

# **An Assessment of High Performance AC Motor Drives Versus DC Motor Drives**

**TR-112111**

Final Report, December 1998

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# REPORT SUMMARY

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In today's rapidly changing market place, drive users are applying AC and DC drives in applications that require more demanding speed and torque performance. Properly matching a drive's rating and unit characteristics to an application are two very effective ways of managing unit cost and cost reduction.

## **Background**

DC motors have traditionally been used in industrial processes where motor speed changes are required. In the case of AC motors, induction motors are used for fixed-speed processes. Since induction motor speed is proportional to the frequency of the applied voltage, it has been more difficult to effect a change in speed for induction motors. With the advent of modern power electronics, it is much easier to change the frequency of the voltage applied to the motor, and this has led to the proliferation of AC drives. Variable speed control of induction motors is now easy and inexpensive by comparison. Newer AC drive technology employing direct torque control schemes allows an induction motor to have the same torque-speed response of a DC motor and provides an opportunity to replace DC motor applications with AC motors.

## **Objectives**

To determine whether new AC motor/drive systems possess the attractive characteristics of DC systems; to establish actual differences between performance characteristics and system compatibility issues of current AC and DC drives under controlled laboratory conditions; and, to identify global trends in AC and DC drive markets by comparing first cost and life-cycle cost for both AC and DC drives.

## **Approach**

The project team held interviews with leading AC and DC drive suppliers. The drive supplier's feedback on drive features, costs, and relevant market trends became a basis for AC and DC drive performance comparisons and specific application considerations. Building on this material, the team developed a methodology for evaluating total life-cycle costs between AC/DC drive systems. In addition, actual system compatibility evaluation tests were performed on three adjustable-speed drives: a DC drive, an AC drive with sensorless vector control, and an AC drive with volts/Hz control. System compatibility tests were designed to characterize interaction between the electric service system and electronic adjustable-speed drives (ASDs). Case studies comparing AC and

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DC drive applications were included to identify and define the diversity of AC and DC drive applications.

## **Results**

This report provides significant findings that can be used in selecting a drive for a given application. Following are some relevant results discussed in this assessment report:

- Advances in both AC-drive and DC-drive technologies will continue to play an integral role in the continued modernization of motor-driven systems. While the industry trend is for AC drive use to continue growing at a faster rate than DC drives, growth of AC drives is in new applications rather than replacement of existing DC drives.
- To make an economic comparison between AC drives and DC drives, it is first necessary to confirm that either type of drive can meet an application's performance requirements. It also is necessary to determine what optional features are required. Nominally comparable features do not always provide equivalent performance when applied with either type of drive.
- The life-cycle cost analysis indicated that for the lower horsepower range (< 50 hp), the AC-drive system has a significant advantage over the DC-drive system.
- One clear trend for DC drives is that the price per horsepower decreases considerably for higher horsepower ratings. Also, on an average, high-performance AC drives are 40 to 60% more expensive than the standard PWM volts/Hz controlled drives.

## **EPRI Perspective**

This study validates that first-cut comparisons of individual features and characteristics of AC and DC motors/drives are frequently confusing to users. System compatibility test results, while only representative, confirm the need for documented electrical and mechanical drive system performance on different ASD technologies. Comprehensive technical data regarding power quality impacts on both electric service and mechanical process can benefit utilities and their customers by maximizing drive system productivity and reliability.

## **TR-112111**

### **Interest Category**

Motor & drive systems

### **Keywords**

Adjustable speed drives

ASD

AC motors

DC motors

Induction motors

## **ABSTRACT**

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The purpose of this study is to determine whether AC drives have advanced to the point that AC motor/drive systems possess the attractive characteristics of DC systems. For example, it may not be clear that AC drives and motors are capable of delivering the same starting torque that DC drives and motors deliver. It is also of interest to determine whether AC motor/drive combinations are as efficient as DC motor/drive combinations. These issues, and more, needed to be researched to establish the system compatibility applications base for both AC and DC drives. To accomplish this assessment, targeted interviews were conducted with leading AC and DC drive suppliers. Their feedback on drive features and costs, and relevant market trends became a basis for AC and DC drive performance comparisons, and specific application considerations. Building on this material, a methodology for evaluating total life-cycle costs between AC/DC drive systems was developed.

In addition to the background research information, actual system compatibility evaluation tests were performed on three types of adjustable-speed drives: a DC drive, an AC drive with sensorless vector control, and an AC drive with Volts/Hz control. The system compatibility tests were designed to characterize the interaction between the electric service system and the ASDs, thus, allowing report readers to develop keener insights into the subsequent impact of ASD loads on the electric service system and the end-user's motor driven process. To complement these technical insights, global market trends and purported improvements offered by AC and DC drive suppliers were excerpted from world wide reference resources to complete the work. Finally, case studies comparing AC and DC drive applications were included that draw on past experiences in various critical process industries to identify and to define the diversity of AC and DC drive applications for improving productivity and efficiency in motor driven systems.



## **EXECUTIVE SUMMARY**

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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 and 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. Investment in the wrong drive technology can cost companies millions of dollars in lost savings.

The purpose of this study is to determine whether AC drives have advanced to the point that AC motor/drive systems possess the attractive characteristics of DC systems. For example, it may not be clear that AC drives and motors are capable of delivering the same starting torque that DC drives and motors deliver. It is also of interest to determine whether AC motor/drive combinations are as efficient as DC motor/drive combinations. These issues, and more, needed to be researched to establish the system compatibility applications base for both AC and DC drives. To accomplish this assessment, targeted interviews were conducted with leading AC and DC drive suppliers. Their feedback on drive features and costs, and relevant market trends became a basis for AC and DC drive performance comparisons, and specific application considerations. Building on this material, a methodology for evaluating total life-cycle costs between AC/DC drive systems was developed.

In addition to the background research information, actual system compatibility and performance evaluation tests were conducted on three adjustable-speed drives: a DC drive, an AC drive with sensorless vector control, and an AC drive with Volts/Hz control. The system compatibility performance evaluation tests were designed to characterize the interaction between the electric service system, the ASDs, and end-user processes. These tests allow report readers to develop keener insights into the subsequent impact of ASD loads on the electric service system and the end-user's motor driven process. To complement these technical insights, global market trends and purported improvements offered by AC and DC drive suppliers were excerpted from world wide reference resources to complete the work. Finally, case studies comparing

AC and DC drive applications were included that draw on past experiences in various critical process industries to identify and to define the diversity of AC and DC drive applications for improving productivity and efficiency in motor driven systems.

This report provides significant findings that can be used in selecting a drive for a given application. The work results cover a wide range of factors for determining which drive technology is best suited for the application. Following are some relevant results discussed in this assessment report:

For many years, DC drives were used in applications requiring high starting torque, high torque at low speed, and applications requiring precise speed and torque regulation. DC drives have a small power package and straightforward controls for operating DC motors. The simplicity and process control versatility of DC drives made them very attractive solutions for process and application engineers, because AC drives (Volts/Hz control drives) could not match the performance specifications of DC drives. However, in recent years, new high performance AC drive technologies have made AC drives practical solutions in many applications where formerly only DC drives were used. The new generation AC drives, for example vector control drives, allow ASD users all the process control benefits once held only by DC drives. The “sensorless” vector control drive allows all the desirable DC motor control characteristics without the need for encoder feedback. This drive uses measurements of two motor currents and motor model parameters to control the speed and torque of the motor independently.

Table ES-1 lists general drive performance parameters for the three most common adjustable-speed drives. Based on each application’s requirements (i.e. tight tolerances for torque control, orienting the work product, or maintaining full torque at zero speed), Table 1 can be used to narrow down to the particular drive technology that best suits the application. In the final analysis, the application engineers of prospective process equipment vendors should be consulted to see if they can suggest enhancements that extend the utility of the best drives from among the varied offerings of drive manufacturers.

