximately equal to the line-to-neutral voltage rating of the motor). A 30-pulse system would be required for a motor with a nominal voltage rating of 4000 V. The transformer for the 30-pulse system would have 15 secondary windings with a 12° phase shift between each winding of each phase and five power cells per phase (Hammond [B8]).

The reliability enhancement typically used in the case of the higher pulse number systems is to provide the capability to operate with some reduction in load with one converter out-of-service. With the

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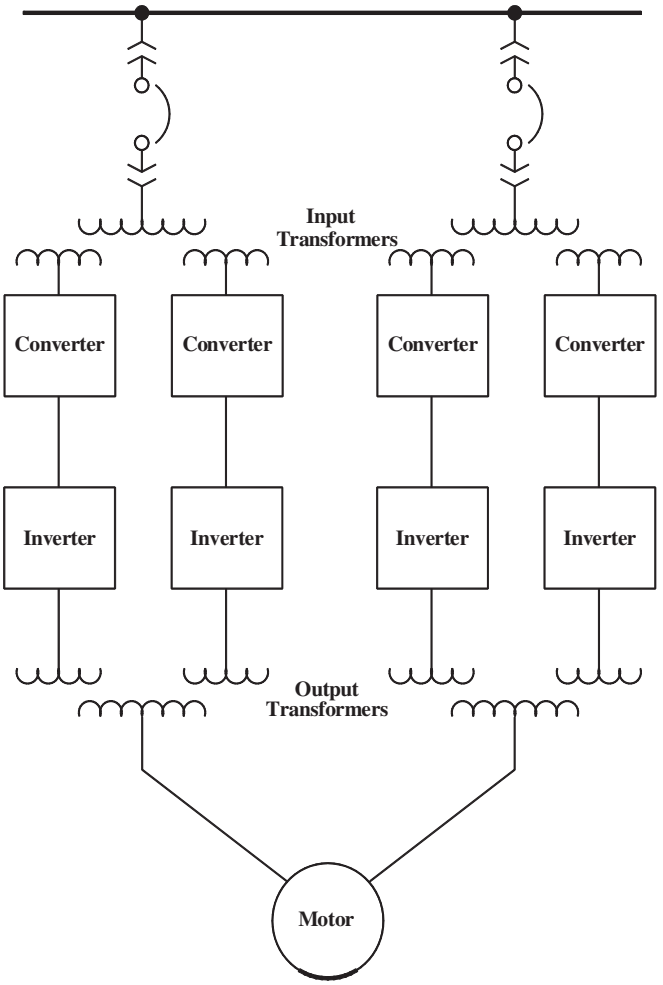


Figure 39—Conventional 24-pulse ASD with dual winding motor

conventional configurations, the ASD can be designed to continue to operate with one channel out-of-service similarly to the dual channel twelve-pulse ASD. In the case of the multi-pulse system of Figure 40, power cell bypass schemes or redundant power cells can be used (Hammond [B8]).

9.5 Serving multiple loads

The previous discussions have concentrated on ASD configurations intended for serving a single motor load. However, for certain applications it may be possible to serve multiple loads from a single ASD or configure the ASD to serve more than one load. Subclauses 9.5.1, 9.5.2, and 9.5.3 will address the most common applications.

9.5.1 Line synchronizing scheme

Some of the earliest drive system applications were installed to modulate flow in a multi-load system similar to the one shown in Figure 42. The drive system is aligned to one of the motors and the motor speed and thus process flow is controlled. As system load increases to the point where it exceeded the capacity of a single load, then that load is synchronized to the line and the drive aligned to a second

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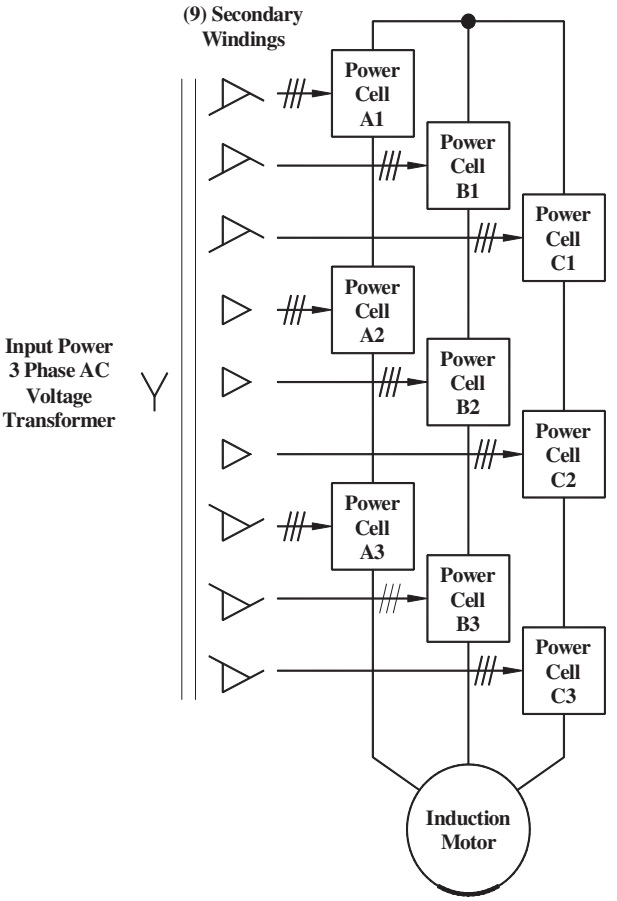


Figure 40—Multilevel 18-pulse power cell VSI-PWM topology

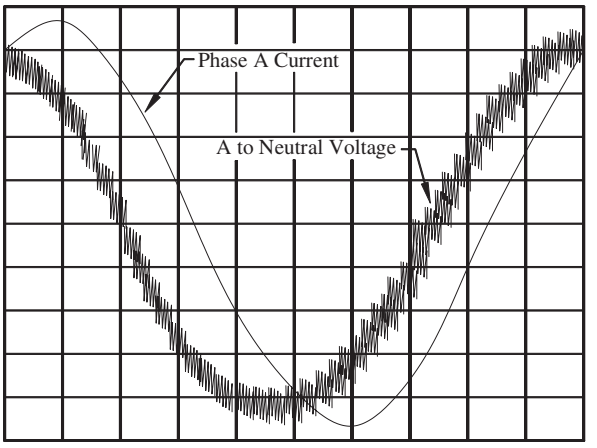


Figure 41—Output voltage for multilevel 18-pulse power cell VSI-PWM

motor. The process is repeated as required to meet the increased demand. Reduction in demand is accommodated in the reverse order.

The ASD can be either a CSI or VSI converter design. To ensure acceptable performance the individual motors should have very similar characteristics. If the system motor characteristics vary

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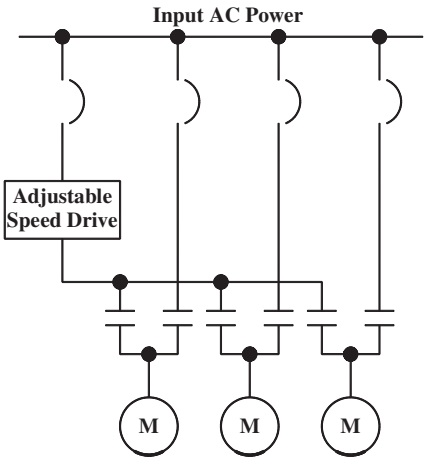


Figure 42—Line synchronizing scheme for serving multiple loads from single ASD

significantly, the ASD controls cannot be tuned to give good operating performance when supplying the different motors.

9.5.2 Common ASD

Another application where a single ASD has been used to supply multiple loads is to connect or *bus* all the loads together on the output of the ASD (see Figure 43). This arrangement does not permit

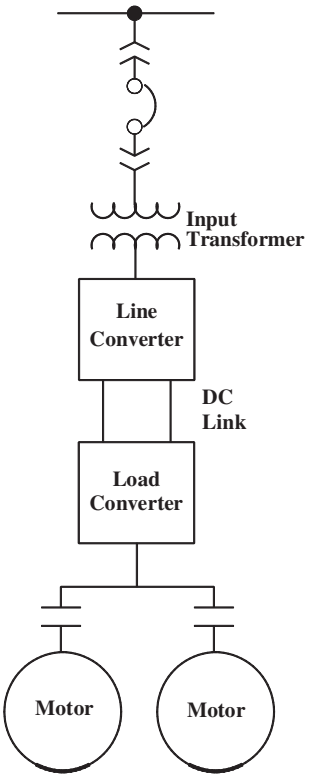


Figure 43—Common ASD serving multiple identical loads

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individual speed control of the loads. The ASD supplies a common output and each motor load will operate at the speed corresponding to this output and the demand of its connected load.

The ASD can be either a CSI or VSI converter design. However, the VSI ASD is better suited for this application. There is a duality between VSI and CSI ASDs. The VSI requires a sufficiently large motor leakage reactance to limit harmonic peak motor currents. A CSI requires a sufficiently small motor leakage reactance to limit harmonic and peak motor voltages. Since the leakage reactance goes up as the motor power rating goes down, a CSI is not well suited for use on a system containing multiple motors that might require the starting of just one group of motors. It should also be noted that this CSI characteristic means that it cannot be operated without damage if there is no motor load connected to its output.

If a CSI ASD is used, the individual loads should be identical to insure equal sharing of drive current. Each motor will operate at the same speed and load for this configuration. Only limited success in these applications has been obtained with CSI ASDs due to the inherit problem of balancing drive current between the motors, and, is therefore not recommended.

9.5.3 Common dc link ASD

Figure 44 shows the common dc link ASD. This arrangement is also referred to as a *Common dc Bus*. The ASD must be a VSI converter design. A single line converter supplies the dc bus with individual load converter supplied for each load. This arrangement permits speed control of the individual loads.

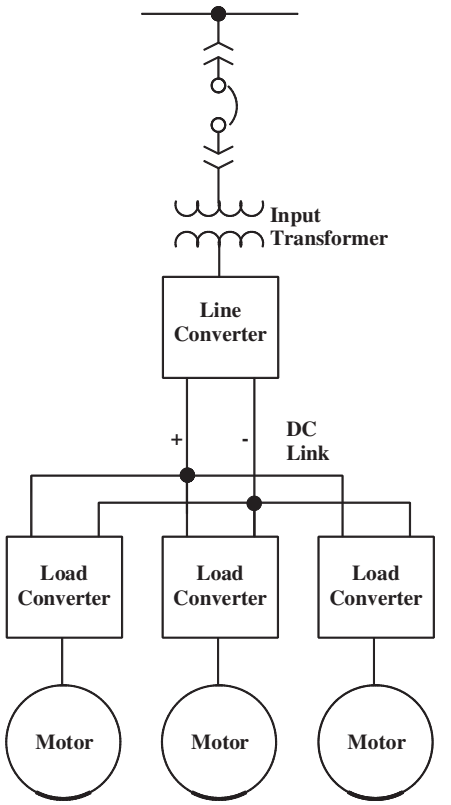


Figure 44—Common dc link ASD serving multiple loads

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9.6 Selection of ASD configuration

The selection of the ASD configuration is based primarily on the following factors:

a) Requirements of the application (load and process to be controlled)
b) Size of the load
c) Economics considerations
d) Harmonics considerations
e) Reliability

Many of these factors are interrelated and they must be weighed against the design objective for the installation. In other words, the selection process for determining the appropriate ASD configuration to employ must be integrated into a set of design objectives that include the design and operation requirements of the generating station where the ASD is to be applied.

9.6.1 Requirements of the application

The application of the load the ASD is applied to has a significant impact on the ASD configuration selected. A single ASD can be used for any application. However, in some applications it may be possible to utilize a single ASD to serve multiple loads.

9.6.2 Size of the load

As noted previously, there are practical limits on the maximum power capability of the various ASD configurations but, in general, both the six- and twelve-pulse systems can be provided with power capabilities necessary for the majority of power plant loads. Except in the case of very large motor loads, the selection of twelve or higher pulse number systems is generally based on harmonic and reliability issues instead of power limits.

9.6.3 Economic considerations

The cost of the ASD is one of the primary factors in electing to use ASD technology. Since the six-pulse drive system is the simplest ASD configuration, it generally represents the lowest cost system. However, it may not be the most economical. Other design objectives such as reliability and harmonics can have a significant impact on the overall ASD installation cost. The incremental cost for using higher pulse ASDs should be evaluated against the cost and potential problems of using harmonic filters.

One of the major cost factors in the ASD itself is the voltage rating of the power electronics converters. The voltage rating is determined by the number of series solid-state power semiconductor devices provided in each leg of the converters. As the operating voltage increases the number of series devices required (and associated heatsinks, snubber circuits, and device protection components) increases resulting in higher cost. For new installations, which utilize an input transformer, the ASD designer has the flexibility to choose both the voltage rating of the converters and the motor by stepping down the source voltage with a transformer.

When retrofitting intermediate-size motors (150 kW to approximately 1000 kW) or high-voltage motors (6600 V and 13 200 V), it may prove more economical to design the converters for a lower voltage class than the rated voltage of the source and/or the motor. This can be accomplished by two methods. The first method utilizes step-down and step-up transformers for interfacing with the system

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and the motor. This arrangement permits the ASD designer the flexibility to optimize the voltage rating of the converters. The second method utilizes a multi-winding step down transformer and multiple low-voltage power cells per phase (see Figure 40). The cost of the converters for various rated voltages can be evaluated versus the cost of the power transformers required to implement either arrangement.

9.6.4 Harmonics considerations

As previously stated, harmonic currents and the resulting electric service supply harmonic voltages caused by the applications of ASDs are a major design consideration. The larger the load supplied by the ASD the larger the harmonic distortion it can create. Also, if additional ASDs and other rectifier type loads are connected to the same electric service source the level of harmonic distortion may be even larger. There are basically three approaches available to reduce the magnitude of harmonic distortion. The first method is to apply harmonic filters to the electric service bus. The second approach is to apply an ASD with a higher pulse number. The final method is to utilize a combination of harmonic filters and an application of an ASD with a higher pulse number to selected loads. Whichever method is selected should be based on an evaluation of the cost of the various approaches and the other benefits and/or potential concerns they may create.

9.6.5 Reliability

The level of reliability required in the ASD depends primarily on the criticality of the load it supplies. If shut down of the ASD and thus the load has a major impact on the output of the generating station then selection of an ASD configuration providing a higher degree reliability can usually be justified. In the proceeding discussion, the various methods available to enhance the reliability of each ASD configuration has been presented. The application engineer should weight these reliability enhancements against the overall requirements for the installation.

10. Adjustable-speed drive application considerations

This clause addresses the application/design considerations related to major components of the ASD. The ASD is a system, composed of many components including transformers, reactors, dc linked converters, filters, power isolating and switching devices, and motors. The parameters of each component affects the operation of the others. The components are interdependent. Each design parameter must be closely coordinated to achieve a successful ASD application. Figure 45 provides an overview of the ASD system and denotes the subclauses where specific information is presented on the functions, requirements, and ratings of the ASD components addressed.

10.1 Electromagnetic elements

This subclause covers the design considerations of the primary electromagnetic elements of the ASD. These electromagnetic elements are the line reactors, input transformers, and output transformers.

10.1.1 General requirements for electromagnetic elements

All electromagnetic elements should be specified for *Rectifier Service*. The electromagnetic components should be designed to accommodate the rated current and voltage requirements of the ASD including

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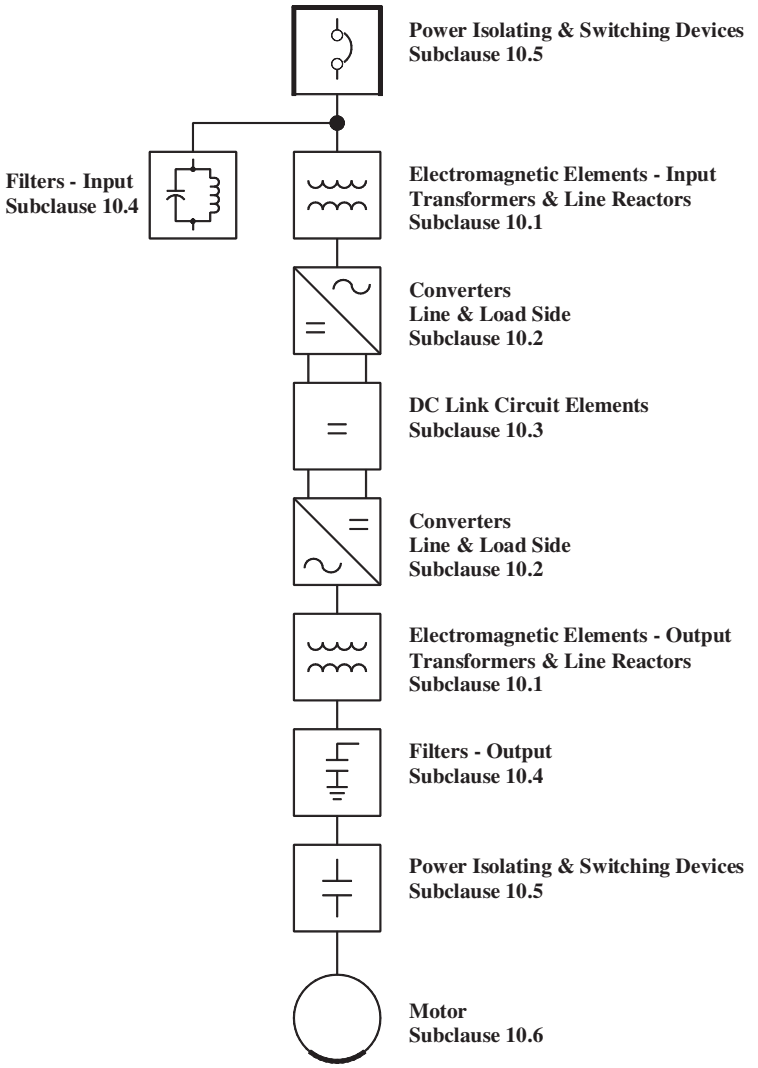


Figure 45—Major components of adjustable-speed drive

the harmonic currents for the particular converter. Conservatism is recommended in regards to temperature rise and insulation withstand capability.

The temperature rise of the electromagnetic system elements should be based on the ASD rating and should include the heating effects of the identified harmonics from the converter. As a guide the following multipliers may be used to account for the additional heating and losses in the power transformers (see Annex E):

a) Six-pulse converter load amperes times 1.25
b) Twelve-pulse converter load amperes times 1.10

Margin in the rated current or kVA of the element is recommended. This margin can be obtained by

1) Specifying a higher rated kVA or current than expected
2) Specifying a lower temperature rise
3) Specifying optional forced cooling

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In the case of forced cooling, it is recommended that the self-cooled rating be adequate for normal expected ASD currents and the forced cooling used only if the temperatures of the electromagnetic elements exceeds acceptable levels after ASD start-up.

For ASDs with multiple channels that are designed to operate with one channel out-of-service, the potential for increased loading of the electromagnetic element should be considered. The load imposed on these elements when one channel is out-of-service, may be higher than for normal operation. This is especially true if the channels are oversized. The effects of the higher loading resulting for channel-out conditions can be addressed in two ways. One is to specify additional temperature margin over those used for normal ASD operation. The other is to operate the elements at a higher temperature during this abnormal operating condition.

