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**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



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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

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**Energy Development and Power Generation Committee
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IEEE Power Engineering Society**

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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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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.

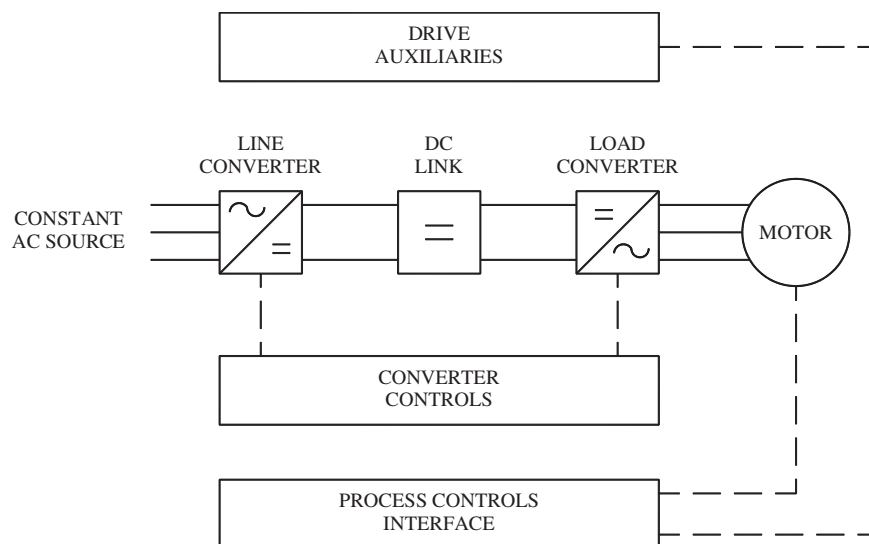


Figure 1—DC linked ac adjustable-speed drive system

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 112TM-1996, IEEE Standard Test Procedure for Polyphase Induction Motors and Generators.^{2,3}

IEEE Std 115TM-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 444TM-1973(W), IEEE Standard Practices and Requirements for Thyristor Converters for Motor Drives—Part 1: Converters for DC Motor Armature Supplies.⁴

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

IEEE Std 995TM-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 C37.96TM-2000, IEEE Guide for AC Motor Protection.

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

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⁴IEEE 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/>).

⁵IEEE Std 995-1987 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/>).

IEEE Std C57.12.01TM-1998, IEEE Standard General Requirements for Dry-Type Distribution and Power Transformers Including Those with Solid Cast and/or Resin Encapsulated Windings.

IEEE Std C57.110TM-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 Authoritative 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.

⁶NEMA publications are available from Global Engineering Documents, 15 Inverness Way East, Englewood, CO 80112-5704, USA (<http://global.ihs.com/>).

⁷The numbers in brackets correspond to those of the bibliography in Annex A.

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.

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]):

$$\varphi = E/(kf) \quad (1)$$

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:

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

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.

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_f) will vary directly with motor speed and the ratio of E_f/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).

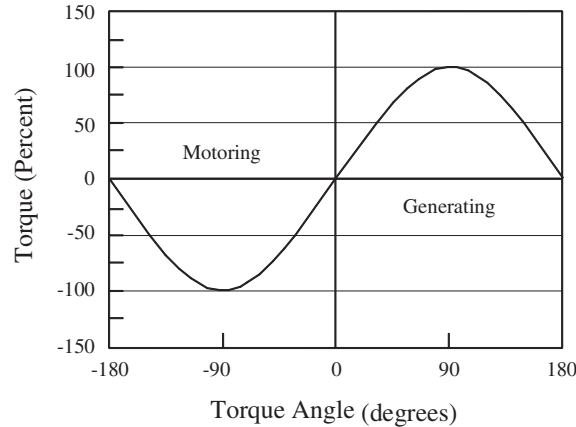


Figure 2—Torque angle characteristic for synchronous machines

If the motor field excitation (E_f) 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]).