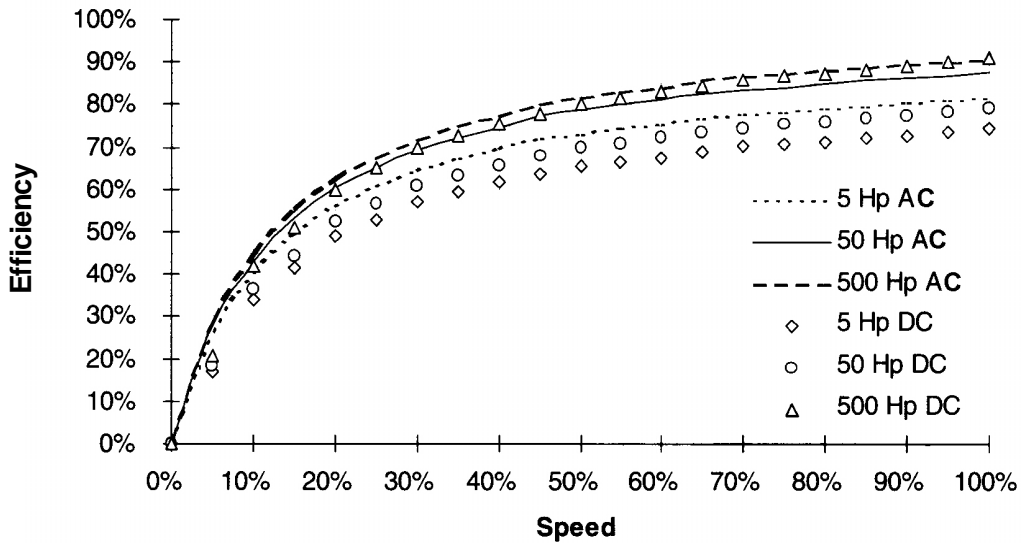
**Table ES-1  
General Drive Performance/Cost Comparisons**

Application Requirements	DC Drive – SCR	AC Drive – Volts/Hz Control	AC Drive – Sensorless Vector Control
Relative speed range	Wide (20:1)	Narrow (5:1-10:1)	Widest (6000:1)
Speed control	Yes	Yes	Yes
Torque control	Maybe	No	Yes
Positioning	Maybe	No	Maybe
Orienting (zero index)	Maybe	No	Yes
Open loop speed	± 2% of base speed	± 3% of base speed	± 0.4 of base speed
Closed loop speed regulation	±1% of set speed	± 1% of set speed	± 0.01% of set speed
Can maintain full torque at zero speed?	No	No	Yes
Motor brushes required?	Yes	No	No
Can operate multiple motors from one control?	Yes, but not recommended	Yes <sup>(2)</sup>	No
Relative cost	\$	\$-\$\$	\$\$-\$\$\$

Notes: <sup>(1)</sup> Governed by motor size and motor percent slip

<sup>(2)</sup> Individual motor protection must be considered

As shown in Figure ES-1, the overall efficiency of an AC drive system can be expected to be a little higher than the efficiency of a DC drive system, especially at lower speed. DC converters are typically slightly more efficient than AC inverters. Except at higher horsepower, DC motors are typically significantly less efficient than AC motors. In addition, as speed is reduced below 100%, the efficiency of a constant torque DC drive system drops off more rapidly than the efficiency of an AC drive system. However, the horsepower, average operating speed and load, and other characteristics of the individual application will determine specific results.

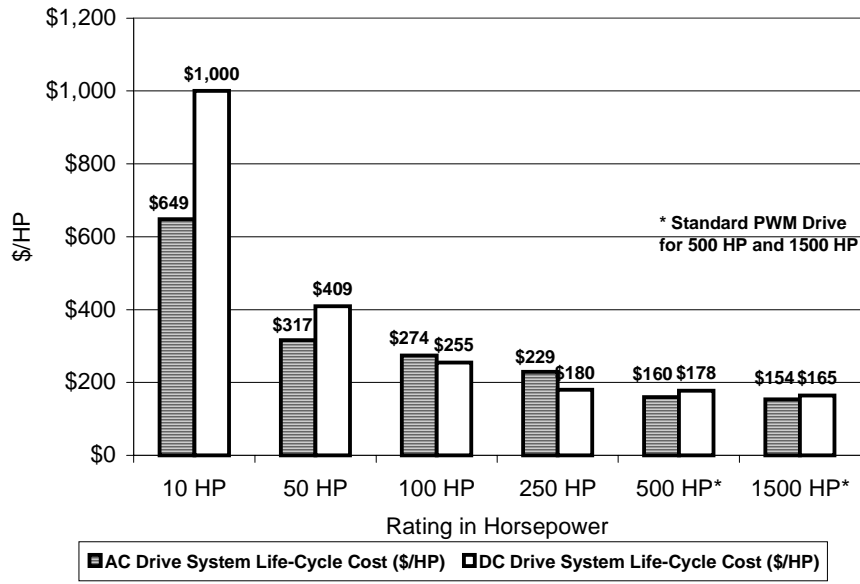


Source: ABB Industrial Systems, Inc.

**Figure ES-1**  
**Drive System Efficiency Comparison for Constant Torque Drives**

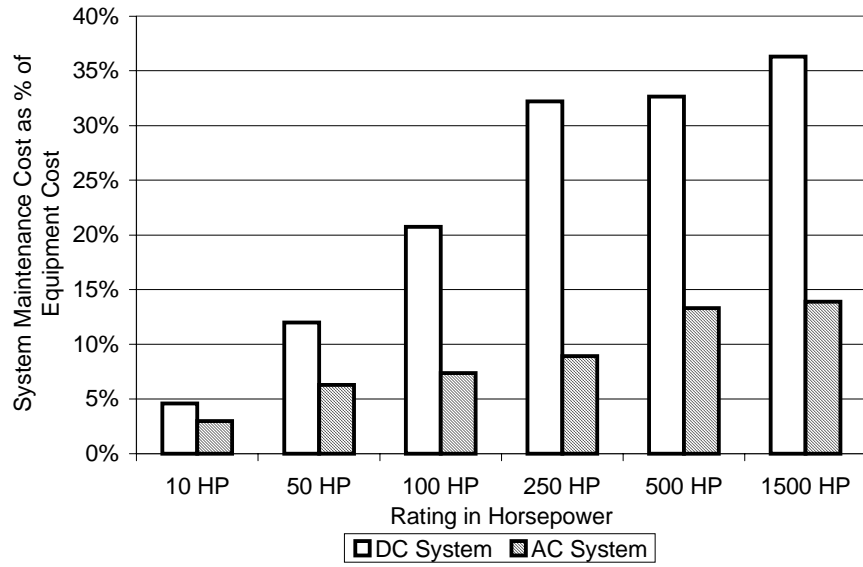
### Life Cycle Cost Estimation

Using the Net Present Value (NPV) method, a life-cycle cost analysis was conducted for AC and DC systems with 20 years expected lifetime and 15% required rate of return. The first costs of motors and drives and the yearly maintenance cost of each system were used as the input variables for the analysis. Figure ES-2 illustrates results of the analysis for different horsepower ranges.