Margin in the insulation withstand capability of the electromagnetic elements is also recommended because of the increased voltage stress resulting from voltage transients caused by converter operation and/or common-mode voltages.

One approach in dealing with this increased voltage stress is to specify a higher than normal basic impulse level (BIL) for the transformer windings.

Energy losses for electromagnetic system elements shall include a separate calculation to determine the losses associated with harmonic impact. When temperature rise tests are specified, the test should be performed at the equivalent thermal loading expected for ASD operation (IEEE Std C57.12.01-1998).

10.1.2 Input transformers

The input transformers provide the following functions (Higgins et al. [B10]):

a) A buffer between the ac electric service source and the converter to minimize voltage disturbances of the ac source voltage and limits the let-through current available at the input converter during normal commutation, commutation failures and/or short-circuit in the converter or dc link.
b) Prevents the circulation of triple harmonic currents if the ac source is grounded.
c) Provides the required phase shifts for twelve and higher pulse ASDs.
d) Provides the correct converter supply voltage if the rated voltage of the converter is different than the nominal ac electric service source voltage.
e) Controls common-mode voltage at the motor windings with the correct grounding.

Because of the isolating effects the transformer provides between the ac source and the input line converter it is also referred to as an *isolation transformer*. Because of the significant benefits the input transformer provides, it should be considered for all ASD applications.

Input isolation transformers will have two or more windings depending on the ASD configuration requirements. Either liquid filled or dry type transformers can be used. In general, the input transformer(s) should be designed to meet the requirements of the ANSI transformer standards (IEEE Std C57.12.00-2000).

The impedance of the transformer is selected by the ASD designer to satisfy the design parameters set for the ac electric service source and the ASD. Thus, the impedance used for the different types of ASD can vary from a low of 5% to a maximum of 12%.

To maximize the harmonic reduction provided by twelve and higher pulse ASD systems, it is important that phase displacement of the various transformer windings be very close to the specified values and that the impedance of each winding not exceed the specified tolerance. Where the ratio of

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the primary to secondary voltage is equal to or greater than three, an electrostatic shield between the primary and secondary windings of the transformer is recommended to reduce electrostatic coupling of the high-frequency harmonics.

10.1.3 Output transformers

The primary functions of an output transformer are the following:

a) Provides the required phase shifts for twelve and higher pulse ASDs.
b) Provides the correct motor voltage if the rated voltage of the converter is different than the nominal motor voltage.

The output transformer can be of either the autotransformer type or power transformer type. Either liquid filled or dry type transformers can be used. In general, the output transformer(s) should be designed to meet the requirements of the ANSI transformer standards (ANSI C50.41-2000, IEEE Std C57.12.00-2000). However, the requirements for output transformers must consider the characteristics of the power supply source from the ASD load side converter. As this supply source represents an adjustable-voltage, adjustable-frequency power supply, the design of the transformer must address the supply source characteristics for the full V/Hz operating range.

The impedance of the output transformer is selected by the ASD designer based on the converter type, the ratio of the required voltage, the distance between the load converter and the motor and the ASD operating requirements.

10.1.4 Input line reactors

Input line reactors can be used in place on the input transformer if the ASD is a six-pulse system and the rated voltage of the converter is designed to match the ac electric service source nominal voltage. As with the input transformer, the impedance of the input line reactors provides a buffer between the ac electric supply and the line converter to minimize voltage disturbances of the ac source voltage and limits the let-through current available at the converter during normal commutation, commutation failures, and/or short-circuits in the ASD's converter or dc link. However, the line reactors provide no isolation to prevent the circulation of triple harmonic currents or ground fault currents. For this reason, input line reactors are not recommended for medium-voltage ASD applications.

10.2 Converters

10.2.1 Power semiconductors

The primary power semiconductors utilized in large ASD converters include diodes, thyristors, gate-turn-off thyristors, IGCTs, and IGBTs. The basic differences between the devices are listed in 10.2.1.1, 10.2.1.2, 10.2.1.3, 10.2.1.4, 10.2.1.5, and 10.2.1.6.

10.2.1.1 Power diodes

A diode is an uncontrolled device that will conduct current in one direction. The device turns on and off relevant to its applied voltages when properly biased without control. A power diode requires no auxiliary circuits for control.

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10.2.1.2 Power thyristors

A power thyristor includes an integral gating circuit which allows the device to be turned on by an external electronic gating circuit when properly biased. To accomplish the switching action a control circuit, including a signal circuit, a relatively low power gate unit and a power supply source, must be provided for each device.

10.2.1.3 Gate-turn-off (GTO) thyristors

A GTO differs from the power thyristor in that the gating circuit allows the device to be switched on when forward biased and switched off at any time. Like the power thyristor, the GTO thyristor requires auxiliary control to accomplish the switching actions. The gate unit power requirements of the GTO are higher than those for the power thyristor.

10.2.1.4 Integrated gate-commutated thyristor (IGCT)

The fundamental difference between a conventional GTO and the IGCT lies in the very low inductance gate drive system, inherent to the IGCT.

10.2.1.5 Insulated gate bipolar transistor (IGBT)

IGBTs are widely used in low-voltage ASDs because they are a low-cost, three-terminal power switch that can be turned on and off by a voltage signal reliably and efficiently.

10.2.1.6 Bipolar transistors

Bipolar transistors are controlled non-latching switching devices that can be turned on by applying a current signal to the device's gate and turned off by removal of the signal.

10.2.2 Rating and selection of power semiconductor

The power semiconductors are generally rated based on the following:

a) Peak forward and reverse blocking voltage
b) On-state current
c) Maximum permissible junction temperature
d) Switching time
e) Surge on-state current

Various dynamic data and criteria, including switching time and rate of response to voltage and current, enter into the detailed design of the converters. Each of these parameters must be carefully evaluated when selecting the power semiconductor device to be used in the converter.

As solid-state power device technology has evolved, higher voltage and current carrying capacity devices have become available to the converter designer. With these higher capacity devices, it has become practical to implement higher power converter designs with fewer power semiconductor devices. These advances in technology have resulted in lower cost for the converters and thus, the ASD.

10.2.3 Converter cooling

10.2.3.1 Power converter cooling

Converters used in large ASDs can be cooled by air or liquid cooling. The configuration and design of the cooling system is a critical element in the overall reliability of the ASD. The design of the ASD equipment enclosure and cooling system for the converter must consider the environment of the

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installation. For fossil fuel generating stations, the presence of airborne contaminants makes closed loop, liquid-cooled systems preferred for these locations (Oliver and Samotyj [B28]).

A prime element of the converter cooling system is the design of the heat sink for the basic semiconductor control elements. The heat sink design should ensure that there is adequate heat transfer from the case of the power semiconductor device to the heat sink. The junction temperature of the power device should be maintained at least 10% below the maximum allowable junction temperature limit. This temperature limit is generally between 125 °C and 135 °C depending on the power semiconductor device applied. In an air-cooled system, the heat sink cooling fins should be designed so they are self-cleaning.

In an air-cooled design, two 100% capacity cooling fans are recommended. In this redundant fan arrangement, the fan controls should be designed to automatically transfer to the back-up fan for a fault of the primary fan with annunciation of the specific system failure.

If a liquid-cooled system is applied, the selection of the cooling transport mechanisms, piping, headers, valving and surge tanks should consider the installed life expectancy of the converter system. The materials utilized in the design of the system should minimize ion build up. Cooling system heat dissipation effectiveness over time due to fouling should also be considered. It is recommended that liquid-cooled systems be equipped with two 100% capacity pumps with automatic transfer provisions, and annunciation of a faulted pump. An in-service replaceable deionizer is also recommended. Typically the deionizer cartridge should have a median life of 18 to 24 months. All stainless steel piping is generally preferred for the cooling water system.

10.2.3.2 Control and excitation cubicle cooling

The cubicles that contain the controls for the ASD and if applicable the excitation controls are generally not cooled by the cooling system provided for the power converters. The control cubicles are either self-cooled or utilize internal cooling fans, for circulation of air within them. Where forced air-cooling is provided, two 100% capacity fans with automatic transfer to the stand-by fan and annunciation of the faulted cooling fan is recommended.

10.3 DC link circuits

The dc link circuits include dc inductors and/or capacitors. The functions of these circuit elements are the following:

a) To smooth (filter) the dc current created by the line side converter
b) To effectively decouple the line and load converters
c) To limit the injection of non-characteristic harmonics into the ac electric service source
d) To provide to the load side converter an adjustable and continuous dc current for CSI or dc voltage supply for the VSI.

The dc link may also contain auxiliary circuits and elements. An example is the diverter circuit elements used in the dc link commutated CSI discussed previously.

In this subclause, the basic criteria, the implementation goal for the design circuit, and the requirements for special protection or isolation provisions will be addressed.

10.3.1 DC link inductors for CSI applications

The dc link inductors for CSI applications are generally air-core inductors. Two inductors per dc link are recommended to minimize common-mode voltages. They are normally mounted external to the

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rest of the ASD cubicles. If the inductors are to be located outdoors an appropriate enclosure should be provided.

The inductors are generally air-cooled with either self- or forced-cooled configurations. Self-cooled designs offer enhanced reliability over the forced-cooled designs. It is recommended that the allowable temperature rise and insulation withstand rating of the dc link reactors be conservatively selected.

The criteria for selecting the inductance of the dc link reactor are as follows:

a) Limit the rate-of-rise of the current to a step change in the dc voltage from the line side converter. Such a step can be caused by an instantaneous change in the ac electric service source voltage or a change in gating of the converter.
b) Limit the rate-of-change of the current in the event of a commutation failure in the load side converter.
c) Limit the current ripple in the dc link circuit to an acceptable value. Typically the current ripple should not exceed 15% rms.
d) Limit interharmonics impact from the load side converter to the power supply. It is noted that these interharmonics are generally not synchronized to line frequency.
e) Limit lower frequency torque pulsations from the motor. These torque pulsations result from differences in the instantaneous dc voltages at the output of the line side converter and the input of the load side converters and the resulting current flows that occur at specific speed. These torque pulsations are most prevalent in ASDs with six-pulse load side converters.

Energy losses for electromagnetic system elements should include a separate calculation to determine the losses associated with harmonic impact. When temperature rise tests are specified, the tests should be performed at equivalent thermal loading expected for ASD operation.

10.3.2 DC capacitors for VSI applications

The capacitors for VSI application are typically dry type. The capacitors are normally mounted in a separate cubicle or cubicles of the ASD layout. An isolation/grounding switch for capacitor discharge is required. This switch should be interlocked with the capacitor cubicle doors to prevent personnel access until the dc link circuit is properly isolated and a zero voltage condition exists.

Conservatism is recommended in selecting the rated voltage of the capacitors. A rated voltage of at least 125% of the maximum operating voltage of the dc link system is recommended. The capacitors should also be individually fused or fused as part of the overall dc link protection scheme.

10.3.3 DC link commutation circuits for CSI applications

The dc link commutating circuits for CSI applications typically contain several thyristors, an inductor and capacitors. The design and ratings of these circuit elements should follow the applicable requirements for converter basic control elements, dc link inductors, and dc link capacitors except as follows:

a) The commutation inductor may be a water-cooled design and located in the commutation circuit cubicle.
b) The commutation capacitors should be individually fused.

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10.3.4 DC link inductors for VSI applications

Where applicable, the design and ratings of dc link inductors for VSI applications should follow the applicable requirements of 10.4, except inductors may be water-cooled and located in one of the ASD cubicles.

10.4 Input and output filters

Input or line filters are applied to filter objectionable harmonic currents generated by the ASD or other nonlinear loads. Output filters also provide a harmonic filtering function. They are also applied for load converter commutation and to shift harmonic resonance frequencies.

10.4.1 Input or line harmonic filters

Input or line harmonic filters are designed to reduce harmonic effects on the ac electric service source and other generating station equipment. These filters are designed to provide a low-impedance path for specific harmonic currents generated by ASDs and other nonlinear loads. For a given application, harmonic filters may or may not be required depending on the characteristics and limits established for the ac source and the magnitude of the harmonics being injected. A harmonic analysis of the power distribution system is required to evaluate the effectiveness and design parameters for the filters. For additional discussion on harmonic analysis refer to IEEE Std C57.110-1998 and Nilsson [B25]. Note the harmonic filters will also have an effect on the 60 Hz electric service bus voltage from reactive contribution to the ac voltage.

Harmonic filters are comprised of ac capacitors, ac inductors, and possibly resistors and control components. One filter circuit is provided for each harmonic to be filtered. Fifth and seventh harmonic filters normally include capacitors and inductors only. Eleventh and higher order harmonic filters normally include resistors in parallel with the ac inductors.

Input filters can be installed on the primary side of the input transformer or connected directly to the ac electric service source bus. The input filter's rated voltage is based on the nominal voltage rating of the ac electric service system at the connection point. The insulation withstand capability of the inductors and capacitors is generally matched to the rating of the input transformer primary.

The thermal rating of the filter components should be conservatively selected. Input harmonic filters should be avoided, if possible. Filters should be detuned slightly from the designed harmonic to prevent overloading from external harmonic voltages (IEEE Task Force Report on the Effects of Harmonics on Equipment [B19]).

Temperature rise calculations should consider both the fundamental and harmonic currents. It is recommended that all filter components be thermally rated for operation without supplementary cooling.

The ac capacitors are normally liquid filled and of a porcelain bushing type design. Individual fuses are provided for each capacitor and the number of capacitors applied in the circuit is normally designed to allow for the loss of a single capacitor without impacting filter performance.

AC inductors can be either air-core or iron-core design. Filters utilizing iron-core reactors can normally be located in a common cubicle along with the capacitors. Air-core reactors require significantly more space to ensure that there is no magnetic linkage between reactor components and nearby metallic objects. Normally air-core ac reactors are designed for open installation in a switchyard location but if enclosures are required they should be non-magnetic.

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When iron core designs are considered, care must be taken to determine the specific inductance of cable runs to ensure proper tuning of filter circuits.

Primary filter isolation is typically provided by means of either an electrically operated disconnect switch or circuit breaker. A grounding disconnect switch for discharging the filter's capacitors should be provided and interlocked with access provisions such that personnel cannot gain access to the filters until the capacitors are fully discharged.

10.4.2 Output filters

The application of output filters is common in ASDs supplying induction motors. The primary filter elements are capacitors, but inductors may be required to avoid harmonic resonance at certain operating speeds. The output filter provides the following functions:

a) Commutation source for the load side converter on LCIs
b) Excitation source for the motor
c) Harmonic filter

The output filter capacitance is highest for the modified load commutated induction motor drives and lowest for PWM-VSI drives. VSI drives may not require output filters.

The specification requirements for the capacitors and inductors basically follow those defined for the input filter except that these elements are now being fed by an adjustable-voltage, adjustable-frequency power supply. A contactor or circuit breaker is normally provided between the output filter and the motor to automatically isolate the motor from the filter capacitor upon ASD shutdown or power loss. The automatic isolation is provided to prevent the possibility of over-exciting the motor.

10.5 Power isolating and switching devices

ASDs generally contain several power isolating and switching devices. These devices can include no-load disconnect switches, circuit breakers, contactors, and grounding switches.

10.5.1 Isolation devices

The most common application of isolation devices is in multi-channel ASDs such as the dual channel twelve-pulse system shown in Figure 35. For this application it is common to provide isolation devices at the input and output of each channel so that a faulty ASD channel can be isolated and the other channel remain in service. Typically, the isolation is provided by load break devices such as contactors or circuit breakers.

The application of contactors or circuit breakers permit isolation of the faulty channel without ASD shutdown. If the isolation device is properly designed it can also serve as clearance for maintenance of the out-of-service channel.

No-load break isolation switches may be provided at select points in the power circuits of the ASD to facilitate safe maintenance.

Continuous voltage and current ratings for the isolation devices must be coordinated with the design values for the power circuit location where they are to be applied. Derating of the continuous current and load current interrupting capability due to harmonic currents may be necessary especially for

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air magnetic type interrupters. Vacuum interrupters are less sensitive to the harmonic load currents (IEEE Task Force Report on the Effects of Harmonics on Equipment [B19]).

The device short-circuit rating must be adequate for the maximum short-circuit currents at the point of application. Since short-circuit levels within the ASD are generally much lower than at the ac electric service source, reduced short-circuit ratings may be practical for some of the isolation devices.

10.5.2 Grounding switches

ASDs provided with dc link or output filter capacitors should be provided with grounding switches as standard practice. These grounding switches should ensure capacitor discharge occurs before personnel access to the capacitors is permitted. Where capacitors are located in enclosures, the cubicle doors should be interlocked with the switch. No-load break switches are generally adequate for this application.

10.5.3 Transfer switches

Transfer switches are required in applications requiring transfer of the motor between the ASD and the ac electric service source or between ASDs. Examples of ASD configurations requiring transfer switches are the bypass scheme (see Figure 33), standby power unit (see Figure 34), and the line synchronizing scheme for multiple loads (see Figure 42).

Depending on the application needs, disconnect switches, contactors or circuit breakers can be provided to transfer between alternate sources. Where on-line transfer is required, the use of contactors or circuit breakers is required. Where the transfer can be made after a shutdown of an affected system, disconnect switches provide a more economical alternative.

In cases where transfer to a spare ASD power unit, or to across-the-line operation is required, the switches must be interlocked to assure that the proper circuit connection is complete. In the case where in-service repair of a faulted element is being considered, the use of draw-out devices should be considered.

10.6 Motors

The function of the motor is to develop the required torque to drive the load at the desired speed. Thus, the motor represents a significant interface between the ASD and the driven load. Design consideration for the motor depends on what type of ASD, including motor type, is applied. The characteristics of the motor torque effects design considerations for the rotating mechanical system comprised of the motor and the driven load. This subclause focuses on the design consideration for the motor. Considerations involving the interactions of the motor torque and the driven load are discussed in Clause 11.

When applying a motor for ASD service many of the traditional design requirements for constant speed motors apply [IEEE Std 995-1987(W)]. However, additional design issues arise when variable voltage, variable frequency, and speed are involved. Other design issues result from the harmonic distortion in the voltage and/or current and other voltage transients impressed on the motor by the different converter configurations. The following are the most significant general design requirements for motors when applied to ASDs:

a) Motor flux
b) Torques

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c) Losses, temperature rise, and cooling
d) Bearing lubrication, and insulation
e) Voltage stresses, including fast transients, i.e., high *dv*/*dt* rates
f) Electrical parameters
g) Starting
h) Accessories

Each of these design issues must be addressed whether the application is considering a new definite purpose motor designed for ASD applications or an existing motor is being retrofitted to ASD service. However, the method used to deal with these design issues can vary significantly between the two cases. In the case of a definite purpose ASD motor, the design of the motor can be coordinated with the design of the load side converter and either modified to provide the best overall ASD/motor system performance.

In the case of a retrofit, the suitability of the motor has to be determined through a design evaluation that may include a combination of a detailed engineering assessment, inspections, and/or field tests.

10.6.1 Motor flux

Stator voltage magnitude is one of the operating parameters of the motor varied over the adjustable-speed range. The motor voltage is a function of per unit flux times per unit speed (frequency). Therefore, flux is proportional to the V/Hz applied to the motor.