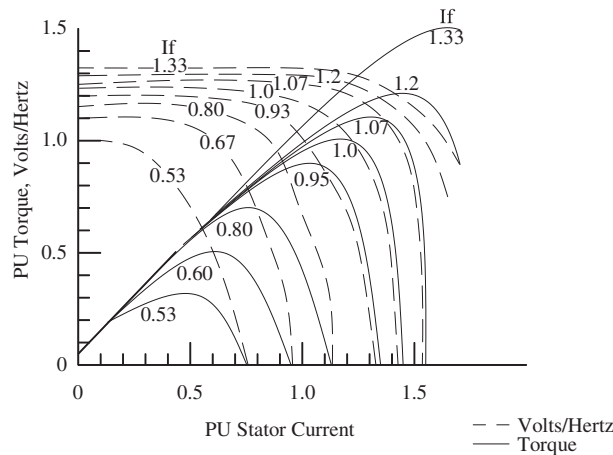


Figure 3—Torque characteristics of synchronous motor supplied from an adjustable-speed drive (Owen and Weiss [B30])

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:

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

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 ($\cos \beta$). 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:

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

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):

$$\omega = 4\pi f / p \quad (5)$$

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

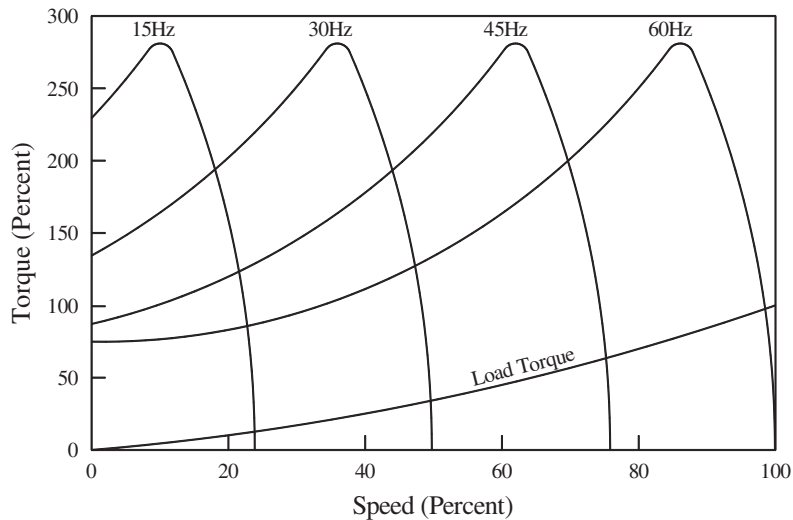


**Figure 4—Torque-speed characteristics for induction motor supplied from a variable voltage and variable frequency source
(Note that the effects of stator resistance are neglected.)**

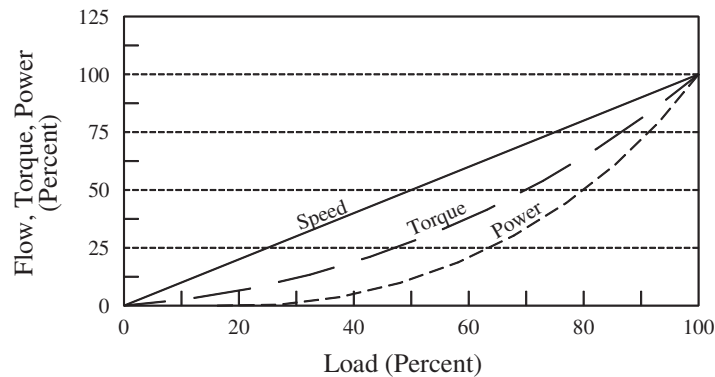


Figure 5—Typical centrifugal pump or fan flow, torque, and power characteristics as a function of speed

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

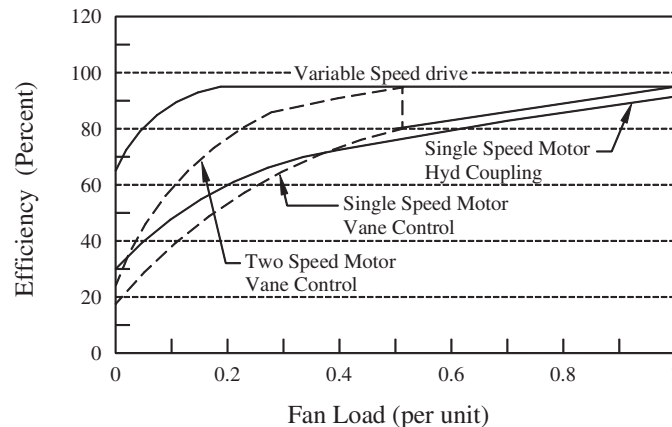


Figure 6—Comparison of common fan drive system efficiencies as a function of fan load (Gripp [B7])

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:

- Constant speed motor with fan inlet vane or damper (throttling) controls
- Two speed motors with fan inlet vane or damper controls
- Adjustable-speed with a hydraulic coupling
- 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.