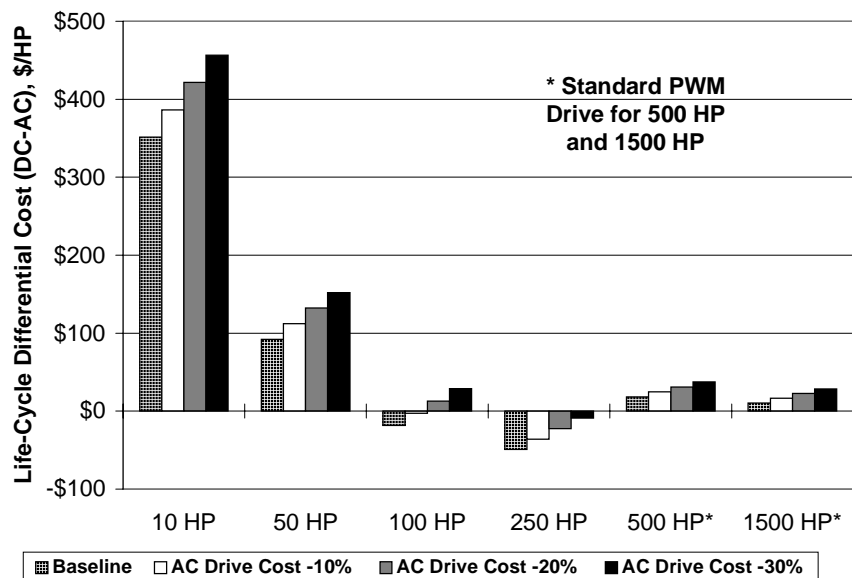
**Figure ES-2**  
**Life-Cycle Cost Analysis for AC and DC Drive Systems**

As can be seen in the Figure ES-2 analysis, for the lower horsepower range (< 50 HP) the AC system has a significant advantage over its DC counterpart. This is mainly due to the first costs of the motor and drive systems. However, as the horsepower size increases the cost of DC converters becomes attractive compared to high performance AC inverters because life-cycle differential cost becomes negligible. Figure ES-3 shows the Net Present Value for the 20-year maintenance cost of AC and DC systems as a percentage of first cost. For higher horsepower systems the maintenance cost associated with a DC system becomes a major part of the initial investment for the first cost of the drive system. Figure ES-3 clearly shows that the maintenance cost can be a significant portion of the total life-cycle cost of a motor drive system.



**Figure ES-3**  
**Net Present Value of System Maintenance Cost as % of First Cost for AC/DC Drive Systems**

In order to determine how price reductions in high performance drives would impact the life-cycle cost analysis, the first cost of the AC drive was varied from base line to 30% less than base line in steps of 10%. The result of that analysis as a differential cost between the AC and DC systems is shown in Figure ES-4. A positive differential cost means the DC system life-cycle cost is more than its AC counterpart and less for a negative differential cost. As AC drive prices start coming down the difference between AC and DC systems for lower horsepower drives increases and for higher horsepower drives the AC system starts to look attractive compared to its DC counterpart.



**Figure ES-4**  
**Impact of AC Drive First Cost on Life-Cycle Cost Differential to DC Drive System**

## System Compatibility Tests

System compatibility is the ability of equipment to work as designed in its intended electrical environment (called equipment immunity) without adversely affecting the operation of other equipment (called equipment emissions). Nine system compatibility tests were conducted on three ASDs: a DC drive, a Pulse-Width Modulated (PWM) Voltage Source Inverter (VSI) AC drive with sensorless vector control, and a PWM-VSI AC drive with Volts/Hz control. The drives chosen for these tests are representative examples of the most common 5 hp AC and DC drive topologies. The test results should not be viewed as standard results for all AC and DC drives because the system compatibility tests were designed to characterize the interactions of typical AC and DC drive topologies with the electric power system and the motors.

The system compatibility tests can be grouped into two categories: the effects of the electric power system on ASDs and the effects of ASDs on the electric power system and motors. The tests for the effects of the electric power system on ASDs were steady-state voltage unbalance, steady-state undervoltage/overvoltage, voltage sag response, and capacitor switching transient response. The tests for the effects of ASDs on the electric power system and motors were electro-magnetic/radio frequency interference, input and output characteristics, power factor, and voltage notching.

## The Effects of the Electric Power System on ASDs

**Steady-State Voltage Unbalance** – The ANSI recommended practice suggests maintaining the voltage unbalance at the point of delivery below 3% because the voltage unbalance of the electric service supply negatively affects the input current of most ASDs. For a given percent voltage unbalance, the resulting percent current unbalance can be much higher. Sustained voltage unbalance conditions may either reduce the life of rectifiers or lead to rectifier failures. The topology differences between the SCR-controlled DC drive and the two AC drives with uncontrolled rectifiers produced different current unbalance measurements. The AC drives tended to produce significantly higher levels of current unbalance than the DC drive. Under high steady-state voltage unbalance conditions (5%), the input line reactors of the sensorless vector control AC drive improved the current unbalance over the Volts/Hz control AC drive, which had no input line reactors or a DC link reactor.

**Steady-State Under/Overvoltage** – Electric supply systems and user systems are designed and operated so that the steady-state supply voltage and utilization voltages normally remain within the expected voltage range. During peak load, electric service companies may lower their distribution line voltages in order to reduce the system power consumption. The steady-state undervoltage and overvoltage tests characterized each drive's ability to maintain output integrity and process control during input voltage variations. The DC drive was able to maintain output speed and torque with no changes as the input voltage was varied between -10% and +10%. For the same input voltage variation, AC drives were able to maintain output speed and torque with speed changes of less than 2%.

**Voltage Sag Response** – Voltage sags and momentary interruptions are common occurrences in low voltage distribution systems. Voltage sag conditions can cause voltage-sensitive equipment, such as AC and DC drives, to trip off-line. When ASDs trip, safe operation of the process can be comprised and costly situations often result. Industrial and commercial ASD users can experience significant losses when ASDs or ASD-driven processes trip during voltage sag conditions.

With the emergence of concerns for power quality and improving customer power, the voltage sag response of ASDs and other voltage-sensitive equipment has become increasingly important. Ongoing ASD voltage sag evaluation tests are moving some of the burden of ASD trips from the utilities to the ASD end-users and manufacturers. As a result, ASD manufacturers have begun adding multiple ASD programming options that can mitigate and improve the ride-through of the ASD application during voltage sag conditions. Even with the added programming options and improved voltage sag ride-through, it is important for ASD users to understand which options are appropriate for their process applications.

AC VSI drives have DC link capacitors that provide some energy storage, however, the main purpose of the DC link capacitors is to filter the output of the rectifier. The energy stored in the capacitors is usually low when compared to the rated power of the drive. Thus, the DC link voltage will drop quickly during voltage sag conditions. Drive manufacturers set lower limits for the DC link voltage, called the undervoltage trip point. When the DC link voltage drops to the undervoltage trip point, the drive reacts according to the restart and ride-through programming options. The undervoltage trip point, the sag depth, the sag duration, the restart and ride-through options, the load type, and the load inertia directly influence the impact of the voltage sag on the ASD-driven process.

Older generation DC drives tended to be more susceptible to voltage sag conditions, especially when voltage sags involved phase shifts, frequency shifts, or multiple zero crossings. However, advances in DC drive control technology may make them somewhat less susceptible to voltage sags. DC drives do not have DC link capacitors. SCR-controlled DC drives use controlled rectifiers to apply voltage to DC motors. DC drives may adjust firing angles in the rectifier to compensate for reduced input voltage. However, adjusting firing angles may cause overcurrent conditions once the input voltage recovers from the sag. Again, the restart and ride-through programming options determine how the drive reacts during voltage sag conditions.

AC VSI drive technologies offer many more ride-through options for ASD users than DC drives. AC VSI drive ride-through alternatives, such as additional DC bus capacitors, boost converters, battery back-up systems, SMES technology, and fuel cells, are commercially available devices. They are used to support the DC bus voltage during voltage sag conditions. DC drive ride-through technologies are often engineered technical solutions. Different DC drive manufacturers usually require individualized solutions.