One of the more common modes of operation of an ASD is referred to as *constant V/Hz operation*. In general, this mode is limited to a region from some minimum operating speed to base speed (design speed for rated voltage and frequency). The lower limit is defined by motor thermal limits, bearing lubrication, or in some cases potential resonance between the motor reactance and the filter capacitance. Thermal limits and bearing lubrication are discussed in this subclause later. Limitation due to resonance between the motor reactance and the filter capacitance is limited to induction motors where a capacitive filter is required.

The upper limit on constant V/Hz operation is approached by reaching rated voltage at base speed. Thus, the voltage cannot be increased with frequency above this design point. If the application requires operating at speeds above base speed, then the voltage must remain fixed for further increases in frequency. This transition results in constant power operation above base speed (see Figure 46).

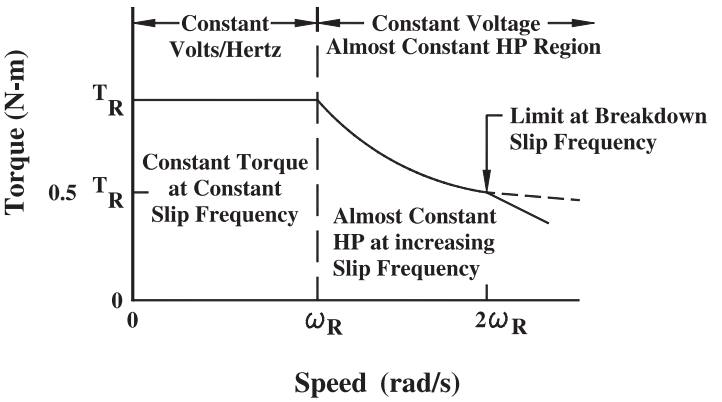


Figure 46—Limitation of V/Hz operation for ASD

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To optimize the performance of the ASD to the application requirements of the process, it may be desirable to use a unique flux profile rather than operate in the constant V/Hz mode. Changing the flux changes the speed–torque characteristics of the motor. By controlling the output of the ASD and the excitation in the case of a synchronous motor, the motor flux can be tailored to provide the desired torque at a given speed. The desired flux profile may apply for all or a portion of the operating speed range. An example of where this approach is particularly appropriate for a fan or pump type load where torque varies with speed squared. For this case the motor can supply the required load torque at a flux level lower than the rated value resulting from constant V/Hz mode. The key point in applying a flux profile different from constant V/Hz is that the motor flux must never exceed rated flux in order not to saturate the magnetic circuit of the motor.

10.6.2 Torques

When the motor is supplied from the output of a converter, two types of torque are produced. The first is the useful torque that results from the fundamental flux and current. This is the torque that drives the load at the desired speed. The second type of torque is produced by the interaction of the flux and the harmonics in the motor current. These torques are referred to as *harmonic torques*. The harmonic torques can cause objectionable vibrations in the rotating mechanical system comprised by the motor and the load.

The existence of harmonic torques can impact the performance and design of the motor. The oscillatory nature of these torques result in impact loading on the motor bearings and bearing supports that may require stiffening the frame and changes in the bearings. The harmonic torques can also excite mechanical resonances in both the fixed and rotational elements of the motor resulting in unacceptable vibration and noise. Examples of potential problems are cooling fan blades, the enclosure, stator core and supports, and stator end windings.

Per Part 30.02.2.7 of NEMA MG-1-1998, only momentary operation is permitted at speeds exciting resonance of motor components. If continuous operation at these speeds are required, then mechanical modifications are required to shift the resonance of the effected components. The avoidance of resonance problems is further complicated by the variable nature of the sources of the excitation. Since the motor speed and the frequency of the currents vary over the speed range, the resulting frequencies of the excitation for the vibrations also varies with speed.

10.6.3 Losses, temperature rise, and cooling

Evaluation of motor performance when applied to ASD service must consider the effects on motor losses, temperature rise, and cooling. These thermal effects are discussed in 10.6.3.1 and 10.6.3.2.

10.6.3.1 Losses

The losses in a motor are generally segregated into the components listed in Table 2 (IEEE Std 112-1996 and IEEE Std 115-1995).

For ASD operation, the motor losses at rated load and base speed will increase and the efficiency will decrease. The motor losses are affected by load, the presence of harmonics in the motor currents, flux levels, and speed (frequency). Motor loading and harmonic currents primarily effect stator, rotor, and stray load losses. Core, windage and friction losses are primarily dependent on flux level and/or speed. Exciter losses, where applicable, depend on the level of excitation required by the synchronous motor. Loss increase may or may not be significant.

10.6.3.1.1 Load and harmonic losses

The effects of load can be approximated by adjusting the rated load losses (stator, rotor, and stray) by the square of the per-unit load. However, when operating a motor from an ASD, additional losses may

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Table 2—Motor losses segregated and compared with ASD operation

Segregated losses	Description	Effect from ASD operation
Stator load loss	Stator I^2R	Increases from higher rms current and stator winding temperature
Rotor load loss	Rotor I^2R	Increases from higher rms current, skin effect in induction motor rotors, and rotor winding temperature
Core loss	Hysteresis and eddy current	Flux level (V/Hz) and frequency
Stray load loss	AC losses in conductors and structural parts of the machine	Load current and frequency
Windage and friction loss	Mechanical	Vary with speed
Exciter loss	Synchronous motors	Excitation

need to be included from harmonic currents. The level of increase in the load losses is a function of the type of load side converter.

The stator load losses may increase from harmonics in the stator current. Stator winding losses may also increase from increases in conductor eddy currents at the harmonic frequencies. The harmonic effect on the conductor losses is accounted for by increasing the stray load loss.

The increase in the rotor losses due to harmonic currents is even more significant. The frequency of the rotor currents induced in the rotor by stator currents is given by Equation (11):

$$f_r = sf_s \tag{11}$$

where

s is the motor slip (pu),

f_s is the fundamental frequency of stator current (Hz).

When supplied from a sinusoidal source, the slip for a synchronous motor is zero and no currents are induced in the rotor. The rotor currents flow only in the main field winding and are dc quantities originating from the dc excitation. In the case of an induction motor, the normal operating slip is low resulting in induced rotor currents of very low frequency, typically on the order of 1–2 Hz for all but class D motors. However, for ASD operation, the harmonic currents in the stator windings induce rotor currents in the rotor with frequencies of "$p \times k$" times the fundamental stator frequency where p is the inverter pulse number and k is any positive integer.

In the case of induction motors, these harmonic currents are induced in the rotor cage winding and result in higher rotor losses. The loss increase is from an increase in the rms value of the rotor current, and an increase in the effective rotor winding resistance from skin effect and the temperature.

In the case of a synchronous motor, the harmonic currents will be induced in the pole faces or in pole face windings (amortisseur or damper winding) where applicable. The net effect is serious unless dual, 30° displaced stator windings are used.

Combining the effects of harmonics and load yields the following approximate expression, Equation (12), for adjusting the load components of motor losses for ASD operation:

$$\text{Load loss} = (\text{per unit load})^2 \{(1 + k_{hs})I^2R_S + (1 + k_{hr})I^2R_R + (1 + k_{hsl})(f_s/f_b)^{1.4}SL\} \tag{12}$$

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where

I^2R_S	is the stator load loss in W for sinusoidal supply and rated load,
I^2R_R	is the rotor load loss in W for sinusoidal supply and rated load,
SL	is the stray load loss in W for sinusoidal supply and rated load and frequency,
k_{hs}, k_{hr}, and k_{hsl}	are the factors to account for harmonic effects on stator, rotor, and stray load loss, respectively,
f_b	is the frequency in Hz at base speed and rated load,
fs	is the fundamental frequency of stator current in Hz.

The magnitude of load loss increase for six-pulse LCI (synchronous motor) is 30% over the sine wave losses and 15% over the sine wave losses for dual winding twelve-pulse systems [IEEE Std 995-1987(W)].

10.6.3.1.2 core losses

The core loss is effected primarily by the flux (V/Hz) and the frequency. In the case of induction motors, harmonics do appear to have some effect on the core loss but the increase is less than 5% (see Annex F). The following expression, Equation (13), provides an approximation of the adjustments in core loss for ASD operation:

$$\text{Core loss} = k_c(\text{V/Hz})^{2.5}(f_s/f_b)^{1.4} \tag{13}$$

where k_c is the core loss in W at rated flux and frequency.

10.6.3.1.3 Windage and friction losses

Windage and friction (W&F) losses are both functions of the mechanical system. The friction loss tends to vary directly with motor speed, with windage losses varying approximately as the cube of speed (Finney [B5]). However, these two loss components cannot be easily segregated during motor test. Thus, they are commonly considered jointly and approximated by Equation (14):

$$\text{W\&F} = k_{wf}(f_s/f_b)^2 \tag{14}$$

where

k_{wf} is the W&F losses in W at rated speed (frequency).

10.6.3.1.4 Exciter losses

For the synchronous motor, exciter losses must also be considered. Typically the exciters are shaft driven and a portion of the loss will vary with speed. The load loss has two basic components. The first component is related to magnetizing flux and does not change significantly with speed for constant V/Hz operation. The second component is related to the change in load current (see Figure 3) and can change by a factor of two or more from no-load to full load (Finney [B5]).

10.6.3.2 Motor cooling

The load capability of ASD operation may be limited by motor cooling. Motors are typically air-cooled by rotor mounted fans and the amount of cooling reduces as the speed of the motor (see Figure 47). The reduction in air flow requires a corresponding reduction in motor torque output for a given temperature rise (Owen and Weiss [B30]). In these cases the controls of the ASD are designed to reduce the voltage as the speed of the motor is reduced. If the load torque demand also reduces with speed such as for a pump or fan there is generally no real operating limitation. If the load torque demand is constant, then some form of auxiliary cooling must be provided to extend the permissible speed range

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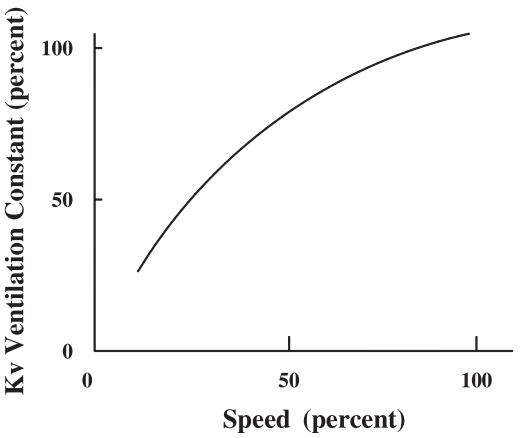


Figure 47—Typical ventilation capability versus speed of self-cooled motor

for constant V/Hz operation. Additional guidance on induction motors is provided in IEEE Std 995-1987(W).

10.6.4 Bearing lubrication and insulation

The following subclauses address bearing application issues.

10.6.4.1 Bearing lubrication

Proper bearing lubrications is an important factor for any motor application. However, the application of a motor to ASD service can expand the scope of this design issue. The lubrication issue relates primarily to the type of bearing (sleeve or anti-friction), operating temperatures of the lubricant and the intended operating speed range of the motor.

With an ASD, the motor speed can have a significant range. Motor operating speed is no longer limited to the narrow operating range at or near synchronous speed. Motor speeds can vary from extremely slow speeds of a few r/min when operating in turning gear mode to 5000 r/min or more when operating in a super-synchronous mode and anywhere in between. In oil ring lubricated systems, operation at both ends of the speed range must be evaluated. The amount of oil the ring delivers to the shaft and bearing is dependent to a large extent on how fast the oil rings turn. When operating at slow speeds, the ring speed may be insufficient to provide proper lubrication. During high-speed operation, the ring may slip on the shaft and not turn fast enough to maintain bearing lubrication. If the viscosity of the oil is low, due to cold temperatures, the problem is worse with the potential for oil ring slippage occurring for both low- and high-speed operation. These problems can be resolved by setting minimum and maximum operating speed limits, applying forced oil lubrication, or in some cases by using grease lubricated anti-friction bearings. The use of grease lubricated anti-friction bearings generally will resolve most low-speed operating concerns. However, anti-friction bearings do have maximum operating speed limitations (Electric Power Research Institute [B22]). Where oil ring lubricated motors are operated at very low speeds and in low ambient temperatures, oil reservoir heaters may be necessary.

10.6.4.2 Bearing insulation

Shaft voltages typically occur on all types of electric motors. If the shaft voltage reaches sufficient levels, the insulating capability of the lubricating film in the bearing will break down resulting in shaft currents that can cause bearing imperfections such as pitting and fluting, which can increase the bearing's rolling resistance that subsequently can lead to bearing failures. The source of the shaft

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voltages has traditionally been attributed to dissymmetry in the magnetic circuit of the motor. These shaft voltages were generally not a concern until the motor size approached 750 kW or larger where most manufacturers insulate the opposite drive end (ODE) bearing (Electric Power Research Institute [B22]). However, shaft current problems are occurring on low-voltage motors controlled by IGBT PWM type ASDs. Some investigators believe the shaft currents are a result of the shifting neutral voltage and the capacitive coupling effects across the bearing lubricating film (Busse et al. [B2]). Based on these observations, insulating both bearings and requiring shaft grounding devices should be considered for these type of ASD applications.

10.6.5 Voltage stresses

The characteristics of the primary voltage stress impressed on the stator windings of motors in ASD applications were discussed previously. How these voltage stresses effect the design and performance of motors is presented in the following subclauses. Since the vast majority of motors within the scope of this Guide have form wound stator coils, the following discussion is limited to this type of winding.

10.6.5.1 Line-to-neutral voltage stress

For ASD controlled motors, the line-to-neutral voltage at the motor terminals can be considerably higher than normal due to neutral voltage shift. The presence and magnitude of these voltages depend on the type and design of the ASD, the grounding system, and the use of an input transformer. Typical voltage magnitudes are shown in Table 3.

Table 3—Typical line-to-neutral voltage stress factors

Drive type	Voltage magnitude
Current source ASD	3.3 pu
Voltage source ASD	1.7 pu

where $1\,\text{pu} = (\sqrt{2}/\sqrt{3})\ V_{LL}$,
V_{LL} is the rated line-to-line voltage of the motor (V).

The application of dc link converter systems requires that proper design considerations be given to the system grounding and the voltage ratings of isolation transformers, the motor, and the power converters. An improperly grounded system can result in excessive ground currents circulating between the electric service source and the motor through the power converter and excessive voltages can occur between ac line or load terminals and ground. These voltages are caused by common-mode voltages generated in the power converter system.

Sequentially, the line and motor voltages are connected through the internal impedance of two phases each of the line and motor with the dc link inductors and the converter thyristors forming a closed loop. Although the voltage around the closed loop sums to zero, the voltage between the effective line neutral and the effective motor neutral does not sum to zero. The per unit magnitude of this voltage is dependent on the conducting angles of the converters and on the dc link inductance. If the line neutral is grounded, the voltage will appear between the effective motor neutral and ground and thereby increase the motor terminal voltage to ground significantly. Likewise, if the motor neutral is grounded, the voltage will appear on the line side.

The magnitude of the terminal-to-ground voltage at the motor can be as high as 2.4 times nominal crest voltage if care is not taken to correctly ground the system. Unless the motor is specifically

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designed for this voltage stress, the motor insulation life can be significantly decreased if the common-mode voltages are allowed to occur at the motor.

The motor terminal-to-ground voltage can be reduced by the following:

a) Isolating the source ground with an input transformer.
b) Utilizing separate reactors in both the positive and negative dc link.
c) Creating a load side neutral ground through an impedance.

If this design practice is properly followed, then neutral offset voltage can be reduced to nearly zero at the motor and to two times nominal phase voltage crest at the transformer line-to-ground. The transformer insulation system is designed for these voltage levels for long service operation.

In addition to grounding for proper ASD operation, safety grounding practices pertaining to transformer casings, motor housings and control cabinets should be followed. For long cable runs between the motor, converters and source circuit breakers and other disconnecting devices, cable tray and cable shield grounding requirements need to be addressed.

10.6.5.2 Commutation voltage spikes

There is widespread confusion about inverters producing voltage spikes that damage motor winding insulation. The confusion derives from two sources. There have been publicized reports of low-voltage motors failing from voltage spikes produced by IGBT PWM inverters. Also, synchronous motor LCI inverters produce significant commutating voltage spikes. From this information, it might be concluded that medium-voltage induction motor inverters produce damaging voltage spikes. This is not true. To clarify this issue, see the following discussion regarding voltage spikes on low-voltage motor/inverter systems and medium-voltage motor/inverter systems.

10.6.5.2.1 The problem of high *dv/dt* switching rates in inverters

Advances in ASD technology have resulted in high inverter switching rates in low-voltage-source PWM type ASDs. This has been done by ASD manufacturers 1) to reduce the current harmonics from the inverter to the motor and 2) to eliminate motor audible magnetic noise. The reduction of motor current harmonics has resulted in nearly negligible harmonic loss in the motor from inverter harmonics, so the motor does not have to be derated because of harmonic heating. It has also resulted in quieter motors, as the audible noise produced by high frequency harmonic resonance vibration of motor stator laminations has been eliminated. The audible noise reduction is good for motors driving air handler fans in air-conditioning systems, but is not a major consideration for many industrial applications.

The downside to 12 kHz or higher inverter switching frequencies in IGBT PWM ASDs has been cases of motor winding failures and motor bearing failures. High PWM inverter switching rates, in the 12 kHz range, are accompanied by high rates-of-rise voltages being applied to motor cables and the motors themselves. The rise time for inverter output voltage has gone from 0.5 μs to 2 μs with bipolar voltage-source ASDs to as short as 0.05 μs with IGBT voltage-source inverters. These low-voltage PWM ASD output voltages are essentially of the same character as the switching surges from some circuit breakers that have been known to puncture motor winding insulation, except these *switching spikes* from the PWM ASD inverter occur at a highly repetitive rate. Some manufacturers offer the choice of 3 kHz and 12 kHz carrier frequencies. The 3 kHz option minimizes the dv/dt issue. Others, marketing the ASD as a commodity, have their product switch at 12 kHz to assure no noise problem.

Depending on the rate of rise of the voltage transient and the length of cable between the inverter and the motor, the classical transmission line reflected wave voltage doubling-effect can occur at the motor terminals. Table 4 shows that the faster the voltage rise time, or the higher the rate of change of voltage, dv/dt, the shorter the critical cable length in which the reflection occurs.

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Table 4—Voltage doubling reflection occurring for cable lengths

PWM pulse rise time, μs	Cable length, m
0.1	6
0.5	30
1.0	60
3.0	180
4.0	240
5.0	300

The reflection of an incident traveling voltage wave at the motor terminals is determined by the surge impedance of the junction point. Consider the incident voltage reflections under the following three extreme conditions:

a) Cable termination surge impedance is zero (e.g., a capacitor). The reflected wave will be equal in magnitude, but negative, compared to the incident wave resulting in zero net transient voltage.
b) Cable is open at the end. The voltage reflection will be equal in magnitude to the incident wave and with the same sign, or, in other words, the voltage doubles.
c) Cable is terminated in the characteristic impedance of the cable. There will be no reflection.

Since the characteristic impedance of a small motor is usually higher than the low surge impedance of the cables, the motor looks like an open connection to the cable. Voltage doubling is then possible, depending on the voltage rise time and the length of the cable.