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.

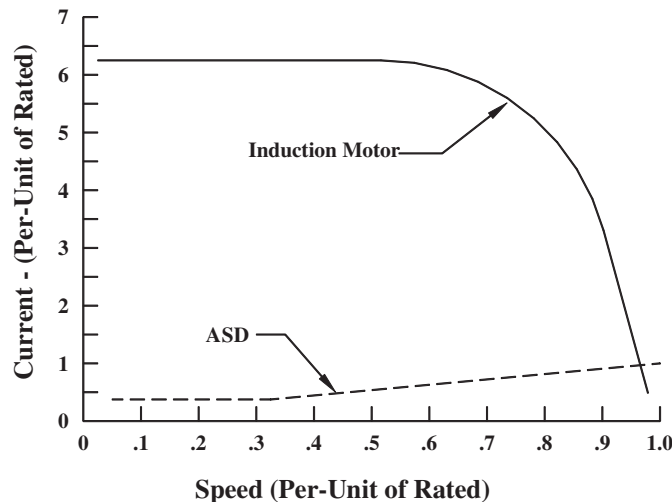


Figure 7—Comparison of current-speed curve for starting of a typical induction motor and ASD system (Higgins et al. [B10])

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

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

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 system 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.

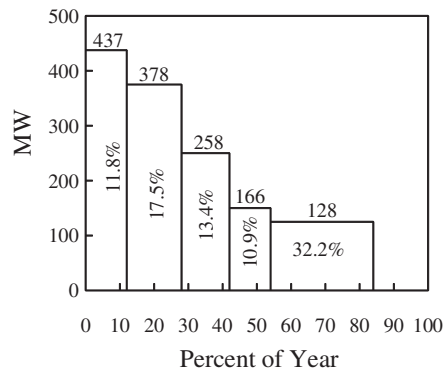


Figure 8—Load duration curve

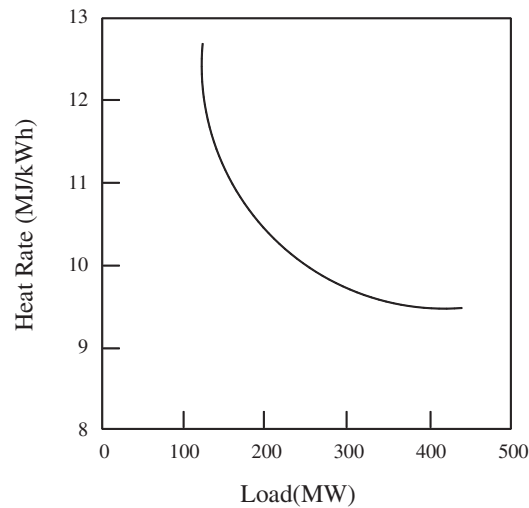


Figure 9—Heat rate versus load

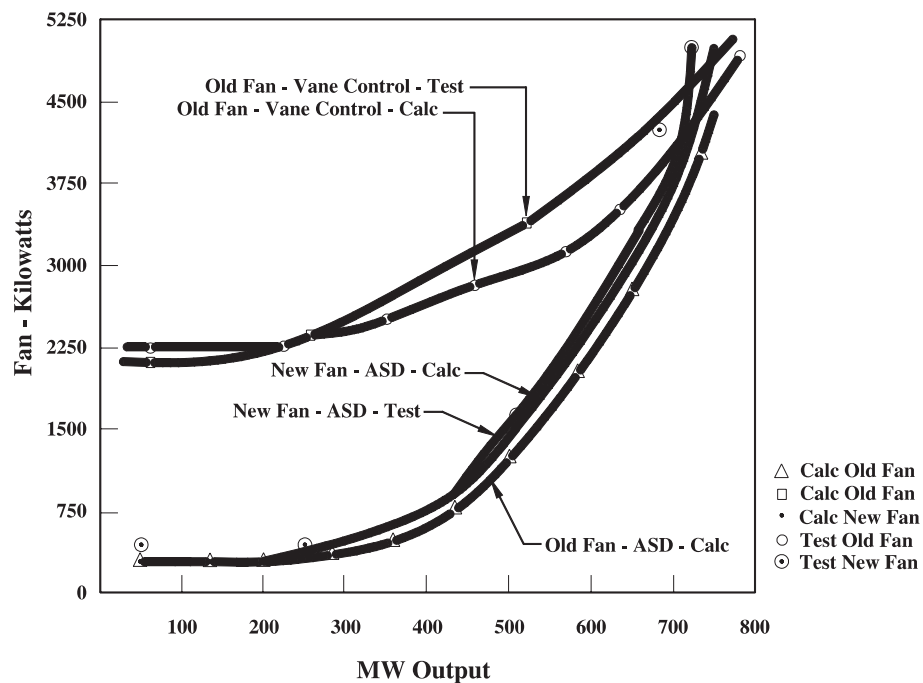