Three-phase voltage sags down to 60% of nominal voltage for 6 and 30 cycle durations were applied to the inputs of the three drive systems. The DC drive was able to ride-through voltage sags of 6 and 30 cycles with little change in speed or torque with ride-through programming features enabled. Even with ride-through features enabled, both AC drive systems produced significant speed and torque changes for 6 and 30 cycle sags.

***Capacitor Switching Transient Response*** – Utilities use capacitor banks for providing reactive power support and maintaining voltage regulation. The banks may be switched onto the system (energized) as needed or they may be connected at all times. When capacitor banks are energized, a transient voltage oscillation occurs between the capacitor and the inductance of the distribution system. The result is a transient overvoltage that can be as high as 2.0 per-unit (above nominal peak voltage) at the capacitor location. The majority of the transients have frequencies in the range of 300 to

800 Hz, with the typical maximum magnitude of 1.2 to 1.5 per-unit (measured line-to-line).

AC drives, with DC link capacitors and uncontrolled rectifiers, are particularly vulnerable to capacitor switching transients. These transients may cause failure of protective devices and electronic components in ASDs. The failures may result from overcurrent conditions of the rectifier or overvoltage conditions on the DC link capacitors. Often, the results are nuisance trips when the voltage on the DC link exceeds a predetermined upper threshold. The drive usually requires the involvement of an operator to reset the drive. These nuisance trips can create costly production delays when capacitor banks are energized to meet load demand, which often occurs at the same time every day.

Capacitor switching transients often involve multiple zero crossings of the line voltages. DC drives that rely on zero cross detection and timing circuits could fire SCRs at the wrong time. These conditions could damage or destroy SCRs in the rectifier. Thus, DC drives may also be susceptible to capacitor switching transients.

The rating of the ASD, the ASD load level, and the impedance between the capacitor banks and the ASD are all factors that determine the magnitude of the transient at the terminals of the drive. Input line reactors are often recommended for reducing the affects of the transients's magnitude on the drive's overvoltage tripping circuit.

All three drive systems were subjected to capacitor switching transients of increasing per unit values up to 1.5 per unit at idle and full-load (5 hp) conditions. The DC drive and AC sensorless vector control drive did not trip at idle and full-load conditions for transients up to 1.5 per unit. The presence of the built-in input line reactors and overvoltage control programming software in the AC sensorless vector control drive made it immune to the capacitor switching transients.

The AC Volts/Hz control drive tripped at 1.26 per unit at idle and full-load conditions.

### **The Effects of ASDs on the Electric Power System and Motors**

*EMI/RFI* – In the 1990s, many ASD manufacturers began to replace bipolar junction transistors (BJTs) with insulated gate bipolar transistors (IGBTs) in AC drive inverters. IGBTs provided manufacturers with several advantages over BJTs such as faster switch times from off-state to on-state and vice versa. This decreased the switching losses and improved the efficiency of the drive. Other advantages included decreased drive package cost and increased carrier or switching frequencies. Higher switching frequencies paved the way for Pulse-Width Modulation (PWM) inverters. PWM inverters with high switching frequencies have reduced harmonic heating of the motor, improved torque performance at low operating frequencies, and reduced audible noise from motor laminations.

IGBTs provided ASD manufacturers with the improvements in motor control and efficiencies, but they also created application issues in other areas as well. Electro Magnetic Interference (EMI) is a common source of concern in PWM-ASD applications. The concerns are created by the fast transition of the AC drive output voltage. The fast transitions are sources of radiated and conducted noise. These interfere with other sensitive equipment, which is connected to the same distribution bus. EMI, both radiated and conducted, can interfere with communication links, encoder feedback, ultrasonic sensors, temperature sensors, computers, AM radios, TV, CAT scanners, security alarms, and many other sensitive electronic devices.

Conducted and radiated EMI measurements were taken for the three ASD systems. The radiated EMI measurements show that the DC drive produced no measurable readings at a distance of one meter from the drive and the motor. The sensorless vector control AC drive had significantly higher radiated electric field measurements than the Volts/Hz control AC drive. The DC drive had lower conducted EMI measurements than both AC drives at frequencies below 1 kHz, but higher measurements above 1 kHz.

***Input Characteristics*** – SCR-controlled DC drives and most AC drives with uncontrolled rectifier are considered nonlinear loads that draw non-sinusoidal currents from the electric utility. The harmonic currents drawn from the electric service system by the two drive types produce different current harmonic distortion levels and power factor measurements. Significant current harmonic distortion can increase system voltage distortion, increase system losses, decrease distribution system equipment life, and increase the likelihood of resonance conditions. The two AC drives tended to draw significantly higher levels of 5<sup>th</sup> and 7<sup>th</sup> harmonic currents, however, the built-in input line reactors of the AC sensorless vector control drive and the addition of the input line reactors to the AC Volts/Hz drive significantly reduced input harmonic current distortion.

***Output Characteristics*** – The improved power semiconductor technology of the IGBT makes PWM inverters possible for next generation AC drives. The output current waveforms of the two PWM AC drives produced low levels of low order harmonic currents. PWM inverters allow motors to operate with lower motor noise, higher efficiency, and lower torque pulsations over other AC drive motor control techniques.

***Power Factor*** – The displacement power factor for AC drives with uncontrolled rectifiers is near unity when fed from a “stiff” electricity source. However, the displacement power factor of AC drives however, is near unity over the entire speed range. This is not the case for DC drives with controlled rectifiers. The displacement power factor for DC drives varies with the speed of the motor. At reduced speed, the displacement power factor is quite low. The opposite is true at higher motor speed. DC drives often operate in continuous current mode because of the ac line and/or dc link reactances that are inherent in their application. One advantage of continuous current

mode is the reduction of harmonic currents drawn by the drive. For AC drives this reduction in harmonic current distortion can be achieved by the application of input line reactors.

Because of low displacement power factor, DC drives require power factor correction capacitors for reactive power support. In most cases, power factor correction capacitors are tuned as filter banks in order to reduce harmonics as well as improve power factor. However, for AC drives, because the displacement power factor is near unity, there is no requirement for reactive power support. Passive harmonic filtering is not suitable for AC drives and active harmonic filters are required for harmonic reduction.

**Voltage Notching** – Large DC drives, with SCR-controlled rectifiers, may interfere with other electronic loads that are connected to the same distribution system. The cause of the problem, voltage notching, occurs when the DC drive begins to transfer current from one phase to another phase. The source reactance prevents instantaneous transfer. As an SCR in an adjacent phase begins to conduct, the commutation time (angle) causes a shorting action across two phases when two SCRs are conducting simultaneously. There is period of reduced voltage until one SCR successfully commutates. Once the SCR commutates, there is a subsequent voltage overshoot due to any circuit stray inductance. The voltage notches can create multiple zero crossings, which can interfere with clocks, phase-angle control welders, and other equipment with controls that utilize zero cross timing circuits. The repetitive overshoots can shorten the life of surge protection devices such as Metal Oxide Varistors (MOV)s. A typical voltage notching waveform was captured at the input terminals of the DC drive operating at no-load conditions.

VSI AC drives with uncontrolled diode rectifiers are the most common ASDs in commercial and industrial applications. Drives with uncontrolled diode rectifiers do not cause voltage notching. However, most Current Source Inverter (CSI) AC drives and most DC drives have SCR-controlled rectifiers, which produce voltage notching conditions.