Large machines have relatively low characteristic impedance since the winding capacitance increases and the equivalent inductance decreases. Table 5 shows typical motor surge impedances.

Table 5—Typical motor surge impedances

Motor kW rating	Surge impedance in ohms
20	1410
37.5	750
75	375
150	188
300	94

With cable characteristic impedances on the order of 50 Ω, it becomes clear that the voltage doubling problem is one for small motors, generally considered to be 35 kW and less.

10.6.5.2.2 Controlling the voltage doubling effect

To control the voltage doubling effect, there are several options:

a) Use 230 V motors. Although the voltage doubles, it is well within the capability of the motor insulation.
b) Reduce the switching frequency to 2.5–3.0 kHz. With the lower rate-of-rise of voltage, there is significantly less transmission line effect.
c) Use only motors with sufficient insulation to withstand the voltage, even if it doubles. The low-voltage PWM ASD output voltage is the same as the dc link voltage. The dc link voltage can be 1.4 times the incoming ASD voltage times 1.1, since motors can operate at 10% above rated

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voltage, or 708 V. Doubling this voltage is 1416 V. Magnet wire manufacturers have developed a wire coating suitable for this duty. The new wire reportedly has 200 times more surge voltage withstand than conventional magnet wire used in motors, and apparently carries no extra cost. Assuming that this wire is as good as advertised, this solution is the simplest one, as far as the motor is concerned. It does not protect the cables, but there have been little published complaints about ASD reflected voltage waves affecting cables.

d) Use appropriate filters. Adding a line reactor at the ASD output will solve many voltage doubling problems. The reactor slopes off the rise time and may increase the allowable cable length by a factor of ten. The reactor should be selected by the ASD manufacturer so that resonance problems do not occur, nullifying the benefit of the reactor.

Commercially available *dv/dt* filters consisting of reactors, capacitors, and resistors can be used at the inverter output (Figure 48). The unit shown in Figure 48 is for a 3.7 kW motor with a cable length of 30 m. $R = 100\,\Omega$, $L = 0.2$ mH, $C = 0.075\,\mu$F.

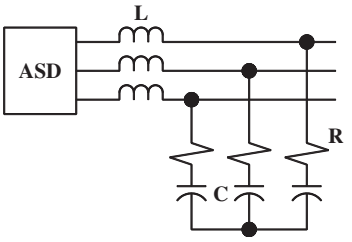


Figure 48—ASD output filter

A line termination network at the motor terminals closely matches the cable surge impedance to eliminate the reflection. Since the cable characteristic impedance changes only slightly from #14 wire to 500 k circular mil wire, a single device can be used for any motor size.

10.6.5.2.3 Medium-voltage motor systems

All dual channel LCI ASD drives, have individual transformer secondary windings, shifted 30 electrical degrees, supplying the ASDs, to cancel 5th and 7th harmonics that otherwise would go to the power system. The inverter outputs of the LCI ASDs go directly to the motor windings. There are no 5th or 7th harmonic current (or their multiples) effects in the rotor from the stator winding mmfs because the motor windings are shifted in space by 30 electrical degrees, which eliminates the 5th and 7th harmonics from the resultant mmf.

The modified LCI type inverter uses a six-pulse inverter (Figure 49) that has a large output capacitor filter to control harmonics to the motor.

The current-source GTO-PWM type ASD, Figure 50, also uses an output filter capacitor. The output voltage wave shape from inverter to motor are different for each of the three types of ASD proposed. Figure 51 is of the voltage of LCI inverter feeding the motor winding. This shows a voltage spike, which has long been recognized by manufacturers of LCIs and is factored into the amount of turn insulation in the motor stator winding.

Figure 52 shows the voltage of the modified LCI inverter for one manufacturer. With the output filter capacitor it does not produce voltage spikes. Similarly, the output filter of the GTO-PWM inverter does not allow voltage spikes to the motor (Figure 53). Some authors fail to differentiate between the voltage characteristics of the synchronous motor and induction motor inverters, which leads to unfounded concerns for the latter.

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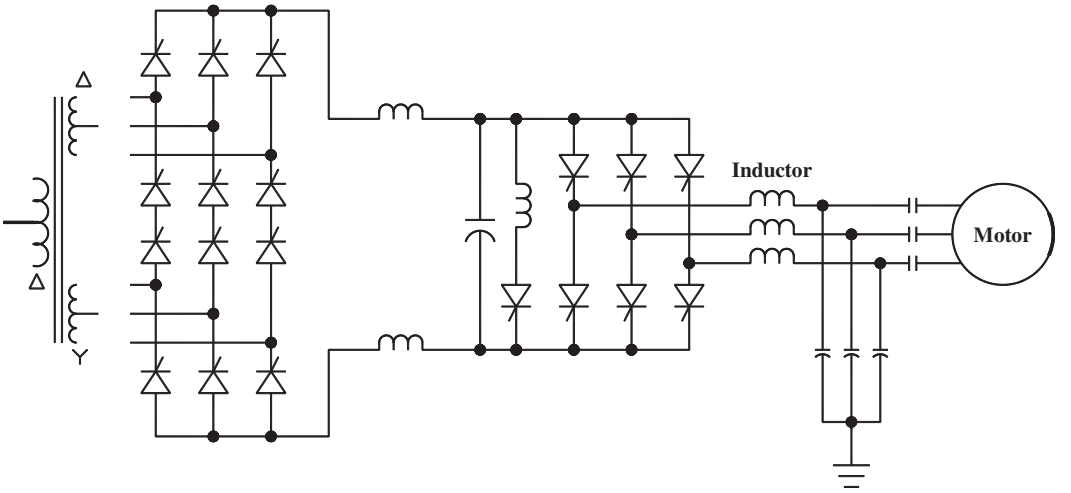


Figure 49—Modified LCI ASD

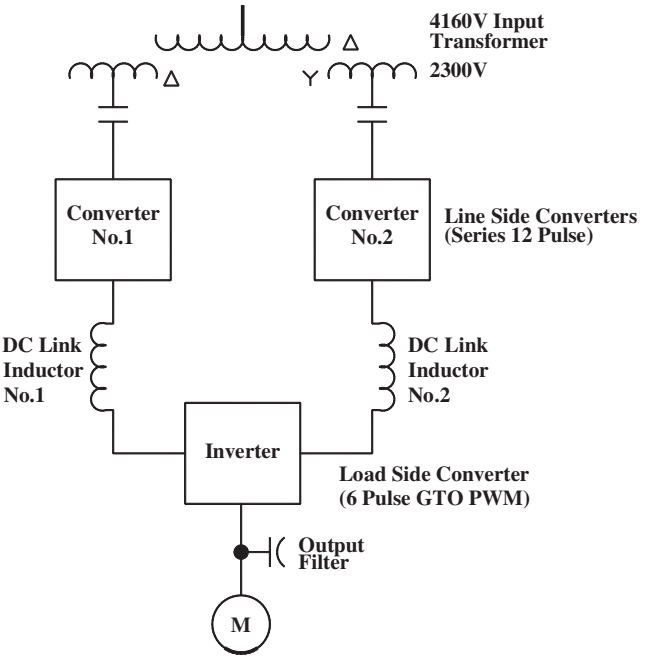


Figure 50—Current-source GTO-PWM ASD

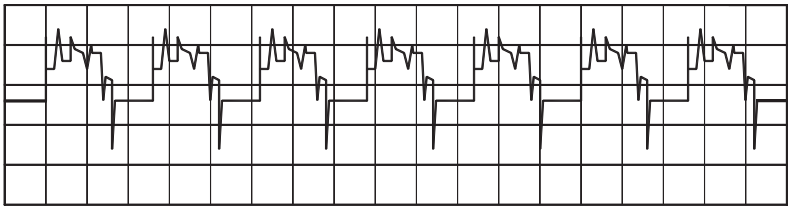


Figure 51—Voltage of LCI inverter

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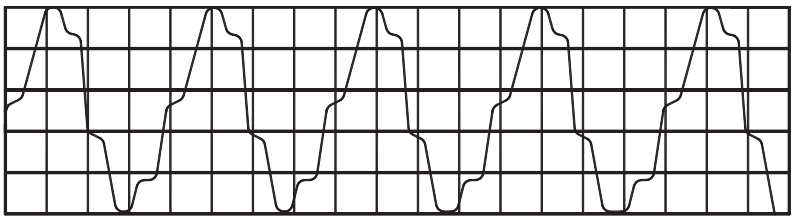


Figure 52—Voltage of modified LCI inverter

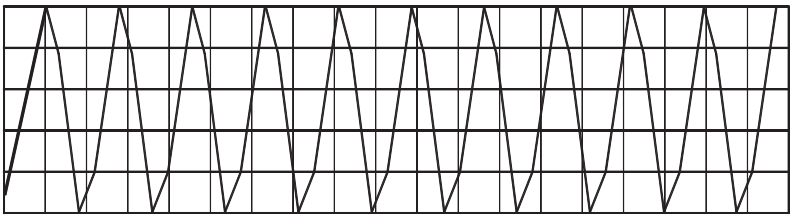


Figure 53—Voltage of GTO-PWM inverter

10.6.5.3 Voltage endurance

There have been questions raised about the long-term aging effects of these voltage stresses on the insulation (Owen [B29]). When present, the shift in the neutral voltages occur at a rate of six times per cycle. The commutation spikes also occur at rate of six times per cycle for CSI type ASDs and rates as high as several 1000 times per cycle for PWM-VSI ASDs. At least one report (Salon [B32]) indicates that the life or voltage endurance of the insulation can be significantly reduced from these voltage transients. Correctly designed motor/ASD systems account for these effects and there is no loss of motor life.

11. Interactions: ASD-electrical system and ASD-motor

11.1 Electric power quality considerations

11.1.1 Background on power quality problems

Advances in technology deserve much of the credit for the new forward-looking approach of the mainstream adjustable-speed drive (ASD) suppliers. The once firmly entrenched analog ac and dc drives have almost entirely been replaced by second- and third-generation digital drives. Incorporation of incremental features and functions in microprocessor-based drives will continue as suppliers attempt to further exploit the potential of technology. This situation is increasing the number of new ASD configurations hitting the market, which are boosting the price/performance of drives. Although the fast pace of both ac and dc drive technologies make it difficult to stay abreast, it is becoming increasingly important to consider the many alternatives in order to maximize business investments. Choosing the wrong drive technology, or ignoring evaluation of the drive's interaction with the electric service source, the motor-driven process, and other facility loads, can cost companies millions of dollars in losses.

In the presently changing marketplace, drive users are applying ac and dc drives in applications that require more demanding speed and torque performance. Drive and motor technologies have had to

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keep pace with these ever more demanding expectations. Additionally, the marketplace is now more focused than ever on unit cost and cost reduction, thus eliminating the tendency towards over applying technology to a process. Properly selecting, installing, and matching the drives' rating and unit characteristics to the application are effective ways of managing costs and operating ASDs to minimize problems. Also, as electronic ASD loads proliferate throughout the production system, so do problems related to electric service power quality. Depending on the ASD manufacturer's design criteria, the ASD can be extremely sensitive to routine power line disturbances, and some ASDs may create their own disturbances that feed back through the facility's wiring to interfere with other production equipment causing a *power quality problem*. Normally voltage sags are not a problem in power plants, but on specific sites they may need to be considered.

What is a power quality problem? It is any deviation of electricity applied to the equipment that results in damage or misoperation of electronic equipment or other electrical devices. Normally, voltage sags are not a problem in power generating stations, but common symptoms of power quality problems in ASD/motor-driven systems in some facilities that may require consideration are the following:

a) An ASD frequently trips or shuts down
b) A motor operated by ASD requires frequent repairs or replacements
c) Erratic control of process parameters
d) Unexplained fuse blowing and/or component failures
e) Misoperation or damage to other electronic equipment

ASD power quality problems can be complicated, involving the facility wiring, natural phenomena such as lightning, interacting facility equipment, and equipment connections to the electric power system. ASDs are typically designed to operate with flawless electricity from the electric service source; however, many things can interfere with electricity as it travels from the motor-control center to the ASD/motor-driven system.

Because power quality issues can create ASD/motor application concerns that affect productivity and profitability, it makes sense for electric service providers, ASD users, and equipment manufacturers to work together to ensure compatibility between the ASD/motor-driven equipment and the power system. While the ASD/motor system offers an opportunity for better utilization of energy and resources, the ASD/motor system can become a source of problems if the operational characteristics (tolerances to electric source anomalies) of the ASD/motor system are not compatible with the characteristics of the power system. System compatibility is a two-way proposition, as not only the ASD equipment must be protected against disturbances (immunity) from the electric source and other *disturbance sources* in the shared distribution bus, but also the ASD equipment itself should not introduce excessive disturbances (emissions) into the electric supply. Ascertaining that ASD system compatibility exists is best demonstrated by addressing the issues of immunity and emissions with the ASD manufacturer.

IEEE Std 519-1992 is a recommended practice that applies to all types of static power converters used on electric service systems. This document addresses specific problems involved in the harmonic control of such converters and an application guide is provided. Limits of disturbances to the ac power distribution system that affect equipment and communications are recommended and are relevant to medium-voltage ASDs. When used properly, it can help you avoid the costs of such problems, as well as ensure the safety and reliability of your electronic-based production equipment. IEEE Std 519-1992 does not provide information necessary to design and install an electrical wiring system, nor does it describe all specialty devices, mechanical protection, and special requirements for ASD/motor-driven processes, and other control systems. For these you should consult a company with qualified engineering services in electrical, mechanical, and process control disciplines, and an electrician having training, experience and knowledge of NFPA 70-2002 [B24], as well as an understanding of the importance of following accepted proper wiring practices as they relate to electric power quality.

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11.2 Responses to system disturbance

11.2.1 Steady-state operation

During steady-state operation, the ASD will encounter tolerances in supply voltage of ±10% of nominal voltage, ±5% tolerance in frequency, and 2.5% voltage phase unbalance. The drive system should meet the speed–torque requirements specified without exceeding component ratings and normal design criteria under these conditions.

11.2.2 Transient system disturbances

During voltage dips to 80% of nominal for 1 min, the drive system should meet the steady-state speed–torque requirements specified, utilizing the overload capabilities of the components.

During voltage dips to 75% of nominal for 1 min, the drive system should operate at the speed–torque command, unless the current is limited to 1.25 per unit.

11.2.3 System disturbance due to ''bus transfer'' and faults

The ASD shall be able to ride through a complete loss of voltage for 6–25 cycles. The ASD shall also have the capability to withstand severe voltage unbalance and single phase voltage for six cycles.

After these disturbances, the drive system shall return to normal operation within 7 s after power is restored. If UPS logic power is supplied, the drive should return to normal operation within 1 s.

11.3 Short circuit contribution

11.3.1 Power source short circuit

The adjustable-speed drive system creates a change in the short-circuit contribution between power source and motor and vice versa.

The motor does not contribute to a short circuit on the power system (source) except when the drive is regenerating at the time the fault on the source occurs. The power converter provides a controlled link between motor and the supply source that will not normally transmit short circuit current to a supply system fault. Current source inverters are capable of transmitting approximately three per unit (pu) rated current into a system short circuit if the drive is in the regenerative mode at the instant of fault.

11.3.2 Motor short circuit

A short circuit at the motor will not appear as a bolted fault to the supply source due to the power converter interface. Depending on the type of inverter and its control, a limited overcurrent on the order of two PU rated current may be contributed by the system. Fault clearing is normally done by the power converter.

11.4 Mechanical interaction between the motor and driven equipment

11.4.1 Electric motor balance

Balance is measured and reported as an amount of weight, which is eccentric to the center of rotation at some location along the shaft. Hence, it will be described as a certain number of ounce-inches

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unbalance at the center of the shaft. The vast majority of electric machines existing in the world today have been produced according to rigid shaft design criteria and can be balanced to an acceptable degree with only two balance planes. A relatively few machines in number (but not size) have been designed as flexible shaft machines and require more than two balance planes for satisfactory operation. Large high-speed turbogenerators are virtually all flexible shaft machines as a result of their size and speed.

11.4.2 Lateral vibration

This is a system characteristic that is determined, not only by the design and balance of the motor or generator, but also by the mounting arrangement and the equipment external to the electric machine. A simple relationship, response equals excitation times amplification, is fundamental to all vibrating systems. This means that the response of a system (vibration expressed in terms of displacement, velocity or acceleration) is the product of the excitation (unbalance force) to which the system is subject and the amplification that results at the frequencies involved due to the system structure (resonance) and damping characteristics. A model of the system consists of various interconnected springs, masses, and damping elements, with many of these elements external to the machine and beyond the control of the motor manufacturer. Experience has shown the importance of an adequate foundation and accurate alignment of the equipment if the equipment is to perform in a satisfactory manner. The mass of the foundation and its supporting stiffness are usually designed with the intent of obtaining the first lateral *resonant speed* above normal operating speed during operation.

11.4.3 Critical speed

This is a calculated characteristic used to design shafts. A *resonant speed* is often recognized as a speed at which the amount of vibration is greater than it is at other adjacent speeds. When a machine is operated over a speed range, the level of vibration will change as the speed is changed. The coincidence of a significant amplitude peak and a sharp 180° phase shift is almost always an indication of a resonance. For most mechanical components, which are not being affected by the presence of a resonant speed, the vibration level increases approximately as the square of the increase in speed. When operating speed coincides with a system resonance, the vibration increases substantially and is determined mainly by the amount of damping that exists in the system. With very little damping, the degree of amplification becomes very large. This potentially high amplification and the extreme vibrations that may result raises a concern whenever the possibility exists that a motor may be operated on or near a resonant speed. There are instances in which a rotor system is designed to operate at or near a critical speed without excessive vibration or other adverse effects. Such systems require more care in system design and equipment operation to avoid malfunction.

The rotors of most electric motors are designed to a simple deflection criterion, which places the rigid bearing lateral critical above normal operating speed. Although there is no widely accepted standard for rigid shaft design, there is some basis for designing rigid bearing lateral critical 30% or more above normal operating speed.

11.4.4 Torsional vibration

Torsional vibrations are the result of torsional disturbances acting on structural components. The disturbances are sometimes amplified by resonant frequencies determined by the torsional spring, mass system. Each resonant frequency has an associated vibration pattern (mode shape), which is characteristic of that resonant frequency.

The motor and its connected load comprise a torsional system of springs and masses with many of the springs and masses external to the motor. The system is capable of responding at one or more resonant

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frequencies as determined by the number of independent elements in the system (degrees of freedom). Torque disturbances created by the motor can excite these resonances to potentially damaging levels and a torsional study of the system is recommended to minimize the risk of unsatisfactory performance. The type of study and consequential cost should be commensurate with the cost of the drive.

In some cases, the motor designer may recommend the use of shock absorbing couplings between the motor and driven equipment.

12. Drive system specification and installation

The following ac electric service source (supply system) information should be provided with the specification information to allow the converter designer to properly define the requirements of the electromagnetic system components:

a) Short circuit limits (minimum and maximum)
b) Steady-state voltage variation
c) Worst case voltage variation (and operating practices during this event)
d) Existing system grounding practices
e) Bus transfer practices
f) Power supply reliability
g) Harmonic limit requirements (voltage and current)
h) Reactive power restrictions (if any)

12.1 Interfaces

12.1.1 Electric power interface

The electrical connection between the switchgear and the ASD isolation transformer is in accordance with standard practice except for adjusting the conductor ampacity to accommodate the harmonic currents generated by the drive ASD.