Figure 10—Typical plant FD fans/ASDs motor output power versus unit gross MW

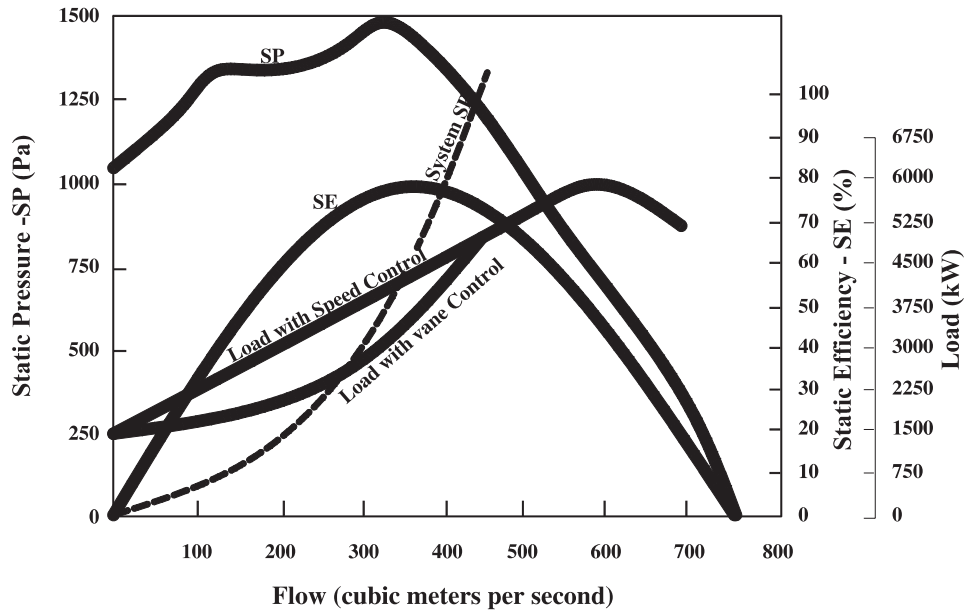


Figure 11—Forced-draft fan performance curve

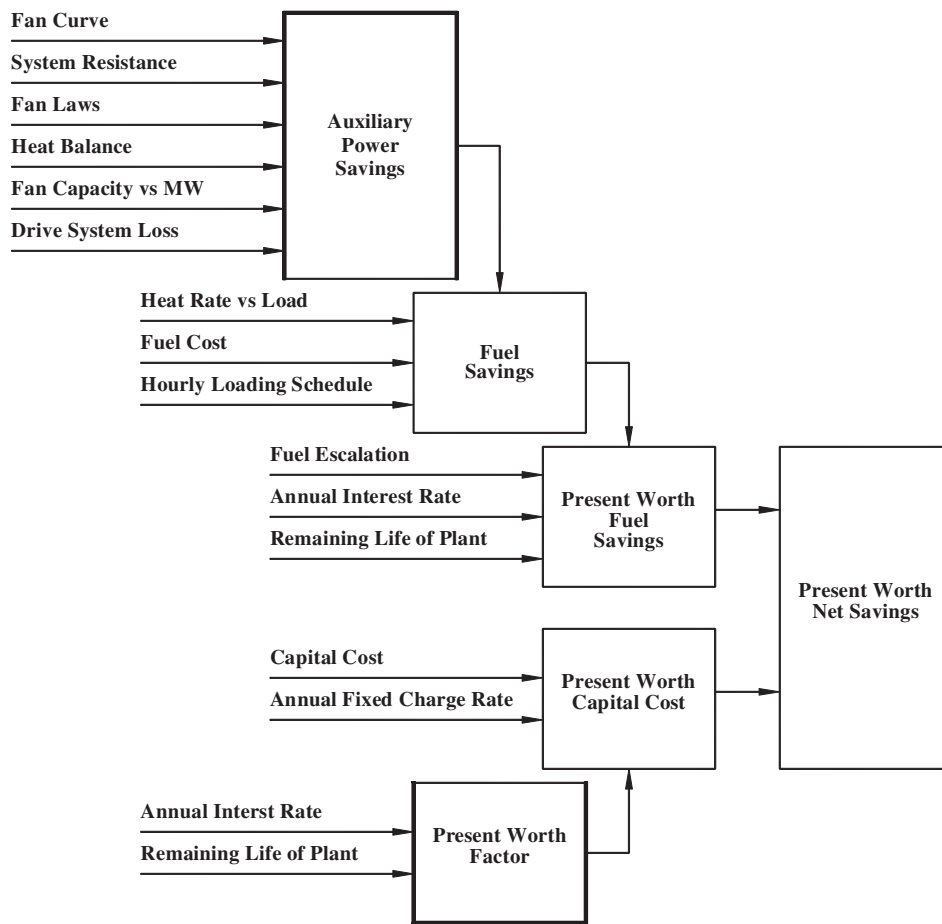


Figure 12—Present worth of energy savings flow chart

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

^aTotal 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.

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.

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):

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

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.

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.