## **Performance Evaluation Tests**

In the past, DC drive systems were chosen over AC drive systems for applications requiring high starting torque, precise speed regulation, or high torque at low speeds. AC drive systems are now being used in many of these applications due to the evolution of the high-performance AC drive. The new generation AC drive systems can achieve many of the same performance characteristics of DC drives systems. Performance evaluation tests were conducted to characterize the starting torque, speed regulation, low-speed high-torque control, and the system efficiencies of the three ASD/Motor combinations.

## **Starting Torque**

The starting torque performance evaluation tests resulted in the DC drive producing 52.4 N-m of starting torque (or  $2.56 \times$  full load torque). The AC sensorless vector control drive produced 47.4 N-m of starting torque (or  $2.31 \times$  full load torque) while the Volts/Hz control AC drive only produced 20.1 N-m of starting torque (or  $0.98 \times$  full load torque). The new generation sensorless vector control AC drive produced nearly as much starting torque as the DC drive and more than twice as much as the Volts/Hz control AC drive.

## **Speed Regulation**

The speed regulation tests were conducted to characterize the speed change for step changes in load torque at two speed setpoints (1800 RPM and 450 RPM). The DC drive and the sensorless vector control AC drive produced similar speed changes at all test points with variations of approximately -130 rpm for increasing load torque and +130 rpm for decreasing load torque. The Volts/Hz control AC drive did not have programming features that enabled speed regulation. Thus, the speed did not return to the setpoint once the load torque changed.

## **Low-Speed High-Torque Control**

The low-speed high-torque control test was designed to characterize the low-speed torque capability of each drive type. The drives were set to operate at 180 rpm. The load torque was increased in step increments up to full-load (20 N-m) or until the load began to overpower the drive and motor under test. The DC drive and the sensorless vector control AC drive produced similar results. Both were capable of producing full-load torque at 180 rpm. The Volts/Hz control AC drive was only able to produce 60% full-load torque before the load overpowered the drive and motor.

## **System Efficiency**

The system efficiency evaluation tests were designed to characterize the efficiencies of the ASD, the motor, and the ASD/Motor combinations at two speed and load torque setpoints (100% speed, 100% torque and 50% speed, 50% torque). The three drive systems produced similar efficiencies ( $\approx 83\%$ ) at the 100% speed and torque setpoint. Both AC drives produced ( $\approx 10\%$ ) higher ASD and ASD/Motor system efficiencies than the DC drive at the 50% speed and torque setpoint.

## **Global Trends In AC And DC Drive Markets**

The motor drive segment is the largest of the motor drive, feedback element, and variable-speed drive market, accounting for 68 percent of total market revenues in 1995 (the latest year with accurate market figures). Table ES-2 shows the total motor drive

market for unit shipments, revenues, and forecasted revenues in the U.S. for 1992-2002. An estimated 920,000 motor drives were shipped in 1995, up from 726,000 in 1992, with shipments expected to top 1 million in 1996. This upward trend should continue through the end of the century, with an anticipated 1.8 million units shipped in 2002. In 1995 the motor drive market experienced revenue growth of approximately 7 percent and unit growth of 9 percent.

**Table ES-2**  
**Total Motor Drive Market:<sup>(1)</sup>**  
**Unit Shipments and Revenue Forecasts (U.S.), 1992-2002**

Year	Units (Million)	Revenues (\$ Billion)	Revenue Growth Rate (%)
1992.....	0.73	2.33	---
1993.....	0.78	1.42	6.5
1994.....	0.85	1.51	6.5
1995.....	0.92	1.62	7.0
1996.....	1.01	1.73	7.5
1997.....	1.11	1.87	7.5
1998.....	1.22	2.01	8.0
1999.....	1.36	2.18	8.5
2000.....	1.51	2.37	8.5
2001.....	1.68	2.56	8.5
2002.....	1.87	2.77	8.0
Compound Annual Growth Rate (1995-2002): 8.0%			

Source: Frost & Sullivan

Notes: <sup>(1)</sup> All figures are rounded; the base year is 1995. The market for motor drives consists of alternating current (AC), direct current (DC), stepper motor drives, and servo motor drives. It is inherently difficult to assess the motor drive market because many of the drives are combined with other offerings to provide complete solutions to customers. AC motor drives are defined as being both the standard inverter drives and vector AC drives. DC motor drives are defined as both thyristor DC drives and brushless DC drives. Servo motor drives<sup>(2)</sup> are defined as both AC and DC servo motor drives, and they include the sequence logic and the power driver. Stepper motor controls are defined as single stepper controllers that include the sequence logic, the amplifier, and the power driver.

<sup>(2)</sup> Servo motor drives are included for completeness in reporting the motor drive market segment, but are not elaborated on because they are outside the present scope of work.

The AC drive market is forecasted to increase through the year 2002 by an average of more than 12% as shown in Table ES-3. The DC drive market, however, is expected to decrease by an average of more than 1.4% over the same period. The forecast trends indicate that AC drives will be used increasingly over the next few years in new and retrofit ASD applications. Most ASD manufacturers focus on developing and improving existing AC drive technologies, rather than DC drive technologies.

**Table ES-3**  
**AC and DC Motor Drive Market:**  
**Unit Shipment, Growth Rate, and Forecast (U.S.) 1992-2002**

Year	*AC (Thousand)	AC Growth Rate (%)	*DC (Thousand)	DC Growth Rate (%)
1992.....	357.6	-	222.6	-
1993.....	397.4	11.1	221.5	-0.5
1994.....	442.9	11.4	219.8	-0.8
1995.....	496.0	12.0	218.0	-0.8
1996.....	558.0	12.5	216.5	-0.7
1997.....	628.9	12.7	214.5	-0.9
1998.....	710.0	12.9	211.5	-1.4
1999.....	802.9	13.1	207.5	-1.9
2000.....	910.0	13.3	203.3	-2.0
2001.....	1029.8	13.2	198.4	-2.4
2002.....	1164.8	13.1	192.6	-2.9
Compound Annual Growth Rate (1995-2002):		<b>12.5%</b>		<b>-1.4%</b>

*All figures are rounded; the base year is 1995.*

*\* Source: Frost & Sullivan*

## Conclusions

Advances in both AC drive and DC drive technologies will continue to play an integral role in the continued modernization of motor driven systems. But most drive users could care less about the “insides” of drive technology. They are more concerned what the drive can do for them and how to cost-optimize the technology. While the industry trend is showing that AC drives are growing at a faster rate than DC drives, the growth of AC drives is in new applications rather than encroaching on DC drives in great numbers.

In order to make an economic comparison between AC drives and DC drives, it is first necessary to confirm that either type of drive can meet the performance requirements of the application. It is also necessary to determine what optional features are required. It is best to review the fundamental requirements of the application rather than specify an AC drive equipped with features equivalent to a particular DC drive configuration that was used in the past. Nominally comparable features do not always provide equivalent performance when applied with either type of drive.

An adequate economic comparison between two types of drives requires an analysis of all of the costs incurred over the entire life-cycle of the equipment. In addition to the purchase price of the drives and related equipment, this includes all of the material and labor costs required to obtain and install the equipment and put it into operation, plus all of the costs to operate and maintain the equipment during the entire time it is expected to be in service.

The life-cycle cost analysis showed for the lower horsepower range (< 50 HP), the AC drive system has a significant advantage over the DC drive system. This is mainly due to the first costs of the motor and drive systems. However, as the drive system ratings increase, the lower cost of the DC drive converters becomes attractive compared to the high performance AC drive inverters. Above the 500 horsepower rating, this situation makes the life-cycle differential cost almost negligible. For 500 and 1500 horsepower ratings, this trend reverses mainly due to the unavailability of high performance AC vector controlled drives in this horsepower range.