In general, the ASD manufacturer should designate the maximum continuous voltage stress to ground for load side converter connections.

One additional consideration for this interface is the use of shielded cable and the length of cable run involved. With some power converter systems, the amount of capacitance to ground (which is a function of cable size, shield and length) can have a detrimental effect on the performance of the converter. The ASD manufacturer should be consulted with regard to the permissible capacitance to ground such that the converter performance is not hampered.

The electric connection between power converter, motor isolator, and motor must also be addressed with regard to harmonic heating, voltage stress and shielding.

12.1.2 Mechanical power interface

The mechanical connection between motor and driven load includes the equipment shafts and coupling. In terms of a spring–mass system this connection represents two springs and three masses.

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The mechanical interface involves shaft diameter, shaft height, axial movement, and the specifics of the coupling installation. The interface information for the couplings includes:

a) Type coupling
b) Shaft diameter—straight shaft
c) Shaft diameter and taper—tapered shaft
d) Locking nut diameter and thread
e) Key way size
f) Coupling fit
g) Half coupling installation and balance

The axial movement (end play), magnetic center, and location of any thrust bearing should be specified to the drive manufacturer. If the motor bearing is required to absorb thrust, this should be specified. The mechanical interface to the structural foundation should follow sound civil engineering and accepted practice.

12.1.3 Process control interface

The general practice is to bring all drive process control interface information together physically at the ASD. The information typically includes the information listed in 12.1.3.1, 12.1.3.2, 12.1.3.3, 12.1.3.4, and 12.1.3.5.

12.1.3.1 Switchgear

a) Trip contact
b) Advance trip contact
c) Circuit breaker status contact (52a)

12.1.3.2 Transformer

a) Transformer sudden pressure device
b) Transformer temperature alarm contact
c) Transformer isolation switch position contact

12.1.3.3 Motor isolator

a) Close and trip contacts
b) Contactor status

12.1.3.4 Motor

a) Motor winding and bearing temperature
b) Motor vibration
c) Speed or shaft position sensor (if required)
d) Motor field current (if a synchronous motor is applied)

12.1.3.5 Process control

This interface determines the operation of the ASD in response to the process or operator commands. The interface information is transmitted by electrical signals from remote locations, typically the control room, to the drive system. Typical process control parameters are summarized in Table 6.

12.2 Enclosures

12.2.1 Enclosure considerations

Each of the subsystems that make up the ASD system package will have its own enclosure or share enclosures with other equipment. The number and physical size of these enclosures can become

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Table 6—Typical process control parameters

Command	Interface
Start/Stop	Contact
Minimum speed set point	Software
Acceleration/deceleration rate limit	Software
Speed command	0–10 V, 4–20 mA or raise/lower
Maximum speed set point	Software
Torque/current limit	Software
Turning gear	Contact
Drive reset	Contact
Return to normal	Contact
Bypass	Contact
Motor speed	4–20 mA
Motor current	4–20 mA
Drive ready	Contact
Drive running	Contact
Alarm	Contact
Fault	Contact

significant. Any special limitations that the user has with regard to handling the drive system enclosures should be specified, such as maximum weight, maximum dimensions and lifting requirements should be specified. Any special fabrication requirements, such as painting or the location grounding pads or connections, should be specified. The user should consider who will supply the tools or test equipment for installation and start up of the adjustable speed drive system.

12.2.2 Power converter enclosure

The power converter enclosure must be suitable for the solid-state equipment it contains. The converter system should be shielded by the enclosure so as to be sufficiently free from radiated and conducted electromagnetic interference (EMI), and radio frequency interference (RFI) to prevent misoperation of the adjustable-speed drive system.

Enclosures should also comply with utility power system standards. Typical enclosure types include NEMA Type 1, NEMA Type 12, and others. The user should consider whether the enclosure is to be free standing, the location of swing panels, and the gauge of steel required. Any special feature such as the following should be specified:

a) Nameplate requirements and location
b) Front mounted or internal display features
c) Front mounted or internal alarm and diagnostic features
d) Front mounted relay devices
e) Remote/local control station
f) Energization and/or operation indicating lights
g) Communications terminal
h) 115 V ac enclosure maintenance lamp

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i) 115 V ac convenience receptacle
j) Location and number of interface terminations

12.2.3 Isolation transformer and filter enclosures

The requirements for the isolation transformer and filter enclosures are similar to those for the power converter enclosure. These devices differ in that they tend to have higher losses and the power equipment contained within tends to be more rugged. Accordingly, they can be located remote from the power converter enclosure outside the adjustable-speed drive control area. For large adjustable-speed drive systems, the isolating transformers may be liquid filled and may be better located outside.

In either case, top cabling or bottom cabling entry (or provision for both) should be specified by the user.

12.3 Relaying and metering

12.3.1 Relaying and metering concepts

The protection and metering for the ASD and motor will reside in the microprocessor, which controls the ASD. Relay protection is often applied to the input transformer.

Harmonics can affect relay response. Induction time overcurrent relays and meters should be used with caution. Magnetic attraction devices (plunger or clapper) will have a flat response. Solid-state relays may not be noticeably affected by harmonic levels, but relays that count zero crossings in a timing scheme can be fooled by notches or harmonic oscillations at the fundamental zero crossing.

Relaying schemes should be both reliable and secure to achieve system component protection and operator safety. Reliability dictates that the schemes operate to protect equipment in the intended manner while security means that they do not misoperate when there is no abnormal condition or operate in a manner other than that intended.

12.3.2 Instrument transformers

AC current transformers (CTs) step down the current in the power feeder circuit for metering and relaying input purposes. CT secondaries are normally rated for 5 A, although, some solid-state relaying schemes are designed for CTs with a secondary rating of 1 A. As in all power applications, good practice dictates that connected relaying and other devices in the CT secondary circuit not exceed the burden capability of the CT. High-frequency harmonics do not cause saturation normally, but it should be noted that reduced frequency operation will decrease CT accuracy.

AC potential (voltage) transformers known as VTs step down power feeder circuit voltages for relaying and metering input purposes. VT secondaries are normally rated 115 V line to line. Three winding VTs can have three phase broken delta connected tertiaries that can be used to provide an overvoltage source for detection of ground faults on delta connected systems. VT burden capability should be observed in designing relay potential schemes.

12.3.3 ASD dead time during a relayed bus transfer

Most drive systems for utility applications will be driven from unit auxiliary busses. These busses are switched manually and automatically from and to reserve or startup sources for unit startup

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and shut down. An automatic transfer is normally one of the following:

a) High-speed early contact sequential transfer
b) Sequential time delay
c) Open and close on voltage decay

For the latter two transfer schemes, the ASD will undergo more than a momentary interruption of power. It is important that the manufacturer of the ASD be made aware of the bus transfer method so that the ASD system can be designed to ride through the transfer without shutting down.

12.3.4 Basic system protection

The exact requirements for the system protection depend on the mission and configuration of the ASD system. A well-designed system will provide protection against contingencies internal and external to the ASD system. These include the following:

a) Voltage surges
b) Over- and undervoltage
c) Phase reversal
d) Phase imbalance
e) Fault currents
f) Ground currents
g) Internal faults
h) Overloads
i) Overtemperature protection

Component protection prevents the components from being subjected to stresses exceeding rated levels. The protection circuits must work selectively and in a coordinated manner. Component protection either prevents the destruction of the components directly or, if this is impossible, protects neighboring components not directly involved in a fault.

The ASDs covered by this guide are intended to be applied in medium-voltage power distribution systems with either induction or synchronous ac motors. The user should select the necessary devices to properly protect the power distribution system and the drive system components, which include, but are not limited to the following:

1) ASD feeder circuit
2) Input isolation transformer
3) Filters

Protection for these system components is provided through the coordination of current interruption devices, circuit impedance, surge arresters, relay, and alarm devices. These devices prevent dangerous overvoltage, overcurrent, and overtemperature conditions. Mechanical sensors may also be provided on motors, transformers, and other equipment when so needed to detect overspeed, excessive vibration, loss of lubrication, and loss of ventilation and other improper running conditions to shut the system down before mechanical damage occurs.

12.3.5 ASD relay protection

Power converters are generally protected by internal solid-state circuits for the common faults listed in Table 7. Most contingencies will cause the converter to take gate protective action (GPA), which will

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Table 7—Typical large adjustable frequency ac motor drive protection functions

Apparatus	Protection	Clear fuse	Local trip	Remote trip	Remote alarm
Harmonic filter	Overcurrent	X			
Capacitor bank	Current unbalance		X		
Transformer	Overcurrent	X	X		
	Sudden pressure		X		
	Differential current		X		
	Ground fault		X		
	Winding overtemperature			X	X
	Top oil overtemperature			X	X
Motor circuit breaker	Overcurrent		X		
Bypass controller	Overload		X		
	Locked rotor		X		
	Ground fault		X		
	Phase reversal		X		
	Line over- and undervoltage		X		
Power converter	Overcurrent	X	X		
	Ground fault			X	X
	Phase reversal		X		
	Line over- and undervoltage		X		
	Overfrequency		X		
	Overtemperature			X	X
	Lost ventilation			X	X
	Differential current	X	X		
Motor	Phase balance differential		X		
	Winding overtemperature			X	X
	Bearing overtemperature			X	X
	Bearing vibration		X		

force the internal currents and the motor current to zero. This is sufficient as long as the controller components have not failed. In the event of a component failure, the controller can signal the line ac circuit breaker to trip.

The power converter typically has less tolerance for voltage surges, overcurrent and overtemperature than motors or transformers. Therefore, limiting current and voltage to protect the power converter generally assures that transformers and motors are also protected. One feature of good relay practice is the application of primary and backup protection schemes. This permits one scheme to be removed from service during operation for testing or maintenance purposes without degrading the overall protection philosophy.

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Annex A

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Annex B

(informative)

Derivation of an ac machine equation for operation from adjustable voltage and frequency sources

This annex contains the derivation of motor output torque as a function of applied voltage and frequency for synchronous and induction motors. Several assumptions are made to simplify the derivations thus these expressions are approximate. The primary assumptions made are the neglection of saturation, stator resistance, and skin effect. Other assumptions are noted in the derivations.

B.1. Synchronous motor equations

Figure B.1 provides a single-phase equivalent circuit of a three-phase cylindrical rotor synchronous motor. In most drive applications, the motor is a salient pole type which is more complex. However, the following derivation covers the fundamentals.

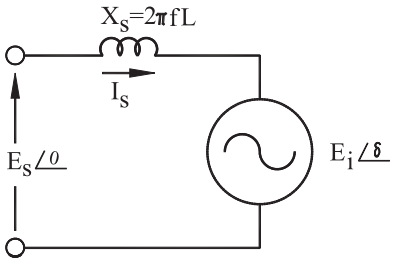


Figure B.1—Per phase equivalent circuit of cylindrical synchronous machine

Neglecting stator resistance, the power output of the motor is given by Equation (B.1) (Fitzgerald et al. [B6]):

$$P = 3E_sE_i \sin(\delta)/(2\pi fL) \quad \text{(B.1)}$$

where

P is the power developed by the motor (W),

E_i is the per phase rms voltage magnitude of the self-generated EMF, produced by motor excitation (V),

E_s is the per phase rms voltage magnitude of the source voltage (V),

δ is the power angle (radians),

L is the machine inductance (H),

f is the frequency (Hz).

The motor output torque can be expressed as Equation (B.2) (Fitzgerald et al. [B6]):

$$T = P/\omega \quad \text{(B.2)}$$

where

T is the output torque of the motor (N·m),

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ω is the synchronous mechanical speed of the motor (rads/s) defined by Equation (B.3):

$$\omega = 4\pi f/p \tag{B.3}$$

where p is the number of poles in the motor.

Substituting Equations (B.1) and (B.3) into Equation (B.2) and simplifying yields Equation (B.4):

$$T = k_{s1}(E_s/f)(E_i/f)\sin(\delta) \tag{B.4}$$

where $k_{s1} = 3p/8\pi^2 L$.

Equation (B.4) shows that the torque is directly related to the ratio of the source and the internal voltages to the applied frequency.

The output power of the motor can also be expressed as Equation (B.5):

$$P = 3E_s I_s \cos(\beta) \tag{B.5}$$

where

I_s is the rms stator current (A),

β is the phase angle between the source voltage E_s and the current I_s.

Substituting Equations (B.5) and (B.3) into Equation (B.2) results in Equation (B.6):

$$T = k_{s2}(E_s/f)I_s \cos(\beta) \tag{B.6}$$

where $k_{s2} = 3p/4\pi$.

B.2. Induction motor equations

Figure B.2 provides the single-phase equivalent circuit of a three-phase induction motor. The torque output is defined by Equation (B.7) (Fitzgerald et al. [B6]):

$$T = 3/\omega |I_r|^2 r_r/s \tag{B.7}$$

where

ω is the synchronous speed of the motor (rads/s) defined by Equation (B.3),

$|I_r|$ is the rms magnitude of the rotor current (A),

r_r is the rotor resistance (Ω),

s is the per unit slip defined by Equation (B.8):

$$s = (\omega - \omega_r)/\omega \tag{B.8}$$

where ω_r is the rotor speed in mechanical radians per second.

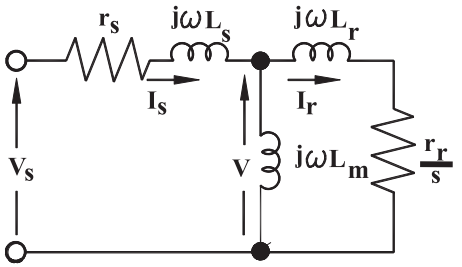


Figure B.2—Per phase equivalent circuit of three-phase induction motor

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Neglecting the stator resistance r_s and then solving for V' yields Equation (B.9):

$$\begin{aligned} V' &= j2\pi f L_m V/(j2\pi f(L_m + L_s)) \\ &= L_m V/(L_m + L_s) \\ &= k_L V \end{aligned} \tag{B.9}$$

where

L_m is the magnetizing inductance,

L_s is the stator leakage inductance,

$k_L = L_m/(L_m + L_s)$.

Note that V' is independent of frequency and depends only on the supply voltage. The magnitude of the rotor current $|I_r|$ in terms of V' is given in Equation (B.10):

$$|I_r| = |V'|/\sqrt{[(r_r/s)^2 + (2\pi f L_r)^2]} \tag{B.10}$$

Substituting Equation (B.10) into Equation (B.7) yields Equation (B.11):

$$T = (3/\omega)|V'|^2(r_r/s)/[(r_r/s)^2 + (2\pi f L_r)^2] \tag{B.11}$$

When an induction motor is operated from a variable frequency source, optimum performance is obtained if the slip is maintained near rated (Finney [B5]). For this mode of operation, the rotor reactance can be neglected resulting in Equation (B.12):

$$T = (3/\omega)|V'|^2 s/r_r \tag{B.12}$$

Substituting Equation (B.8) for slip yields Equation (B.13):

$$T = 3/\omega^2|V'|^2(\omega - \omega_r)/r_r \tag{B.13}$$

Finally, substituting Equation (B.3) for ω and Equation (B.9) for V' results in Equation (B.14) for motor torque:

$$T = k_i|V/f|^2(\omega - \omega_r)/r_r \tag{B.14}$$

where $k_i = 3(p/4\pi)^2 k_L$ and $\omega - \omega_r$ represents the speed differences between the rotor speed and the synchronous speed corresponding to the applied frequency.

Equation (B.14) shows that the output torque of an induction motor is a function of the ratio of the supply V/Hz and the change in the speed of the rotor ($\omega - \omega_r$).

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Annex C

(informative)

Sample economic evaluation

The following example provides a basic economic evaluation between retaining an existing constant speed motor drive for a vane controlled ID fan versus the replacement of the motor and the vane controls with an ASD. The existing motor is rated at 3730 kW, 4000 V.

C.1. Evaluation data

The data for the project are provided in C.1.1 through C.1.7.

C.1.1 Life expectancy

The life expectance of the plant and the project is 20 years.

C.1.2 Interest rate

The interest rate is assumed to be 10% and no inflation or other factors are used to adjust the time value of money.

C.1.3 Load projections

The load projections for the fan are grouped into three bands as follows:

a) 25% of the time the fan is off line
b) 25% of the time the fan is operating at 50% of fan test block
c) 50% of the time fan is operating at 75% of fan test block (MCR)

C.1.4 Drive option efficiencies and power consumption

Table C.1 summarizes the physical parameters of the existing fan and motor and the ASD. The efficiencies of the two options are from Figure 6. The power consumed by both options along with the energy saved by utilizing an ASD are included in Table C.2. The energy cost in this example is based on the incremental fuel cost of 2.5 cents per kilowatt hour (kWH). No other allowances such as unit heat rate improvements are included. The total energy saved is 5925 kW per year (see Table C.2). The net results is an annual savings of $148 125 for the ASD over the existing constant speed motor and fan vane controls.

Table C.1—Operating data on drive options

	Test block (TB)	Maximum continuous rated (MCR)	Light load
Gas volume	36 800 m^3/min	31 700 m^3/min	27 600 m^3/min
Shaft power	3725 kW	2800 kW	1865 kW
Efficiency of constant speed motor and fan with vane control	95%	90%	81%
Efficiency of ASD and motor	95%	95%	95%

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Table C.2—Power consumption and energy savings

Vane control				ASD				Comparison	
Time (h/yr)	Motor output power (kW)	Motor eff (%)	Motor input power (kW)	Motor output power (kW)	Motor eff (%)	ASD eff (%)	ASD input power (kW)	Power saved (kW)	Energy saved (MW-h)
4380	3725	97.0	3652	2800	97.0	95.0	3035	617	2704
2190	3725	97.0	3652	1865	96.0	95.0	2044	1608	3521
2190	Off	—	—	Off	—	—	—	—	—
8760 Total	—	—	—	—	—	—	—	—	5925

C.1.5 Equipment cost

No additional equipment is required for the existing fan and motor. The cost of the ASD equipment is estimated to be $300 000 with an engineering and installation cost estimate of $100 000. Therefore, the total cost for the installed ASD is $400 000.

C.1.6 O&M cost

Estimates are that it will take an additional 200 man-hours of maintenance by a technician each year to properly maintain the ASD. The cost of this activity is estimated to be at $4125 per year. There may also be positive cost benefits associated with applying an ASD such as reduced maintenance on switchgear, fan dampers, fan damper controls, and other equipment. However, for the purposes of this example, a least profitable (or worst case) scenario is computed and so these factors will not be included.

C.1.7 Other cost/benefits

In actual evaluation there may be other factors to consider such as taxes, reliability, capacity, and environmental. When appropriate they can be incorporated into the evaluation. These additional cost and benefits can be significant but for simplicity they are not considered in this example.

C.2. Evaluation of options

From the above data the net annual benefit for installing the ASD over retaining the existing constant speed motor and fan vane controls is $144 000 per year (see Table C.3). A variety of evaluation methods are available to determine if the annual savings justifies the cost of installing the new ASD. Three such techniques, payback period, net present value, and profitability index are summarized below.