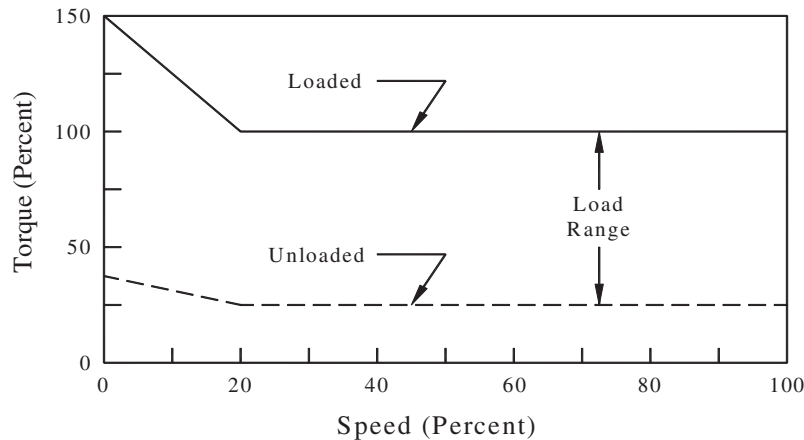


Figure 13—Typical speed–torque curve for conveyor

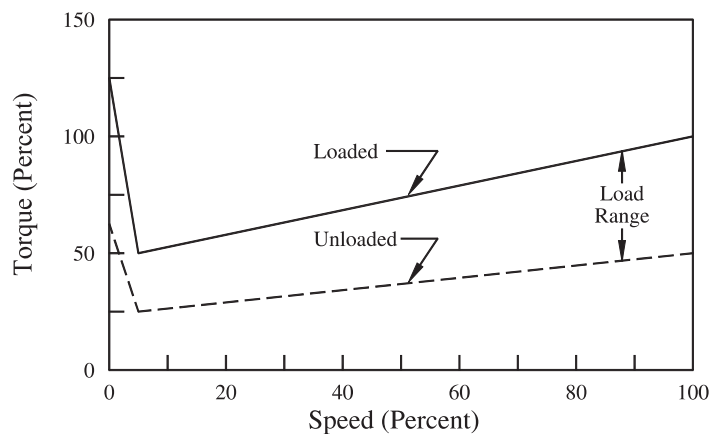


Figure 14—Typical speed–torque curves for crusher

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

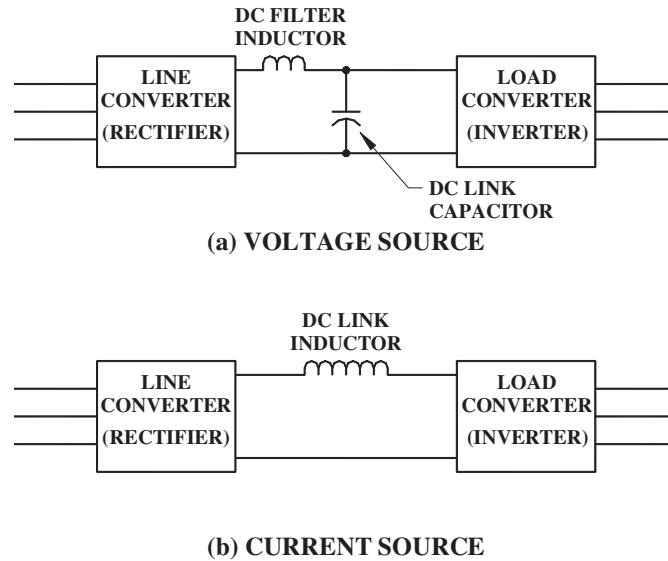


Figure 15—Types of dc linked converters (Hassan [B9])

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]):

$$V_{d0} = 1.35V_{L-L} \quad (7)$$

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

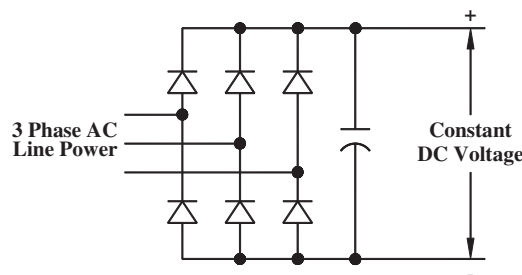


Figure 16—Uncontrolled line converter (Oliver [B26])

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]).