One clear trend that is apparent from this research is that for DC drives the price per horsepower decreases considerably for higher horsepower ratings. Also, on an average, high performance AC drives are 40 to 60% more expensive than the standard PWM Volts/Hz controlled drives. It appears from present ASD equipment supplier feedback, that both AC and DC drive prices will remain stable for the foreseeable future.

The system compatibility test results, while only representative, confirm the need for documented electrical and mechanical drive system performance on different ASD technologies. This information illustrates the ASD's response to both the steady-state and active process dynamics in real time to the ASD electric supply input voltage conditions. Comprehensive technical data regarding the power quality impacts on both the electric service and mechanical process can benefit utilities and their customers to maximize drive system productivity and reliability.

In the context of the above conclusions, it is noteworthy to mention that first-cut comparisons of individual features and characteristics of AC and DC motors/drives are frequently confusing. Both AC and DC drive systems enjoy technology advantages that can, however, be offset by details of the specific application, economics, or user preference. For instance, AC drives are relatively easier to interface with the electric service source while DC drives are easier to interface with their motors. Said another way, AC drives can create significant EMI/RFI interference on its motor circuit, while DC drives can create significant EMI/RFI interference on the electric service source. There are no "rules of thumb" that will consistently and accurately predict the outcome of the drive selection process.

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# 1

## BACKGROUND AND INTRODUCTION

---

### 1.1 Purpose of the Work

DC motors have traditionally been used in industrial processes where motor speed changes are required. This was due to the relative ease of speed control with DC motors. The DC drives used simply controlled the armature voltage in order to control motor speed. In the case of AC motors, induction motors are the workhorses of industry, but only for fixed-speed processes. Since induction motor speed is proportional to the frequency of the applied voltage, it was more difficult to effect a change in speed for induction motors.

With the advent of modern power electronics, it is much easier to change the frequency of the voltage applied to the motor, and this has led to the proliferation of AC drives on the market. Variable speed control of induction motors is now easy and inexpensive by comparison. Newer drive technology employing direct torque control schemes now allow an induction motor to have the same torque-speed response of a DC motor and provides an opportunity to replace DC motor applications with AC motors.

The purpose of this work is to determine whether AC drives have advanced to the point that AC motor/drive systems possess the attractive characteristics of DC systems. For example, it may not be clear that AC drives and motors are capable of delivering the same starting torque that DC drives and motors deliver. It is also of interest to determine whether AC motor/drive combinations are as efficient as DC motor/drive combinations. These issues needed to be researched to establish the system compatibility issues for both AC and DC drives.

### 1.2 Description of Assessment Methodology

To accomplish this assessment, targeted interviews were conducted with leading AC and DC drive suppliers. Their feedback on drive features and costs, and relevant market trends became a basis for AC and DC drive performance comparisons, and specific application considerations. Building on this material, a methodology for evaluating total life-cycle costs between AC/DC drive systems was developed (see Section 2). In addition to the background research information, actual system compatibility evaluation tests were performed on three adjustable-speed drives: a DC

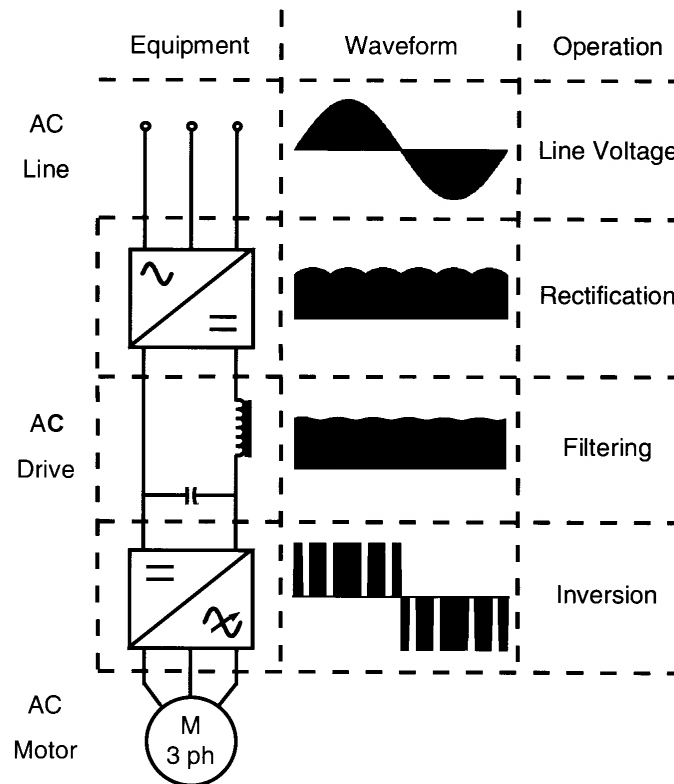
drive, an AC drive with sensorless control, and an AC drive with Volts/Hz control. The system compatibility tests were designed to characterize the interaction between the electric service system and the ASDs, thus, allowing report readers to develop keener insights to the subsequent impact of ASD loads on the electric service system and the end-user's motor driven process (see Sections 3 and 4). To complement these technical insights, global market trends and purported improvements offered by AC and DC drive suppliers were excerpted from world wide reference resources to complete the work (see Section 5). Finally, case studies comparing AC and DC drive applications were included that draw on past experiences in various critical process industries to identify and the define the diversity of AC and DC drive applications for improving productivity and efficiency in motor driven systems (see Section 6).

### **1.3 AC and DC Drive Technical Issues**

Selecting an AC or DC drive to use in a given application is a two step process.<sup>[1]</sup> The first step is to determine what drive types can meet the essential performance requirements of the application. The second step is to make an economic comparison of the qualified candidates (see Section 2). Adjustable-frequency drives are pulse width modulated (PWM) drives as are most AC drives that are available today. Figure 1-1 illustrates the basic principles of PWM drives. The rectifier converts input line power which has a fixed voltage and frequency to fixed voltage dc power. The fixed voltage dc power is then filtered to reduce the ripple voltage passed through the rectifier from the ac line. The inverter changes the fixed voltage dc power to ac output power with adjustable voltage and frequency.

The output waveform consists of a series of rectangular pulses with a fixed height and adjustable width. The overall pattern of positive versus negative pulses is adjusted to control the output frequency. The width of the individual pulses is modulated so that the effective voltage is regulated in proportion to the frequency.

The AC motor is essentially a standard, NEMA design B, three-phase squirrel cage motor designed to operate from fixed frequency sinusoidal power.

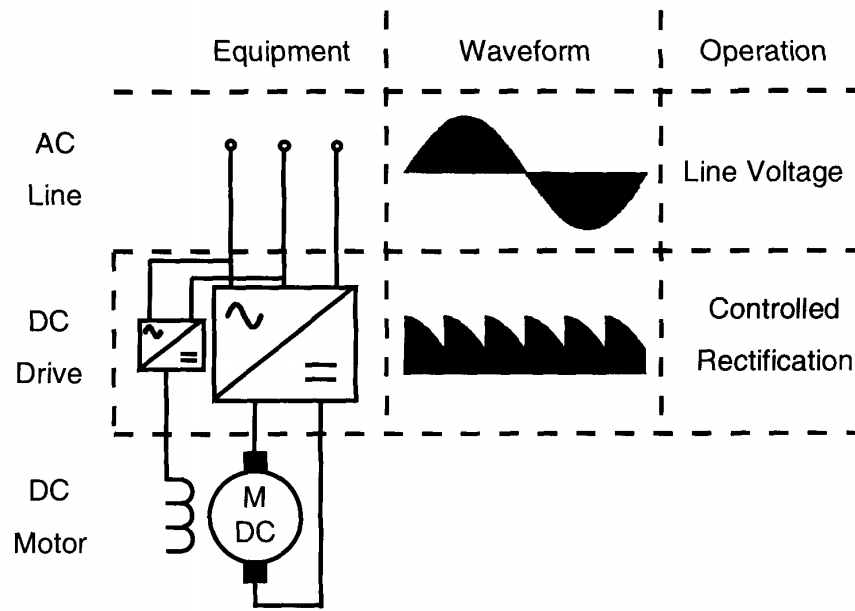


Source: ABB Industrial Systems, Inc.