C.2.1 Payback period

The payback period (PP) is the break even point where the benefits begin to exceed the costs. This variable has the dimension of time and is normally measured in years of fractions thereof. The cost is the total installation cost. The benefits are the annual savings benefits ($AB_1, AB_2 \ldots AB_n$) to be realized by proceeding with the project. The payback period is equal to the total installed costs (IC) divided by the sum of the annual savings benefits as shown by Equation (C.1):

$$PP = IC \Big/ \left[\sum_{i=1}^{n} (AB_i) \right] \tag{C.1}$$

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Table C.3—Results of economic evaluation

Item	Value
Annual benefit 1 (energy savings)	$148 125.00
Annual benefit 2 (maintenance)	−$4125.00
Total annual benefits	$144 000.00
Present worth factor (10% interest, 20 years)	8.51356
Present worth of annual benefits	$1 225 950.00
Initial cost	$400 000.00
Payback period [see Equation (C.1)]	2.78 years
Net present value [see Equation (C.2)]	$825 950.00
Profitability index [see Equation (C.3)]	3.065

C.2.2 Net present value

The net present value (NPV) is the difference between the summation of the present worth of the benefits ($PW_1, PW_2 \ldots PW_N$) and the total installation cost [see Equation (C.2)]. If the annual benefits are the same year after year they can be present worthed by applying the present value of an annuity factor (present worth of a uniformed annual series) to one of the annual savings. One-time benefits are converted to present worth by applying the present value compound interest factor to each one-time benefit.

$$NPV = \sum_{i=1}^{n} PW_i - IC \tag{C.2}$$

C.2.3 Profitability index

The profitability index (PI) compares the present worth of the benefits to the installation cost [see Equation (C.3)]. Generally, for a project to be considered profitable, this index should exceed unity.

$$PI = \left[\sum_{i=1}^{n} PW_i\right] / IC \tag{C.3}$$

C.2.4 Results of evaluation

The key results of the evaluation are presented in Table C.3. The final decision on whether to install the ASD is dependent on the decision criterion set for the plant. For this example, the installation of the ASD would be very attractive having a short payback period, a sizable net present value, and a profitability index greater than 1.

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Annex D

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Harmonic voltage distortion factors

Harmonic voltage distortion factor (VDF) is a function of harmonic magnitude and order, which is generated by the drive, and the source impedance. This relationship can be quantified for a specific set of operating parameters and a relationship between the drive rating and source impedance identified as SCR (short circuit ratio).

$$\text{SCR} = \frac{\text{System short circuit MVA}}{\text{Drive MVA}}$$

A specific set of operating parameters is used in the following example:

Given

4.16 kV auxiliary bus

250 MVA short circuit

5.0 MVA drive rated 4.0 kV

$$\text{Source } X = \frac{(\text{kV})^2}{\text{MVA}} = \frac{(4.16\,\text{kV})^2}{250\,\text{MVA}} = 0.069\,\Omega$$

$$\text{Rated drive current} = \frac{5000\,\text{MVA}}{4.0\,\text{kV} \times 1.73} = 723\,\text{A}$$

The drive operating parameters are taken at 93% of rated speed and 87% of rated torque (fan load). The drive isolation transformer impedance is taken as 7% on 5 MVA.

For this condition, source converter gating angle is taken as 30°, and fundamental drive current is $0.87 \times 723\,\text{A} = 629\,\text{A}$. Individual harmonic voltages are calculated:

$$\%VDF = \left[\sum_{H=5}^{H=50} \frac{V_h^2}{V_1^2}\right]^{1/2} \times 100 = \left[\frac{14\,526}{5.76 \times 10^6}\right]^{1/2} \times 100 = 5.02 \quad \text{6-pulse system}$$

$$\%VDF = \left[\frac{6335}{5.76 \times 10^6}\right]^{1/2} \times 100 = 3.3 \quad \text{12-pulse system}$$

For any given set of operating parameters, the VDF will be an inverse function of the short circuit ratio, which directly affects the individual harmonic voltages. The values given in Table D.1 are based on this inverse ratio.

Note that the values in Table D.1 are in reasonable agreement with the values present in Table 13.1 of IEEE Std 519-1992.

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Table D.1—Harmonic analysis

h	Ih %	Ih	Xh	6-Pulse $(Ih\ Xh)^2$	12-Pulse $(Ih\ Xh)^2$
5	19.7	124	0.345	1830	—
7	13.9	87	0.483	1766	—
11	8.6	54	0.759	1680	1680
13	7.1	45	0.897	1629	1629
17	5.1	32	1.173	1409	—
19	4.4	28	1.311	1347	—
23	3.3	21	1.587	1111	1111
25	2.9	18	1.725	964	964
29	2.2	14	2.001	785	—
31	1.9	12	2.139	659	—
35	1.4	8.8	2.415	452	452
37	1.2	7.5	2.553	367	367
41	0.85	5.3	2.829	225	—
43	0.70	4.4	2.967	170	—
47	0.45	2.8	3.243	82	82
49	0.34	2.1	3.381	50	50
—	—	—	—	14 526	6335

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Annex E

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Harmonic heating in transformers

When supplying ASDs, transformers are subjected to additional heating and losses due to harmonics. See IEEE Std C57.110-1998. An example follows.

A nominal operating condition is selected for the drive source side converter to define the magnitude of harmonic current for the example. Converter gating angle 20° and commutating reactance $X = 0.08$ pu. This would be typical for a drive operating at rated speed and power. See Table E.1.

Table E.1—Sample transformer harmonic heating evaluation

h	Ih (pu)	6-Pulse In(pu)^2 h^2	12-Pulse In(pu)^{2}h^2
1	0.955	0.912	0.960
5	0.19	0.903	—
7	0.13	0.828	—
11	0.076	0.699	0.699
13	0.060	0.608	0.608
17	0.037	0.396	—
19	0.029	0.304	—
23	0.017	0.153	0.153
25	0.013	0.106	0.106
—	—	4.909	2.526

The transformer stray loss is taken as $0.15 \times I^2R$ loss and is considered to be totally winding eddy-current loss P_{EC}.

$$\text{Total loss density } P_{LL}(\text{pu}) = 1.00 + 0.15 \times 4.909 = 1.74\,\text{pu}$$

$$I\ \text{pu} = \left[\frac{1.15}{1.74}\right]^{1/2} = 0.813\,\text{pu}$$

For equivalent sinusoidal heating, multiply the converter fundamental rms load current by

$$\frac{1}{0.813} = 1.23 \sim 1.25$$

For the twelve-pulse converter:

$$P_{LL}(\text{pu}) = 1.00 + 0.15 \times 2.526 = 1.38\,\text{pu}$$

$$I\ \text{pu} = \left[\frac{1.15}{1.38}\right]^{1/2} = 0.913\ \text{pu}$$

$$\text{Multiplier}\frac{1}{0.913} = 1.10$$

NOTE—When the transformer stray loss is known, the above method can be used to adjust the multiplier accordingly.

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Annex F

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Sample low-voltage PWM ASD specification

This annex provides an example of a starting point for developing a comprehensive low-voltage ASD drive system technical specification for an electric power generating station application.

F.1. Scope

The ASDs covered by this document are intended to be supplied in medium-voltage power distribution systems with either induction or synchronous ac motors using transformers to accommodate low-voltage drives.

F.2. General requirements

F.2.1 General

a) The ASD shall convert incoming fixed frequency three-phase ac power into a variable frequency and voltage for controlling the speed of three-phase ac induction motors. The motor current shall closely approximate a sine wave. Motor voltage shall be varied with frequency to maintain desired motor magnetization current suitable for control of constant or variable torque loads.
b) The ASD shall use microprocessor technology and ASICs (application specific integrated circuits) to regulate motor operation.
c) An advanced sine wave approximation and voltage vector control shall be used to allow operation at rated motor shaft output at nominal speed with no motor derating.
d) Means shall be provided for local and remote operation.
e) There shall be a back lighted three line LCD alphanumeric display capable of displaying fault conditions, and suitable selectors to allow the display of operating conditions, set up of parameters, and ASD configuration.
f) The ASD shall have UL listing and CUL listing (equivalent to CSA) where applicable.
g) The manufacturer shall demonstrate a continuous period of manufacture and development for at least 10 years.
h) The manufacturer shall have integral add-on systems available for the addition of an ac line disconnect, bypass switchgear and other devices as specified.

F.3. Package requirements and service conditions

a) The ASD shall be available as a NEMA 12 enclosure directly from the manufacturer without the need to enclose the unit inside another enclosure.
b) The enclosure shall be sized to allow the drive to operate at full rated current continuously with no additional cooling in ambient temperatures from -10°C to $+40^{\circ}$C at altitudes up to 1000 m.
c) The ASD shall withstand storage temperatures from -40°C to $+70^{\circ}$C.
d) The ASD shall be rated to operate at a humidity of 95% relative humidity in accordance with the EEC 68-2.3 standard.

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e) The ASD shall comply with the following vibration standards:

IEC 60068-2-6, (1995-03) [B13]
IEC 60068-2-64, (1993-05) [B14]

f) The ASD shall comply with the following EMC (electromagnetic compatibility) standards:

Emission—BS EN 55011-1998/CISPR 11-2003 (with RFI filter option) [B3]
Immunity—EN 50082-2-1995 [B4]
Immunity—IEC 61000-4-2 (2000-4) [B16]
Immunity—IEC 61000-4-3 (2002-09) [B17]

F.3.1 Unusual service conditions

The manufacturer should be consulted if any unusual service conditions exist, which may affect the construction or operation of the ASD. Among such conditions are the following:

a) Exposure to:
   1) Combustible, explosive, abrasive, or conducting dusts
   2) Lint or very dirty operating conditions where the accumulation of dirt may interfere with normal ventilation
   3) Chemical fumes, flammable or explosive gases
   4) Nuclear radiation
   5) Steam, salt-laden air, or oil vapor
   6) Damp or very dry locations, radiant heat, vermin infestation, or atmospheres conducive to the growth of fungus
   7) Abnormal shock, vibration, or mechanical loading from external sources
b) Operation where:
   1) There is excessive departure from rated voltage or frequency, or both
   2) Low noise levels are required
   3) The voltage at the ASD input terminals is unbalanced by more than 1%
c) Operation at loads above the rated power
d) Operation in a poorly ventilated room, in a pit, or in an inclined position
e) Operation where subjected to:
   1) Mechanical impact loads
   2) Repetitive abnormal electric overloads
   3) Reversing or electric braking voltage/current surges

F.4. Input power

a) ASDs rated nominal 460 VAC shall meet all specifications when operating from input voltages of 360–550 V, three-phase, and input frequencies of 45–65 Hz.
b) ASDs rated nominal 230 VAC shall meet all specifications when operating from input voltages of 180–253 V, three-phase, and input frequencies of 45–65 Hz.
c) The ASD manufacturer shall determine the tradeoff benefits of utilizing dc link inductors, or input isolation transformer for minimizing voltage transient impact on motor performance, drive input harmonic current reduction, reducing drive tripping susceptibility, drive dc current injection, and drive operation with unbalanced ac input voltages. Benefits shall be documented for both steady-state and dynamic input/output conditions.

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d) The ASD shall be capable of being powered from an ac distribution system having a symmetrical short-circuit current rating of 65 000 amperes rms when the manufacturer's recommended fuses are used.
e) The ASD shall incorporate filters in the dc link section sized so as to limit the ac line current 5th harmonic to approximately 35%. External ac line reactors are not permitted.
f) Displacement power factor shall be 90% or greater from no load to full load.
g) Full load efficiency shall be greater than 96% at 100% load and greater than 92% at 20% load.
h) The ASD shall be insensitive to input phase rotation. Changing input phase rotation during shut down must have no effect on the ASD operation and shall not require reconnection of incoming power or motor wiring.
i) Inrush current shall be limited to a value that will not cause nuisance blowing of the incoming power line fuses when drive manufacturer recommended fuses are used
j) The ASD's ac line input shall comply to the following EMC (electromagnetic compatibility) standards:

Emission—BS EN 55011-1998 [B3], Class A group 1 or Class B group 1 as applicable (with optional RFI filter)

Immunity—IEC 61000 family of standards [B15]

Immunity—VDE 0160 Section 73.1.1 ac line transient

$V_{peak} = 2.3 \times$ ac line, 1.3 ms half value time

F.5. Output power

a) The output shall be variable frequency variable voltage capable of operating NEMA A, B, C, or D 230 VAC or 460 VAC (as applicable) 60 Hz three-phase induction motors and shall be capable of being field reprogrammed to operate other standard three-phase induction motors (IEC 60034, VDE0530 [B12]).
b) The ASD shall have the capacity to deliver full motor output voltage 10% greater than the supply voltage continuously.
c) The ASD will be supplied with output coils as standard to limit output voltage rate of rise to 200–300 V/μs (45–220 kW CT mode, 55–560 kW VT mode). The addition of external coils is not permitted.
d) The ASD shall be self-protected while running or at rest against:
    1) Switching motors on the drive output
    2) Output line-to-line short circuits
    3) Output line-to-ground short circuits
e) The ASD output shall be capable of driving multiple motors connected in parallel. Switching individual motors on and off the drive output shall not cause failure or tripping as long as the combination of motors is within the ASD's rating.
f) The ASD shall be capable of driving a motor up to 300 m away without the addition of output reactors.
g) The ASD shall be cable of operating without a motor connected for service.
h) The ASD shall be capable of operating in the following load characteristics:

Constant torque operation providing up to 160% of nominal torque for 1–5 min (dependent on load history).

Variable torque operation selectable from three (3) operation curves.

Variable torque which is cable of starting in a constant torque mode to provide high starting torque (160% of CT rating) with automatic switching to a variable torque mode.

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i) The ASD shall be capable of operating a motor sized one standard size larger than the drive rating. The ASD is not required to operate this larger motor beyond the drive rating.
j) The ASD design (1–40 kW) shall include a motor preheat circuit to prevent condensation forming in the ASD motor during shutdown periods.
k) The ASD shall have electronic thermal overload protection to prevent damage to the adjustable frequency drive.
l) Electronic thermal overload protection shall be available with or without motor temperature feedback. This protection shall include the effects of the speed of the motor and the length of time of operation at a given speed and current in the calculation of the motor protection. The overload protection will be UL recognized as a Class 20 overload device.

F.6. Performance

a) Advanced PWM control shall be used to generate sine wave current output between the ASD and motor. Predictive control techniques shall be used to calculate pulse widths and spaces.
b) The ASD shall be capable of adaptive motor tuning motor-specific parameters to a nominal value. Parameters affected shall be motor magnetizing, start voltage, start compensation, volt/frequency ratio, slip compensation and negative slip compensation.
c) The speed regulation of the ASD shall be ±0.5% of rated speed, with a 10–90% load variation from 6–60 Hz.
d) There shall be programmable start and slip compensation so that the adjustable frequency drive can optimize motor performance.
e) The ASD shall have built in dc injection braking programmable from 0–15 s with programmable dc injection voltage.
f) The ASD will have adjustable ramp times from 0.1 to 3600 s.
g) The ASD shall be capable of a flying start function. It shall be able to start into a rotating load (forward or reverse) without tripping or creating overload currents.
h) The ASD shall have four programmable critical bypass frequencies to skip over resonant frequency ranges during acceleration/deceleration. The width of the bypass frequencies shall be adjustable.
i) The ASD shall be programmable for extended power loss ride-through capability utilizing the stored energy of the rotating load.
j) There shall be provided as standard a closed loop PID controller, which can be programmed to be supplied by a standard analog signal (0–5 V, 0–10 V, 0–20 mA, 4–20 mA) or a maximum pulse signal of 100 Hz, 1 kHz, 10 kHz. The PID controller shall have a programmable low-pass filter, programmable feed-forward function, and programmable feedback scaling.

F.7. Displays and programming

a) Data shall be displayed on a back-lighted three-line LCD alphanumeric keypad mounted on the front of the ASD. The keypad shall be able to perform all programming and configuration functions of the drive system.
b) The programming keypad shall be remotely mountable to a distance of up to 3 m.
c) The keypad shall include a red FAULT lamp and a green POWER ON lamp.
d) The ASD shall be programmable to display *any one* of the following items during operation:

Reference signal (%)
Frequency of the output (Hz)
Feedback (programmable unit)
Motor current (amperes)

Motor torque (%)
Power (kW)

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Energy (kWh)
Output voltage (V)

DC bus voltage (V)
Motor temperature (% until trip)
Drive temperature (% until trip)

e) The keypad display shall continuously display the ASD operating status and fault conditions in plain text.
f) There shall be provided a lock switch inside the ASD to prevent any unwanted programming.
g) The ASD shall include an RS485 serial communication port. The port shall permit monitoring, programming and control of the ASD. The ASD manufacturer shall provide a DOS based ASD programming program upon request.

F.8. Programmed control inputs/outputs

a) Potential free terminals shall be provided for contact closure control inputs. A nominal +24 V dc supply shall be provided to operate these inputs or an external voltage between +10 and +37 V dc may be applied to operate the control.
b) The control inputs shall be operable with any mechanical or solid state switching device rated for a closed circuit current of 25 mA dc, and having an open circuit leakage of 100 uA or less at 24 V dc.
c) Control inputs shall be isolated from the ac line and power components sufficiently to withstand a test voltage of 2500 V rms for 1 min. The control inputs shall be tested to the following standard.
d) The ASD control inputs shall comply to the following EMC (electromagnetic compatibility) standards:

Immunity—IEC 61000 family of standards [B15]

Logic terminals shall be programmable. A minimum of eight shall be programmable for the following functions:

Start (two-wire nonlatching control)

Reverse

Start (three-wire latching control)

Start (reverse three-wire nonlatching control)

Stop (ramping)

Stop (alternate deceleration rate)

Stop (coast to stop)

Stop (dc brake to stop)

Jog

Reset

Preset speed select (20 preset speeds)

Parameter set select (4 parameter sets)

Speed increment/decrement

Pulse train follower/feedback input

Motor thermistor input

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Terminals shall be provided for analog control of motor speed. Two terminals shall be programmable for the following functions:

Voltage input: 0–10 V dc, 2–10 V dc, and 1–5 V dc signal (or inverted)

Current input: 0–20 mA and 4–20 mA signal, 226 Ω (or inverted)

A 4–20 mA signal loss detection function shall switch the ASD to the last speed, full speed jog speed, or zero speed following a signal loss.

The ASD shall have two relay outputs (one form A, one form C, UL rated 240 V ac 2 A) programmable to provide the following indications:

Ready

Alarm (fault)

Warning

Current limit

Motor overload

Running on reference

Running

Out of frequency range

Out of current range

The ASD shall have two analog outputs (rated 0–20 mA or 4–20 mA, 470 Ω maximum) programmable to provide the following analog or digital signals:

Frequency

Current

Torque

Reference

Ready

Alarm/fault

Warning

Current limit

Motor overload

Running on refer

Running

Out of frequency range

Out of current range

An option shall be available that will allow the ASD to interface with the customer's serial communications networks.

An option shall be available that will allow the ASD to interface with other customer-specified serial communication networks.