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]).

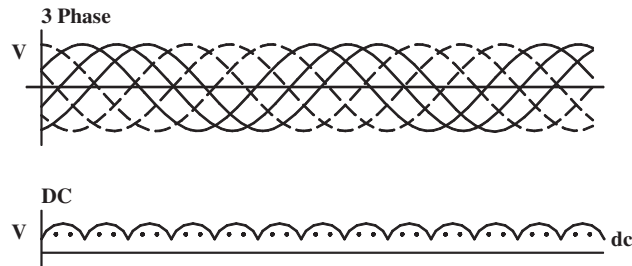


Figure 17—Sample average uncontrolled line converter output voltage (Oliver [B26])

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 consists 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

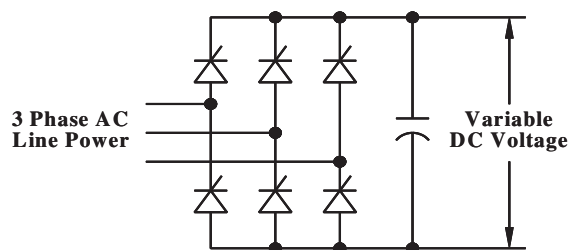


Figure 18—Phase controlled line converter (Oliver [B26])

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]).

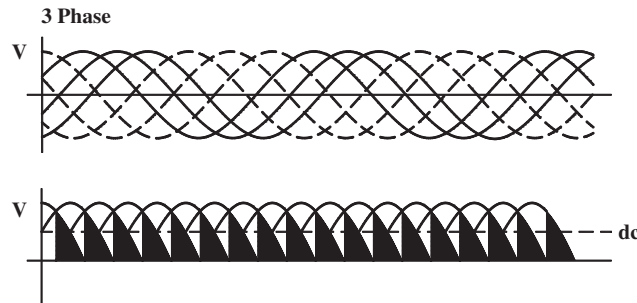


Figure 19—Sample no-load output voltage for phase controlled line converter

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.

⁸Information on references can be found in Clause 2.