**Figure 1-1**  
Principles of Operation for Typical Adjustable Frequency PWM Drives

Figure 1-2 illustrates the basic principles of DC drives. The converter is a three-phase controlled rectifier that converts fixed voltage input line power to adjustable voltage dc power. This is the most common converter configuration, called a 6-pulse converter. Regulating the armature current controls the torque developed by the motor. Motor speed is regulated by controlling the armature voltage. A small DC power supply provides a fixed or regulated current for motor field excitation.

In the DC motor, current flows through brushes and a commutator to the armature windings in the motor's rotor. Field excitation current flows through windings in the motor's stator. The commutator in the DC motor allows the magnetic field in the motor's armature to remain stationary while the armature rotates.



Source: ABB Industrial Systems, Inc.

**Figure 1-2**  
Principles of Operation for 6-Pulse Non-Regenerative DC Drives

Building on the above AC and DC drive configurations, here's a brief summary of the operating principles on which today's four most common adjustable-speed topologies operate.

**DC Silicon Controlled Rectifier (SCR) Drives.** This is the simplest and least expensive type of control, but higher motor cost can neutralize controller cost savings on the overall drive package. In all DC SCR controls, an ac input is rectified to dc via a full-wave SCR rectifier bridge. There are a number of variations in the manner in which speed control is achieved, some depending on the particular motor type. Usually, however, dc is supplied to the motor armature up to rated voltage, and armature voltage is varied to yield the desired speed.

**Variable Voltage Variable Frequency (VVVF) Inverter Drives.** Speed of all AC induction motors varies directly with frequency of the AC delivered to the motor. Most AC inverter controls operate on the principle of PWM, wherein an approximation of a sine wave is synthesized by varying the width of DC pulses. The control receives its ac input at line frequency, converts the AC into DC, and then converts the DC to a simulated AC waveform in the drive's inverter section at a frequency selected by the user. Motor speed and inrush current are controlled by varying voltage and frequency; hence the designation "variable voltage, variable frequency," or VVVF. Voltage and frequency are varied in a fixed ratio. Some types, however, have a "torque boost"

feature that raises voltage at low speeds, and most permit the voltage/frequency ratio to be selected by the user.

**Brushless DC.** A brushless DC motor has a stator somewhat like that of an induction motor, except that it has a permanent magnet rotor. The controller power section is, therefore, similar to an inverter drive. Rotor position is fed back to the control, with the control energizing the proper sequence of stator coils to repel and attract the proper rotor magnets based on their polarity. In the simplest designs, this positioning is done by a magnet wheel and Hall effect sensors. On more elaborate controls delivering better resolution and positioning, it is done with a resolver or encoder. As with the inverter drive, voltage and frequency are of a fixed ratio to change motor speed.

**Vector Drive.** The power section of a vector drive is also similar to that of an inverter drive, but the inverter firing control circuitry is much more complex. In contrast with a simple inverter drive, the vector drive permits motor current and voltage to be varied independently. Full motor torque can be achieved with precise, smooth speed control, from zero to the upper limit of the speed range. Some vector drives require an encoder be added as an adjunct to the motor to indicate rotor position. Other “sensorless” true flux vector drives apply advanced software methods<sup>[2]</sup> to individually control and orient the magnetizing and torque-producing components (or vectors) of flux to derive a resultant that is a measure of maximum output torque. In short, ac flux vector control drives are claimed to model the desirable characteristics of DC control.

#### 1.4 Purported Improvements Offered by AC and DC Drives

Advances in adjustable-frequency AC drive technology are making these drives practical for many applications that were formerly the domain of DC drives.<sup>[3]</sup> Many critical processes in textiles, man-made fibers, metal rolling mills, and plastic and paper products industries are important examples of these applications. The evaluation of competing high performance AC and DC drive systems is now more complex. The potential purchaser must choose not only from among competing drive vendors but also from competing technologies. Because of this situation, it is essential that the selection of any drive equipment should include an analysis of performance, reliability, safety, and cost. While it is necessary that the drive equipment provides minimum acceptable performance for the successful operation of the process, business decisions are almost always based on economic comparisons. Ideally, these comparisons should be made on equal terms, but unfortunately direct comparisons are not always easy.

A number of factors differentiate AC from DC motors, including construction, torque production, equivalent circuits, load ranges, and power and torque ratings.<sup>[4]</sup> These differences often reflect relative advantages and disadvantages of each motor type in adjustable-speed drives. Moreover, while trying to make AC motor controllers behave like DC, engineers have uncovered ways to better optimize AC motor design for

extended process applications. Also, until recently, the maturer DC technology didn't keep up with advances, as did its chief competitor – alternating current control.<sup>[5]</sup> Today, DC motor drives embrace the latest technologies in user interfaces, software, and manufacturing.

First-cut comparisons of individual features and characteristics of AC and DC motors/drives are frequently confusing, because they may be based on a combination of NEMA standards and physics principles. Simple generalizations are rare when comparing DC and AC drives. Each enjoys technology advantages that can, however, be offset by details of the specific application, economics, or user preference. Most comparisons match a new digital DC drive with a similar standard (Volts/Hertz) AC drive. For performance, the real AC competitor is closed-loop flux vector control. Yet flux vector is more complex, usually costlier, and to date has relatively low market share. Brushless DC is another alternative, but its availability with industrial-type, nonservo motors is very limited.

DC drives draw on their traditional strengths of high torque at low speeds, wide constant torque-speed range, and low-cost regeneration – the return of motor power to the ac supply when braking or handling decelerating loads. DC control is growing, but at a much slower rate than AC. Growth of AC is in new applications rather than encroaching on DC in great numbers.

## 1.5 DC Drive and AC Drive Strengths and Weaknesses<sup>[6]</sup>

**DC Drive Strengths** – Since the late 1960s, drives have been the popular choice for the prime mover in rolling mills, plastic extruders, and other critical torque control process applications. There are several features of a DC drive that lend themselves to these applications. First, DC drives are capable of a wide speed range. With speed feedback, speed ranges of 50:1 or 100:1 are readily accomplished. The natural output characteristic of this drive is constant torque from zero to base speed. The DC drive is one of the smallest power packages available today. The power circuit of SCRs is compact and simple and the regulator itself is straightforward. Great advances in small packaging have been made with the application of surface mount technology and large-scale integration. The combination of small size and simple construction have allowed the DC drive to be a cost effective choice in a number of applications.

**DC Drive Weaknesses** – The primary weakness of the DC drive is not a weakness of the drive itself but a weakness of the motor. DC drives use DC motors which employ brushes to mechanically commutate the torque producing current in the motor. Brushes are not a performance issue, but are a maintenance one. Properly maintained, a DC motor will run for a long time. However, if the brushes are neglected and not replaced when worn, the ensuing reduction in brush pressure on the commutator will result in rapid and catastrophic wear on the commutator. The result will be an

expensive and time consuming repair of the DC motor. DC drives in order to provide the type of speed regulation required by the application will employ speed feedback devices. These can either be AC or DC tachometers, encoders or resolvers. They add expense and mechanical complexity. When the DC drive is operated in the constant torque (or armature control range), it produces variable power factor. The best power factor can be achieved at top speed of approximately 0.87%. Speed range with constant power factor can be implemented when employing a field current controller and operating the motor in the constant horsepower range. Across this speed range the power factor is constant.