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F.9. Adjustments

The ASD shall provide the following programmable adjustments:

- Start frequency
- Four acceleration and deceleration ramps (0.1–3600 s)
- Four bypass frequencies and adjustable bandwidth
- Preset speed (20 speeds)
- Acceleration/deceleration ramp profile
- Current limit
- Start compensation
- Start voltage
- Slip compensation
- Magnetization current
- V/Hz ratio
- Auto restart times (0–10 restarts)
- PID parameters
- P Gain
- I Integral time
- D Differential time
- FF Feed forward
- LP Low-pass filter
- Feedback scale factor
- Warning frequency high/low
- Motor parameters:
  - power output
  - voltage
  - frequency
- Custom display:
  - Engineering unit
  - Scale factor
- DC brake time
- DC brake voltage
- DC brake cut in frequency
- Power loss ride through mode
- Flying start mode
- Adaptive motor tuning

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F.10. Diagnostics

The ASD shall have on-board diagnostics which will display faults and status messages. A log recording fault codes, time, and value will be stored for the past eight faults. ASD operational data for the last fault shall be stored every 120 ms or immediately upon a trip condition for later analysis.

F.11. Service and warranty

a) The ASD shall have a manufacturer's warranty period of 1 year from date of invoice or 18 months from date of manufacture, whichever expires first. An extended service contract shall be available.
b) The ASD manufacturer shall maintain a network of factory trained, stocking authorized service centers.

F.12. Accessories

a) The ASD manufacturer shall provide an intergrated UL/CUL listed NEMA 1 Adaptable Packaged Unit (APU) housing the following devices:

   1) AC line disconnect, lockable, door interlocked
   2) AC line fuses
   3) ASD bypass circuit (3 contactor w/ac line isolating contactor)
   4) Thermal overload relay
   5) Control transformer, fused

b) The APU shall be capable of housing the following devices:

   1) Start pushbutton
   2) Stop pushbutton
   3) Reset pushbutton
   4) ASD-line selector switch
   5) Speed meter
   6) Ammeter
   7) Fault lamp
   8) Bypass mode lamp
   9) 3–15 psi input
   10) Auto bypass circuit

   The ASD shall have provisions to accommodate other control devices as specified.

F.13. Inverter-drive and motor compatibility

The following items are to be addressed in the drive system specification in the context of interfacing with definite purpose squirrel-cage induction motors driven by PWM-VSI ASDs:

a) Shaft voltages
b) Voltage spikes
c) Starting requirements
d) Special temperature rise issues
e) Overspeed
f) Bearing lubrication
g) Testing

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h) Assessing mounting
i) Motor speed
j) Motor power cables

F.14. Guide to pertinent motor application information

F.14.1 Service conditions

Motors should be specifically designed with respect to their service conditions, usual or unusual, both of which involve the environmental conditions to which the motor is subjected and the operating conditions. Service conditions, other than those specified as usual, may involve some degree of hazard. The additional hazard depends upon the degree of departure from usual operating conditions and the severity of the environment to which the motor is exposed. The additional hazard results from such things as overheating, mechanical failure, abnormal deterioration of the insulation system, corrosion, fire, and explosion. The motor manufacturer's proposal shall state the motor manufacturer's estimated degree of departure from each usual operating condition that the aforementioned additional hazards are likely to result. The motor manufacturer shall identify specific technical information that is required from the manufacturer of the driven mechanical equipment and the drive in order to ensure proper motor operation under unusual service or operating condition. The motor manufacturer shall identify unusual service conditions that may effect the construction or operation of the motor. Among such conditions are exposure to:

a) Combustible, explosive, abrasive, or conducting dusts
b) Lint or very dirty operating conditions where the accumulation of dirt may interfere with normal ventilation
c) Chemical fumes, flammable or explosive gases
d) Nuclear radiation
e) Steam, salt-laden air, or oil vapor
f) Damp or very dry locations, radiant heat, vermin infestation, or atmospheres conducive to the growth of fungus
g) Abnormal shock, vibration, or mechanical loading from external sources
h) Abnormal axial or side thrust imposed on the motor shaft
i) Loading which requires the motor to operate at or above its rated service factor for long time intervals.
j) There is excessive departure from rated voltage or frequency, or both
k) Low noise levels are required
l) The voltage at the motor terminals is unbalanced by more than 1%
m) Operation at speeds above the highest rated speed
n) Operation in a poorly ventilated room, in a pit, or in an inclined position
o) Operation where subjected to:
p) Torsional impact loads
q) Repetitive abnormal overloads
r) Reversing or electric braking

F.14.2 Voltage spikes

Most PWM-VSI drives used to supply adjustable frequency power to induction motors do not produce sinusoidal output voltage waveforms. In addition to lower order harmonics, these waveforms also have superimposed on them steep-fronted, single-amplitude voltage spikes as shown in Figure F.1. Turn-to-turn, phase-to-phase, and ground insulation of stator windings are subjected to the

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resulting dielectric stresses. These high dv/dt voltage spikes can evolve standing wave voltages, which appear at the motor terminals. The resultant voltages depend on both the characteristic impedance of the PWM-VSI drive output cable assembly, the distance between the drive and the motor, the terminal impedance to ground of the motor, and the magnitude and frequency of the PWM-VSI drive output voltage components. Although there is no industry consensus on the level of these voltage spikes, several different studies have pointed to a maximum possible repetitive voltage that is significantly higher than that initially adopted by standards making bodies.

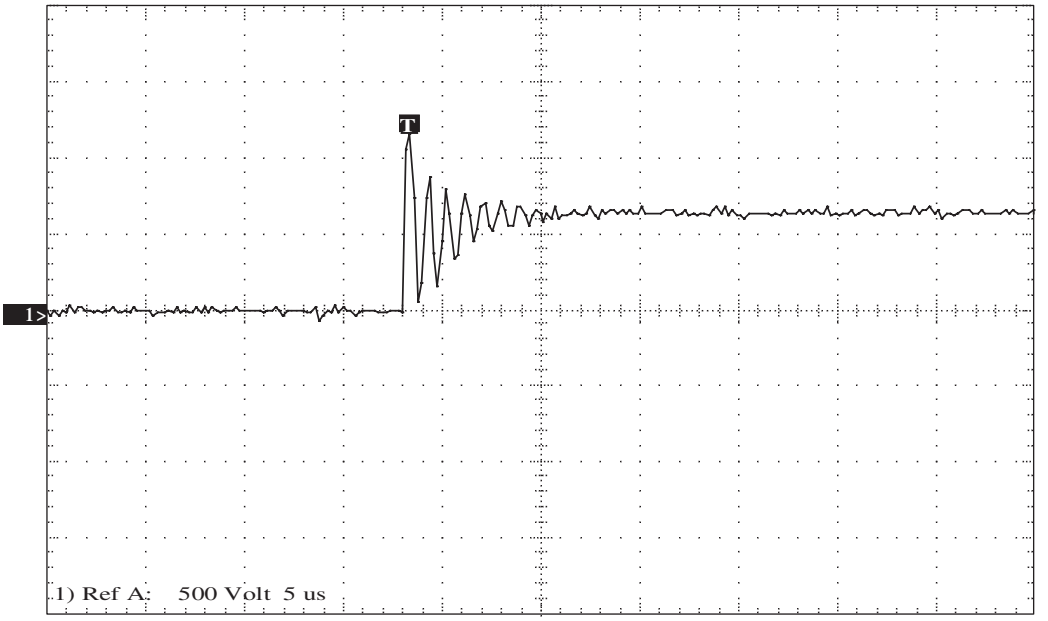


Figure F.1—Peak–peak voltage spike at motor terminal (500 V/div, 5 μs/div)

When operated under usual service conditions, stator winding insulation systems for definite-purpose PWM-VSI fed motors shall be designed to operate under the following limits at the motor terminals.

Motors with base rating voltages $\leq$600 V:

$V_{peak} \leq 1600$ V

Rise time ≥ 0.1 μs

where V_{peak} is single amplitude of the line-to-ground voltage at the maximum operating speed point.

NOTE—A 1600 V line-to-ground insulation system capability means line-to-ground peak, involving all the insulation components in the motor, of which the wire covering is only one.

Assuming a motor is rated 600 V (line-to-line), peak line-to-ground voltage would be about $\sqrt{2} \times 600/\sqrt{3}$ or 490 V; 3.3 times that value is nearly 1600 V. The motor manufacturer shall provide information to the buyer regarding which one or more of the following key features have been added to augment the motor insulation system:

a) Magnet wire with increased dielectric strength
b) Improved insulation on end turns, in the slots and between phases
c) Heavy duty lacing or taping of end-turns
d) Extra cycles of varnish dip or vacuum pressure impregnated
e) Maximized copper content
f) High-temperature insulation with low thermal rise levels

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Measuring the peak overvoltage at the motor terminal should be a required start-up test. Care must be exercised in using the right type of measuring equipment. Typical analog or digital voltmeters cannot properly measure the peak voltages since the duration of these pulses is in nanoseconds. A hand-held oscilloscope with isolated input channels and sufficient sampling rate should be used. If the voltage measurement shows peak overvoltages exceeding the 1600 V limit, then the use of motor output filters should be considered.

F.14.3 Shaft voltages and bearing insulation

Additional shaft voltages occur for motors driven by PWM inverters due to the electrostatic coupling effect between the stator and rotor. These voltages will cause currents to flow through the bearings. The resulting bearing currents can cause pitting of the bearings, scoring of the shafts, and eventual bearing failure. Various field data collected from motors fed by PWM-VSI drives have shown a large variance in both the magnitude of shaft voltages and their affects on bearings via the currents they generate. At this point, there has been no conclusive study that has served to quantify the extremely diverse issue of bearing currents. However, it appears that this discharge current is more likely to happen with inverters using a higher switching frequency (10–20 kHz).

Due to this lack of understanding, values of shaft voltage cannot consistently be determined in advance of the installation of a variable speed application. Measuring the peak shaft voltage on a motor driven by a PWM inverter indicates the likelihood of the presence of discharge currents. However, depending on many actors (one of which is the oil film thickness discharge), current can occur for a voltage peak of as low as a couple of volts to as high as 30–40 V. Typically, the discharge currents are an order of magnitude higher (2–5 A) than the normal dv/dt currents, which are in hundreds of milliamperes range, and coincide with the falling edge of the shaft-to-ground voltage pulses. It is recommended that for high-risk installation the user should require a test during commissioning using a grounding strap and a current probe to verify the presence of discharge currents.

Although insulated motor bearings stop the flow of discharge current through the motor bearings, they do not prevent damage to the bearings of other shaft-connected equipment, such as tachometers, fans, pumps, or compressors. Even if the mechanical loads are operated by pulleys and belts, the bearings of the driven equipment may still be affected due to rotor charge accumulation. If the driven equipment is completely isolated (i.e., provides no high-frequency path for shaft voltages) then insulated bearings may work. Another solution is to keep the shaft and frame at the same potential by using a shaft grounding device. Soft carbon brushes are not suitable because they may create a nonconductive film that prevents electrical contact between the brushes and shaft.

F.14.4 Neutral shift

Neutral shift is the voltage difference between the source neutral and the motor neutral. Its magnitude is a function of the total system design and in the case of some types of current source inverters can be as high as 2.3 per unit ($1\,\text{pu} = \sqrt{2}/\sqrt{3}V_{LL}$), resulting in motor line-to-ground voltages of up to 3.3 per unit, or 3.3 times the crest of the nominal sinusoidal line-to-ground voltage. In the case of a typical voltage source inverter, the magnitude of the line-to-ground voltage can be as high as $\sqrt{3}$ times the crest of the nominal sinusoidal line-to-ground voltage. If the motor stator insulation system, which includes phase-to-ground insulation is designed to withstand the 1600 V peak stress as specified in NEMA MG-1-1998 Part 31, neutral shift will not be a problem for PWM inverter driven motors.

In a current-source inverter system, the source (usually a transformer) neutral or the motor neutral is grounded but not both. Depending which part of the system is grounded, the ungrounded part of the

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system will be subjected to higher than normal voltage stress to ground. Reestablishing the ground on the output of the inverter will reduce the high phase-ground potential at the motor terminal. However, reestablishing the ground on the motor side would mean that the neutral shift is transferred to the input transformer for the inverter. Installing a three-phase 5 kVA, 480/120 V delta/wye transformer at each inverter output and grounding the wye of the neutral is a simple and inexpensive method to reestablish ground on the motor side and avoid the neutral shift problem. These grounding transformers are not loaded and do not have to be derated for the inverter output harmonics.

F.14.5 Resonances, sound, and vibration

The motor and the driven equipment (system) have natural resonant frequencies in the lateral, axial, and torsional modes. When an adjustable frequency control is applied to the motor, the system is excited by a spectrum of harmonics coming from the PWM-VSI drive. This can affect the sound level, vibration level, and torsional response of the system. The motor manufacturer shall discuss these effects with the purchaser to ensure successful system performance. Machine sound and vibration are influenced by the following parameters:

a) Electromagnetic design
b) Type of electronic power supply
c) Resonance of frame structure and enclosure
d) Integrity, mass, and configuration of the base mounting structure
e) Reflection of sound and vibration originating in or at the load and shaft coupling
f) Windage
g) Bearing design

It is a goal that motors, applied on PWM-VSI drive type supply systems for adjustable-speed service, should be designed and applied to optimize the reduction of sound and vibration in accordance with the precepts explained above. However, since many of these influencing factors are outside of the motor itself, to the extent possible, the motor manufacturer will discuss with the buyer the sound and vibration concerns through the design of the motor alone.

F.14.6 Torsional considerations

When an induction motor is operated from a PWM-VSI drive, torque ripple at various frequencies may exist over the operating speed range. Consideration should be given to identifying the frequency and amplitude of these torques and determining the possible effect upon the motor and the driven equipment. It is of particular importance that the equipment not be operated longer than momentarily at a speed where a resonant condition exists between the torsional system and the electrical system (i.e., the motor electrical torque). At low speeds, such torque ripple may be apparent as observable oscillations of the shaft speed or as torque and speed pulsation (usually termed *cogging*). It is also possible that some speeds within the operating range may correspond to the natural mechanical frequencies of the load or support structure and operation other than momentarily should be avoided at those speeds. Based on the PWM-VSI drive output waveforms and mechanical driven-system data provided by the buyer, the motor manufacturer shall point out potential resonant conditions.

F.14.7 Bearing lubrication at low and high speeds

Successful operation of the bearings depends on their ability to function within acceptable temperatures. Above a certain operating speed, depending on the design, size, and load, the losses in an oil lubricated sleeve bearing may increase to a point that the temperature exceeds the permissible

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limits with self-lubrication. Below a certain speed, self-lubrication may not be adequate and may result in abnormal wear or high temperature or both. In either case, forced lubrication will be required. Grease-lubricated anti-friction bearings do not have similar problems at low speeds. Maximum operating speed for these bearings is limited due to temperature considerations and is a function of the bearing design, its size, the load, and other considerations. The motor manufacturer shall request from the user the specific mechanical and electrical system parameters at the maximum and minimum operating speeds to be taken into consideration by the motor manufacturer in the selection of the bearing and lubrication systems for motors covered by this specification.

F.14.8 Motor to inverter-drive compatibility

The motor manufacturer's proposal shall comment on each of the following items as to what, if any, affect each item can have on reliable motor performance and life-cycle.

F.14.8.1 Voltage rating of motor power leads

Motor leads and cabling between the motor and drive are subjected to the same repetitive voltage spikes that are seen by the motor windings; however, the weak link is usually the end turns of the motor coils. For 460 V and 575 V systems, under normal service condition, a 600 V rated cable shall be used. Under unusual service condition, such as exposure to steam, salt-laden air, oil vapor, damp location, or for 575 V systems if the possibility of voltage reflection exists, a 2000 V rated cable system shall be used. In addition to the voltage rating, the following cable type and general configuration is recommended:

General:

Type MC Metal-Clad Three-Phase Cable per NEC 334-1, UL approved

Conductors:

Three (3)—Phase conductors—Ampacity per NEC

Three (3)—Ground conductors—Ampacity per NEC for

1) single cable motor circuit
2) parallel motor circuits

Metallic sheath:

Continuous corrugated aluminum—Welded or seamless, with wall thickness as heavy as practical

Overall jacket:

PVC or equivalent

F.14.9 Role of external filter networks

External networks in the form of line reactors (inductors), tuned low-pass filters (R–L–C) or voltage snubbers (R–C) have been used either at the inverter output terminal or at the motor input terminal for attenuating the voltage transients resulting from the operation of PWM inverters. The purpose of these external networks is to minimize voltage stress. If successful, a standard motor, with long cable runs may be used without the possibility of voltage stress exceeding their insulation capability. A low-pass R–L–C filter at the drive output terminal is recommended if such external networks are required. In order to verify that the external network is able to reduce the voltage stress at the motor terminal

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below the voltage rating of the motor insulation system, the voltage at the motor terminal should be measured during start-up. Figure F.2 shows the voltage at the motor terminal with and without a low-pass R–L–C filter network installed at the inverter output terminal. Clearly successful application of these networks will reduce the voltage to a level that may allow standard 600 V motors to be used with inverters. In addition to attenuating the voltage transient, the application of these filters also increases the rise time of the voltage pulses lowering the possibility of discharge current and bearing problems associated with these discharge currents.

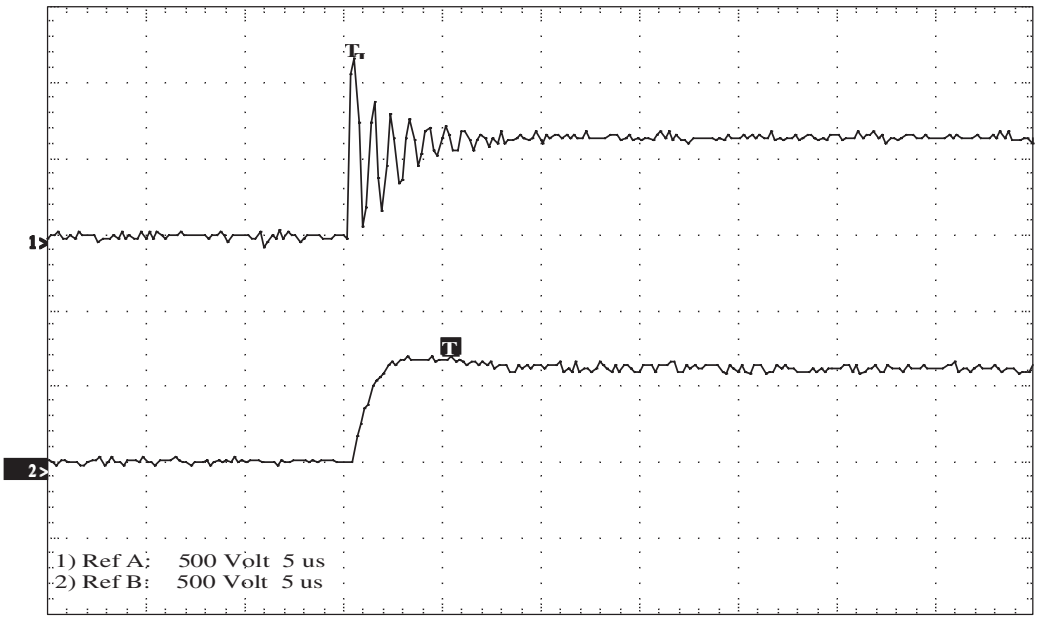


Figure F.2—Peak–peak voltage spike at motor terminal with (lower graph) and without (upper graph) R–L–C filter network (500 V/div, 5 μs/div)

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Annex G

(informative)

Sample medium-voltage ASD specification

This annex provides an example of a starting point for developing a comprehensive medium-voltage ASD drive system technical specification for an electric power generating station application.