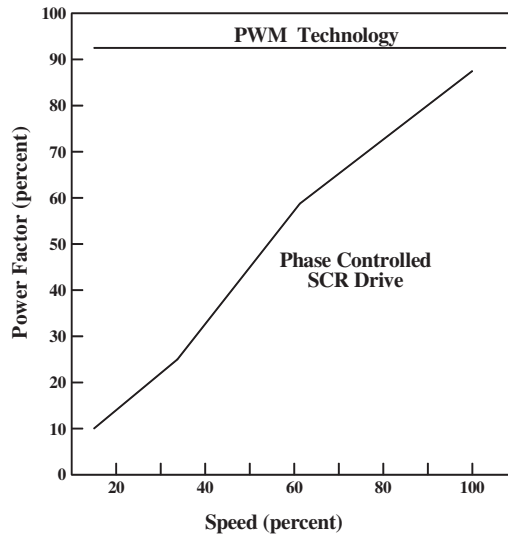


Figure 20—Comparison of power factor on line converters (Hammond [B8])

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,

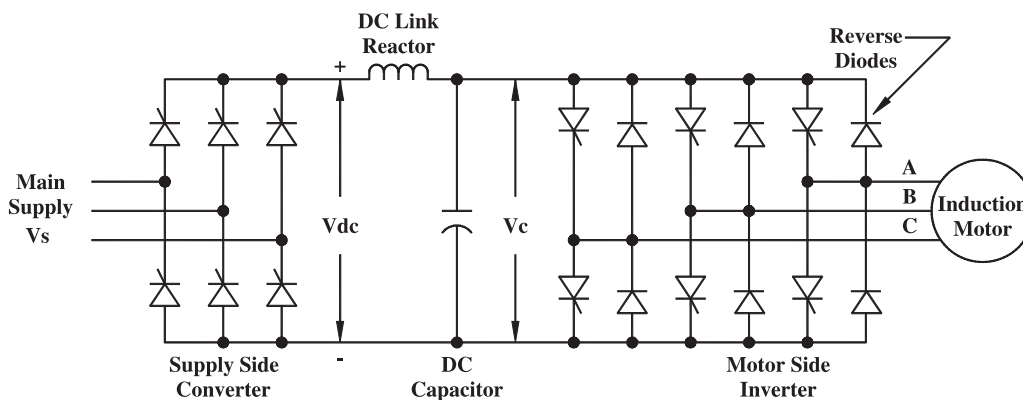


Figure 21—Basic six-step voltage source inverter (VSI) drive system (Finney [B5])

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.

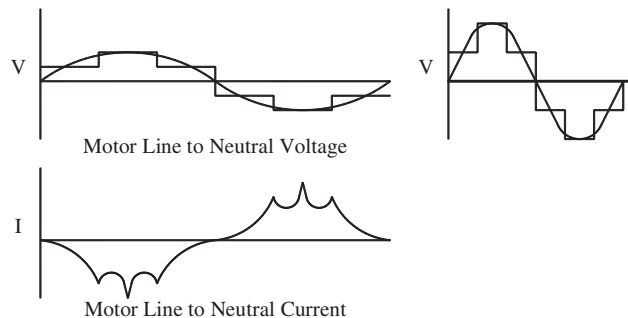


Figure 22—Motor voltages and currents for six-step VSI drive (Oliver [B26])

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

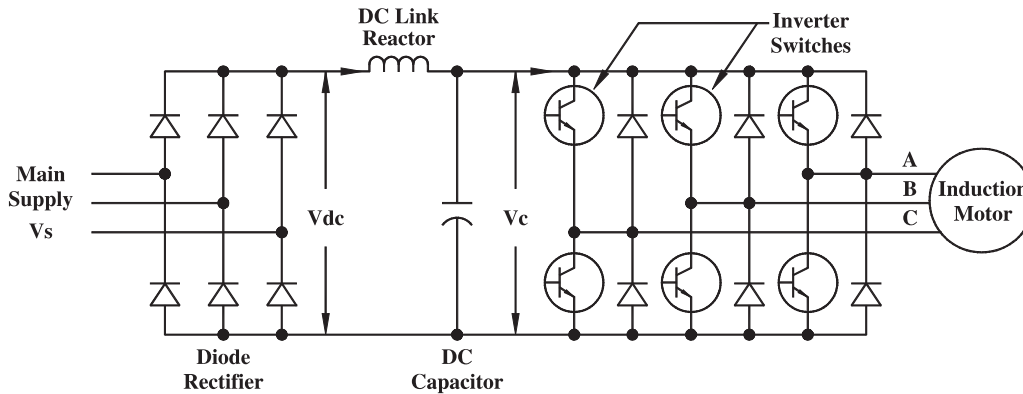


Figure 23—Diagram of PWM-VSI drive system (Finney [B5])