G.1. Scope

G.1.1 Seller's responsibility

a) Provide all labor, materials, and tools, and perform all operations necessary for the engineering, design, fabrication, inspection, testing, documentation, delivery to the jobsite, and commissioning of solid-state adjustable-speed drive systems, including motors, adjustable-speed drives (ASDs), input transformers, medium-voltage switchgear, motor control center, and uninterruptable power supply (UPS) for ASD control power.

   ASDs shall each consist of a ____ kW continuous output rated, electronic adjustable-speed drive, and all associated hardware and software, except as defined in this specification. Associated hardware for provision by the seller shall include, but not be limited to, input power transformer, and associated control and protection apparatus. Each adjustable-speed drive shall be a fully integrated system, compatible with motors, electricity supplied, and other system interfaces, and shall be capable of providing the specified power requirements of the motor to which it is applied over the motor's rated speed plus 15% overspeed and the associated load range. The ASD shall be as completely factory assembled as possible within shipping and handling limitations in accordance with this specification. The ASDs shall be fully tested at the factory prior to shipment.

   Information in conflict with this specification shall be brought to the attention of the buyer. Improvements to lower cost or improve performance or reliability shall be offered as an alternate.

b) Provide all shipping F.O.B. ____ , City, State.
c) Provide technical assistance to commission the total integrated system.
d) Provide necessary operator and maintenance training.
e) Provide jobsite scheduling coordination required for timely installation, checkout, start-up, operation and testing of the ASD system.

G.2. Quality standards

G.2.1 General

a) The seller shall submit to the buyer for his approval the applicable Quality Assurance (QA) and Quality Control (QC) policies and associated procedures.
b) The seller shall submit to the buyer the necessary documentation throughout the project implementation to assure the performance of applicable tasks and services stipulated in the submitted QA and QC manuals, which had been approved by the buyer.

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c) The seller shall comply with all latest editions of applicable codes and standards, but not be limited to, those referenced in this specification. Where a standard is referred to and conflicts with a part of this specification, the buyer should be consulted in writing for immediate resolution.
d) The seller shall provide the buyer with certified copies of all test reports performed in accordance with required tests specified in this specification.

G.2.2 Referenced codes and standards

Sponsor	Number		Subject
ANSI	C57.13	1993	Requirements for Instrument Transformers
ANSI	Z55.1	1967	Gray Finishes for Industrial Apparatus and Equipment
ANSI	MC096.1	1975	Temperature Measurement Thermocouples
API	541	1995	Form-Wound Squirrel-Cage Induction Motors—250 Horsepower and Larger
API	546	1997	Brushless Synchronous Machines—500 kVA and Larger
IEEE	444	1973	Standard Practice and Requirements for Thyristor Converters for Motor Drives
IEEE	519	1992	Guide for Harmonic Control and Reactive Compensation in Electrical Power Systems
ANSI	C34.2	1968	Standard Practices and Requirements for Semiconductor Power Rectifiers
IEEE	59	1962	Standard Semiconductor Rectifier Components
ANSI	C57.12.00	2000	General Requirements for Liquid-Immersed Distribution, Power and Regulating Transformers
ANSI	C57.16	1996	Requirements, Terminology and Test Code for Dry-Type Air-Core Series Connected Reactors
ANSI	C57.18.10	1998	Standard Practice and Requirements for Semiconductor Power Rectifier Transformers
ANSI	C37.30	1971	Requirements for High-Voltage Air Switches, Insulators and Bus Supports
ANSI	C37.20	1978	Switchgear Assemblies including Metal Enclosed Bus
NEMA	CP-1	1976	Shunt Capacitors
NEMA	SG-5	1975	Power Switchgear Assemblies
NEMA	ICS 3.1	1978	Safety Standards for Construction and Guide for Installation and Operation of Adjustable-Speed Drive Systems
NEMA	C55.1	1968	Shunt Power Capacitors

G.3. Service requirements

G.3.1 Conditions of service

Site, city, state

Ambient temperature

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Altitude level

Humidity

Wind (side wall)

Air entrained salt, ppm

Solar radiation

Dust, $\mu g/m^3$

Rain/wind

Seismic zone

G.3.2 Design life

The design life of the equipment should not be less than 35 years with nominal maintenance and repair, to be consistent with the design life of other utility generation, transmission, and distribution equipment.

G.4. Overall system requirements

G.4.1 Seller responsibility

a) The seller shall have complete responsibility for all equipment and accessories included in this specification. The seller shall perform the necessary analysis of the operation of the seller's motor when powered by the seller's power conversion equipment to assure the following:

   1) The motor will operate in a stable manner without undue heating, vibration, or noise and with adequate torque margin for the specified acceleration requirements.

      Undue vibration shall be defined as an increase of 0.00254 mm (peak to peak displacement) or more in mechanical vibration on the motor bearing caps, an increase of 0.00762 mm (peak to peak displacement) or more of mechanical vibration on the motor housing, or any increase in torsional vibration on the motor or driven equipment shaft as determined by the buyer's tests conducted with and without electric power to the driven equipment.

      Undue noise shall be defined as any measurable increase in motor noise as determined by the buyer's tests conducted with and without electric power on the driven equipment.

      Undue heating shall be defined as additional heating that causes a stator RTD temperature to rise above rated temperature rise at any motor speed up to rated speed and at any motor output up to rated.

   2) The ASD shall not cause the motor to operate in excess of its design limits.
   3) The ASD shall not introduce sufficient harmonics into the power system to exceed IEEE Std 519-1992 recommendations. The ASD shall not cause misoperation of, or damage to, the motors or to other equipment. The existing electric service system impedance data shall be provided by the buyer.
   4) The motor shall satisfactorily operate over the full speed and load ranges while power is supplied from the ASD without compromising motor, related system capabilities, reliability, life expectancy, or impacting adversely existing operation and maintenance practices.

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a) The total harmonic distortion from the rectifier shall not exceed 3.0% voltage distortion or 12.0% current distortion at 4160 V supply breaker with the ASD operating.
b) The seller shall perform any special analyses that may be required for satisfactory operation in the intended application. Such analyses may include: 1) Harmonic analysis of currents and voltages distorted by the ASD in the buyer's electric system over the full ASD speed and load ranges; 2) Harmonic analysis of currents and voltages to the motors over the full speed and load ranges; 3) Torsional analysis of driven equipment and motor machinery; 4) Motor and driven mechanical equipment performance and capabilities over the full speed and load ranges; 5) Failure mode and effect analysis of the supplied drive system to support any reliability analysis the seller may choose to perform.

G.4.2 Scope of supply

a) The seller shall supply all the components necessary for the successful operation of the ASD, whether or not specifically identified in this specification. Each unit shall be considered as a package, which shall include, but not be limited to, the following:

    1) Power and control modules (consisting of a line converter to change the ac supply to dc and a load inverter to change the dc to an adjustable frequency ac for controlling motor speed) needed for a fully functional system. Power thrysistors shall be liquid cooled.
    2) Input isolation power transformers to be outdoor, oil-cooled, type OA complete with current transformers as required for transformer protection.
    3) Ancillary equipment including redundant cooling systems.
    4) Controls and instrumentation with provision for local and remote supervision and control.
    5) Redundant coolant system elements with automatic control shall be supplied for both internal (drive) and external cooling (house) cooling loops.

G.4.3 Performance

a) The induction motor shall start and accelerate its load, as shown on the load speed–torque curves, at reduced frequency and voltage to limit starting current to approximately 125% or more of rated full load current. The motor shall be capable of accelerating the WK^2 of the load per the buyer's requirements and ramping up to 100% of motor rated speed. Curves demonstrating this capability shall be submitted showing that the motor torque at the minimum voltage is above the load torque at all speeds and that the motor safe-heating limits will not be exceeded during starting under the conditions of specified maximum starting current.
b) Motor and control equipment shall be capable of accelerating the driven equipment by a minimum rate of 5% of operating speed per second in the operating speed range.
c) The maximum reactive power (kVAr) requirement at all operating load levels shall not exceed the kVAr required at rated motor output (kW).
d) 97% or better efficiency of the ASD, ac to ac is required at ____ power rating. At 25% load, the efficiency should not fall below 90%.
e) The seller shall design the proposed ASD systems to offer the following features:

    1) Optimized harmonic generation to reduce total sine wave distortion to the extent necessary in the buyer's power source and motor power supply, while assuring satisfactory performance without misoperation of or damage to, interfacing plant systems. Harmonic voltages and currents at the high-voltage side of the input transformer shall not exceed a total harmonic distortion of 3.0% voltage or 12.0% current.
    2) Optimized ASD design to yield minimum sine wave deviation to the extent possible while assuring satisfactory performance without misoperation of, or damage to, interfacing electric systems.
    3) Optimized thyristor selection to yield maximum reliability, minimum losses, maximum voltage withstand and minimum protective circuits.

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4) Optimized number of thyristors and associated electronic components to yield total system cost effectiveness, maximum reliability and minimum maintenance.

f) The ASD shall be sufficiently free of radiated and conducted EMI, RFI, and TIF, so as to not result in misoperation of instrumentation and communications equipment.

g) The ASD system shall be designed to correct automatically for internally or externally generated malfunctions, which could cause operation beyond its design capability.

G.5. Design requirements—ASD system

G.5.1 Power conversion and control modules

a) The rectifier/inverter equipment shall be a coordinated assembly of freestanding NEMA Type l enclosures in a weather-proof housing with ancillaries including cooling and heating system. The equipment shall be capable of continuous operation at ____ kW. Operation with output frequency from 0 of 60 Hz is anticipated. The drive equipment shall be capable of ±10% voltage operation. The normal operating current limit of the drive is 100% based on ____ kW.

b) The input isolation transformers shall be suitable for rectifier service and shall contain no PCB fluid. Transformer impedance shall be selected considering harmonic control, and to limit initial fault current to a safe value for ASD system thyristors. Oil-cooled type equipment shall be furnished.

c) The rectifier/inverter equipment shall be a twelve-pulse or greater input rectifier system.

d) The ASD, including all power equipment peripherals such as input and output transformers, switches, dc link inductors and capacitors, etc. shall be sized to deliver the specified kW output continuously for the total range of the driven load with a system input voltage variation of ±10%.

e) Thyristors shall have at least a 250% peak repetitive voltage margin and shall not be paralleled without the proper impedance separating the two legs. Thyristors shall be fired through fiber optics where applicable. Cell stacks shall be of modular design and interchangeable to facilitate replacement. All bus work shall be prefabricated and copper.

f) The electronic components in the ASD shall be protected against overtemperature as a result of loss of cooling.

g) Thyristors and/or module combination should be protected against voltage transient disturbances in the reverse and forward directions as well as against the rate of the associated transient without regard to voltage transient amplitudes.

h) The ASD modules shall be of proven design with the specified reliability. The rectifier and inverter thyristor stacks shall be so designed to normally operate at full voltage with $N-1$ thyristor operation in each leg of the associated bridges.

i) The printed circuit boards of the ASD modules shall be so designed that hardwired connections are minimized and remain intact when the printed circuit boards are removed.

j) The ASD shall be protected against, but not be limited to, input open circuit, output open circuit, open phase, loss of control power, loss of gating power, power supply over- and undervoltage, shorted thyristors, loss of cooling, electronic ground fault, excessive speed and overspeed indication, V/Hz limit, and high temperature.

k) The control modules shall provide the following control functions:

1) Controlled acceleration or deceleration, separately adjustable with current limit override acceleration protection.
2) Frequency control shall have a steady-state accuracy of 0.5%.
3) Separately adjustable minimum/maximum frequency limits compatible with full speed and load ranges shall be provided.
4) Process follower—to accept 4–20 mA transmitter signal. A relay and terminals shall be available for switching to an alternate external source.

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5) Low-frequency start/stop—adjustable linear ramp up/down to required speed
6) Current limit regulator
7) Speed regulator
8) Current and voltage feedback with isolation
9) Drive sequencing logic
10) Drive protection functions
11) Local start, stop and speed controls for field test and startup
12) Coordinated safe stop on protection signal, i.e., breaker trip, boiler control
13) LED or LCD display for semiconductor and control monitoring
14) Voltmeter, motor
15) Ammeter, motor
16) Power output meter, motor
17) Speed meter, motor
18) Optimize the ASD design for motor V/Hz control
19) Continuous frequency range 0–110 Hz

l) The following signal interfaces shall be provided between the drive and other equipment:

1) 1—Analog input channel (4–20 mA)
2) 3—Analog output channels (4–20 mA) for speed, amperes, and volts
3) 6—Contact closure inputs
4) 6—Contact closure outputs or optional serial bus system

m) The control modules shall provide the following protection functions, which will shut down the drive and be indicated by LEDs:

1) Stator winding overcurrent
2) Stator overvoltage
3) Overspeed
4) Open phase or missing gate
5) Commutation failure
6) Loss of cooling air
7) Transformer overtemperature
8) Shorted thyristor leg
9) Loss of logic control power
10) Loss of gate power supply
11) Speed command signal failure
12) Overcurrent rectifier and inverter
13) AC power supply undervoltage
14) External trip
15) External permissive shut down
16) Electronic ground fault detector
17) Stator RTD temperature

n) The following signals shall be sent from the drive to the customer's control room:

1) Speed indicating signal
2) Alarm signal (close on alarm)
3) Fault signal (close on fault)
4) Motor amperes

o) The following operator devices shall be furnished on or inside the door of the control cabinet:

1) Fault indicating lights
2) Alarm indicating lights
3) Reset button
4) Drive ready light
5) Output power indicator

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6) Motor speed indication
7) Motor ammeter
8) Motor voltmeter
9) Stop push button
10) Start push button
11) Manual speed potentiometer
12) Local/remote selector

p) The control modules shall include the following diagnostic capabilities:

1) Continuous on-line full coverage self diagnostics for both hardware (to the circuit board level or lower) and software
2) First fault indication and ability to locate subsequent system faults
3) Ability to recall events that preceded a shutdown of system
4) Ability to monitor major system components with status lights for replaceable elements
5) Diagnostic printer with English language output and capability to communicate all diagnostic information to distributed process computer

G.5.2 Isolation transformers

a) Input isolation transformers shall be suitable for ____ kV primary voltage. They shall be three (or more)-winding type, outdoor, oil-filled type OA, self-cooled rated 55 °C rise over 50 °C ambient, continuous for ANSI T1 duty class, ____ volt primary volts, 60 Hz multiple secondary, phase-shifted, ungrounded for use with a multi-pulse converter. The input transformers shall not be adversely affected by harmonics in the ASD input voltage and currents.
b) Input transformer impedance shall be selected to limit initial fault current to a safe value for converter thyristors and for control of input harmonics.
c) The following accessories shall be provided with each transformer:

1) Ground pad
2) Welded or bolted cover with bolted, gasketed inspection plates
3) Provisions for jacking and lifting
4) Base designed for skidding or rolling in either direction
5) Transformer shall be separate from drive skid
6) Connectors for incoming and outgoing power cables

d) High-voltage terminals shall be provided with suitable porcelain bushings.
e) Two $2\frac{1}{2}$% rated kVA high-voltage taps above and below rated voltage with manual tap changer for de-energized operation shall be provided on the input transformer.
f) Low-voltage connection shall be metal enclosed, air filled terminal compartment.
g) Devices shall be provided to alarm the following conditions:

1) High oil temperature
2) Hot spot winding temperature
3) Pressure relief
4) Low oil level

G.5.3 Control panels

a) All panel wiring shall be drive manufacturer's insulated switchboard wire 600 V, 90 °C, single conductor.
b) All power connections above 30 A shall be pressure (crimp) type connectors with a NEMA pad, including terminations for purchaser's connections.

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c) Wire connections, other than factory soldered connections, shall be made with non-insulated straight shank, crimp type, plated, terminals.
d) Each terminal block and each point used on terminal block shall be labeled with tape or stick on labels.
e) All circuit boards shall be accessible for quick and easy replacement without special tools.
f) Components shall be accessible through lockable hinged door.
g) No electrically-energized components shall be accessible with doors closed.
h) Hardware shall be properly designed and/or treated to resist corrosion.
i) Power bus shall be conservatively rated and so designed for maximum current rating and maintenance-free operation.
j) All interconnecting wiring, equipment and terminal board points shall be properly identified using approved identification marking.
k) Modular construction shall be used to minimize maintenance and change-out required during the troubleshooting process.
l) Thermostatically controlled space heaters shall be provided.
m) All panels and equipment shall be designed to maximize safety of operating and maintenance personnel.

G.5.4 DC link inductors

DC link inductors shall be copper wound, 90 °C temperature rise with Class H insulation. DC link inductors shall be of air-core design.

G.5.5 Tools and test equipment

a) The supplier shall supply a complete list of testing equipment, and any special tools required to install and maintain the drive system. Price adders should be included for the supplier to supply any special tools or special testing equipment required.

G.6. Shipping, handling, and storage

a) The method of preparation for shipment shall protect converters and all other parts, auxiliary devices and accessories against corrosion, dampness, breakage, or vibration injury that might be encountered in transportation and handling. The manner of packaging shall be such as to prevent tampering or pilfering and shall be acceptable to the transportation companies.
b) The units shall be delivered in the largest subassemblies practical for transportation.
c) The seller shall provide instructions for on site storage and handling to be performed by the buyer.

G.7. Inspection and testing

G.7.1 Shop tests

a) Power rectifier and inverter equipment to be given routine tests in accordance with IEEE Std 444-1973(W).
b) Certified copies of all test reports shall be submitted.
c) The buyer reserves the right to witness final shop tests and shall be notified a minimum of 14 days prior to such tests.

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G.7.2 Field tests

a) The seller shall demonstrate trouble free, stable operation for conditions of starting, stopping, full load, three-quarter load, half load, quarter load, no load, and intermediate loads.
b) Tests shall include 100 h of operation at full load to demonstrate adequacy of equipment for thermal and voltage stresses.
c) Tests shall demonstrate 60 days of trouble-free operation.

G.8. Guide to pertinent motor application information

G.8.1 Motor data sheets

The motor data sheets, which are an integral part of the specification, contain specific information regarding the motor application. In particular, the load speed–torque curve and load inertia have been supplied and must be taken into account when meeting the requirements of this specification.

G.8.2 General motor construction

The frame construction of all motors shall be of fabricated steel not less than 5/16 in (8 mm) thickness. All enclosures shall be suitably treated to inhibit corrosion and adequately braced to resist distortion and vibration. Enclosures manufactured from synthetic materials are not acceptable. Bearing bracket to housing must be a rabbet fit.

G.8.3 Electrical requirements

State that the motor will be operated with a variable frequency drive at variable voltages and frequency, as specified on the data sheet.

G.8.4 Excitation system (if applicable)

Synchronous motors shall be provided with a shaft-mounted brushless exciter with redundant semiconductor devices and synchronizing circuit.

G.8.5 Other considerations

Other design considerations are as follows:

a) ASD and motor coordinated interface
b) Bearings selection
c) Rotor construction and balancing
d) Coupling installation
e) Terminal boxes
f) Nameplates
g) Accessories, such as space heaters, air filters, lifting lugs, and base plate
h) Noise requirement
i) Quality control program
j) Testing and inspection
k) Painting
l) Shipping preparation

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