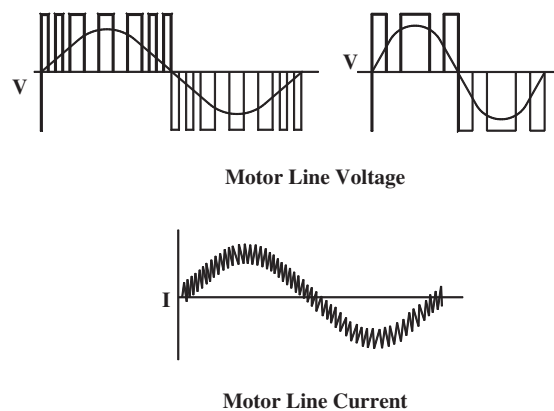


Figure 24—Motor voltage and current PWM-VSI drive (Oliver [B26])

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

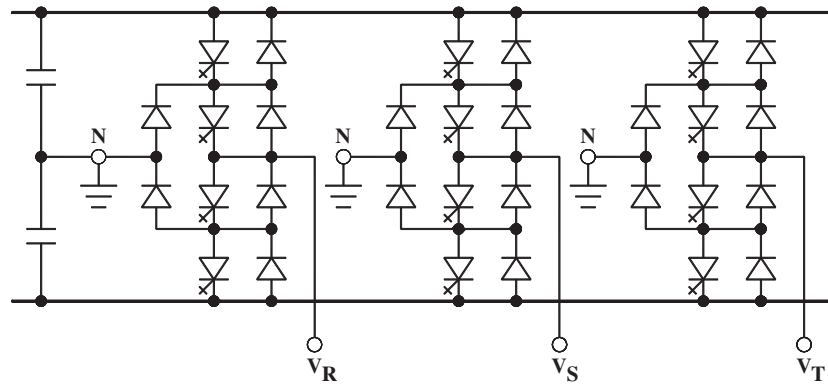


Figure 25—Three-level PWM-VSI drive (Bose [B1])

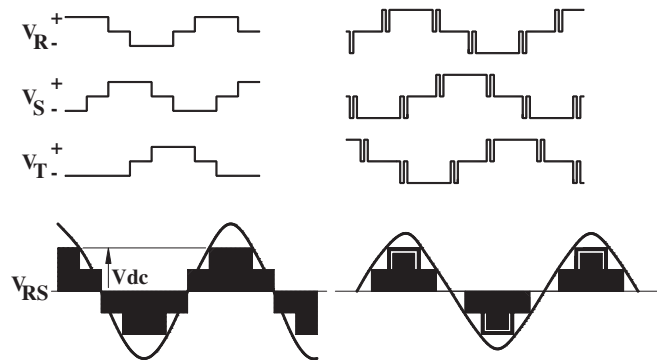


Figure 26—Comparison of output voltages for two- and three-level PWM-VSI drives (Oliver [B26])

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

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):

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

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

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.

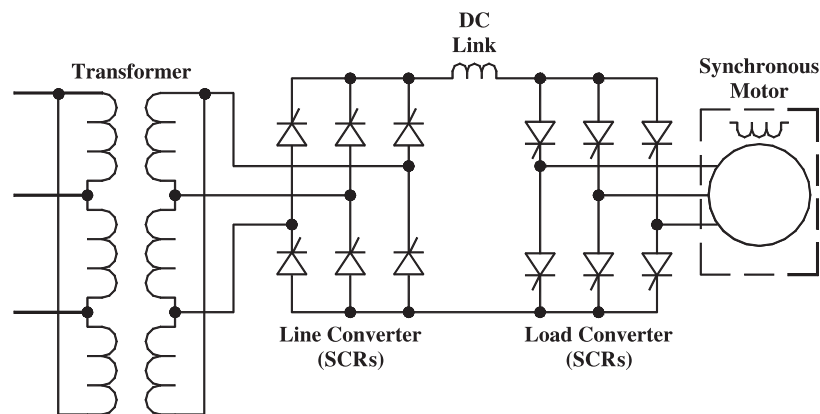


Figure 27—Load commutated current source inverter synchronous motor drive system

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.