**AC Drive Strengths** – The greatest strength of the AC drive is the fact that it employs an induction motor. This motor is the simplest electric machine that we know how to build today. There is one moving part and only the bearings are maintenance items. Another plus for AC drives is the fact they can be built to deliver constant power factor across the speed range. This is becoming increasingly important as power utilities begin to charge penalties for lagging power factor.

**AC Drive Weaknesses** – The motor is also a major weakness of the AC drive. In order to produce constant torque, constant current (approximately) is required. This creates a condition where there is constant heating of the motor regardless of the speed at which it is running. This means, that when applied over wide constant torque range, the cooling of the motor must depend on the speed of the shaft (as is traditionally the case with an AC motor). In a number of critical process applications, AC motors are being equipped with separately driven blowers to deliver constant cooling to the motor at all times.

Another weakness of the AC drive is size. AC drives will generally always be larger than DC drives by a factor of 1.5 – 2:1. In order to produce adjustable-frequency current, first you must rectify the AC line to a DC bus (a DC drive) and then rectify that bus back into variable frequency. Therefore, there are twice as many power components in an AC drive as in a DC drive. In the past, the regulator has been approximately twice as complex as that of a DC drive. Present state-of-the-art electronics allows this factor of complexity to come much closer to 1:1 than 2:1. Circuits that were difficult to produce with discrete parts can now be accomplished with large scale chips and microprocessors. This has greatly reduced the complexity differences between AC and DC drives.

## 1.6 Fundamental Steps in the Selection Process

The first step in determining which drive technology is best for the application is to define the type of load: variable torque, constant torque, or constant horsepower (see reference<sup>8</sup> for typical motor load torque characteristics).<sup>[7]</sup> The next step is to determine the range over which speed is to be controlled. Speed range defines the span over

which the ASD controller is capable of varying motor speed, and is usually expressed as a ratio. For example, a drive with a speed range of 20:1 is capable of operating a 1750 RPM motor at anywhere between 87.5 RPM to 1750 RPM. Most controllers, in fact, have a speed range exceeding the motor's temperature limitations, and most also permit the motor to be operated above base speed. With integral horsepower DC motors, operation above base speed is achieved by weakening the motor field. With AC motors, operation above base speed is attained by setting the inverter output frequency above 60 Hz. In all cases, operation above base speed should be checked with the motor manufacturer to determine the applicable motor limitations. Also, the type of motor and its companion controller may affect the drive's permissible constant torque speed range.

Speed regulation is the percentage of motor speed change that accompanies a load change. In a dc SCR drive using armature feedback, speed regulation is on the order of 1% to 2% of motor base speed. With an inverter drive the figure is about 3% of base speed. A drive using no feedback from motor to controller to indicate exact operating speed is called "open loop." By adding a tachometer to communicate motor speed back to the controller, the dc motor/SCR controller combination can deliver speed regulation within 1% of set speed. Such an arrangement is known as "closed loop" control. Using an encoder or resolver in lieu of a tachometer for feedback, dc SCR and vector drives can attain regulation on the order of 0.01% of set speed.

Feedback from an encoder or resolver can also be used to index or position the motor shaft. Addition of a programmable motion controller can adapt most adjustable-speed technologies for positioning applications. Need for a programmable motion controller depends on whether the load needs to be moved incrementally. Many applications such as cut-to-length require that the motor perform a prescribed number of revolutions under command.

Traditionally, servos have been used in applications requiring fast acceleration, deceleration, or incremental positioning. For this reason, they are ideally suited — and widely used — as OEM machine tool components. Servos also have a place in some types of in-plant-engineered projects, but in most applications where the user is likely to select and specify the drive, dc SCR, brushless dc, and vector drives can all perform satisfactorily in what has traditionally been considered to be a "servo" mode. Acceleration and deceleration times are a function of motor inertia and the control's peak inrush current.

Other considerations in drive selection involve load specifics. If the load is such that the motor is required to rotate in only one direction and is nonoverhauling, a nonregenerative drive may be used. Typical applications would be fans, centrifugal pumps, and extruders. Stopping can be handled by removing power and coasting to a stop, or by dynamic braking. With dynamic braking, energy generated by the motor's rotation (back EMF) is fed into a resistor to make the motor stop faster than if it were

coasting. On AC motors, stopping time can also be shortened by feeding a DC voltage into the motor (DC injection braking). None of these methods, however, should be used to replace a holding brake. If the load must be held in position after stopping, a mechanical brake should be used.

With dc SCR drives, a nonregenerative control may be used for bi-directional dc drive applications through use of reversing relays. Inverter, vector, and brushless dc drives do not require external reversing devices. With a regenerative drive, excess power generated by the load stopping may be fed back into the ac input line, instead of being bled off into a resistor. Such a control can also be used to hold the load in place, but it is advisable to also use a mechanical brake in case power is removed. Care should be taken to isolate regenerative controls because of their poor power line harmonics. Recently, some VVVF inverter and vector drives have become available in designs meeting IEEE Std 519 specifications for harmonic distortion.

## 1.7 Overview of AC and DC Drive Performance Comparisons, and Specific Application Considerations

Table 1-1 lists general drive performance parameters for the three most common adjustable-speed drives. Based on each application's requirements (i.e. tight tolerances for torque control, orienting the work product, or maintaining full torque at zero speed), Table 1-1 can be used to narrow down to the particular drive technology that best suits the application. Naturally, the final considerations also need to include:

- What overall control scheme will the drive be integrated?
- Must the controls be operated in a leader/follower mode that allows one or more motors to follow a lead motor?
- Will the process utilize a serial network for communicating control intelligence?
- How *user-friendly* is the programming of the selected drive's performance parameters?

In the final analysis, the application engineers of prospective process equipment vendors should be consulted to see if they can suggest enhancements that extend the utility of the best drives from among the varied offerings of drive manufacturers.

**Table 1-1  
General Drive Performance/Cost Comparisons**

<b>Application Requirements</b>	<b>DC Drive – SCR</b>	<b>AC Drive – Volts/Hz Control</b>	<b>AC Drive – Sensorless Vector</b>
Relative speed range	Wide (20:1)	Narrow (5:1-10:1)	Widest (6000:1)
Speed control	Yes	Yes	Yes
Torque control	Maybe	No	Yes
Positioning	Maybe	No	Maybe
Orienting (zero index)	Maybe	No	Yes
Open loop speed regulation	± 2% of base speed	± 3% of base speed <sup>(1)</sup>	± 0.4 of base speed <sup>(1)</sup>
Closed loop speed regulation	±1% of set speed	± 1% of set speed	± 0.01% of set speed
Can maintain full torque at zero speed?	No	No	Yes
Motor brushes required?	Yes	No	No
Can operate multiple motors from one control?	Yes, but not recommended	Yes <sup>(2)</sup>	No
Relative cost	\$	\$-\$\$	\$\$-\$\$\$

Notes:{1} Governed by motor size and motor percent slip

{2} Individual motor protection must be considered

# 2

## TOTAL LIFE-CYCLE COST EVALUATIONS FOR AC/DC DRIVE SYSTEMS

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### 2.1 Performance Requirements of the Application

In order to make an economic comparison between AC drives and DC drives, it is first necessary to confirm that either type of drive can meet the performance requirements of the application. It is also necessary to determine what optional features and accessories are required.

It is best to review the fundamental requirements of the application rather than specify an AC drive equipped with features equivalent to a particular DC drive configuration that was used in the past. Nominally comparable features do not always provide equivalent performance when applied with either type of drive. For example, AC drives without tach feedback can provide better speed regulation than DC drives without tach feedback. DC drives typically require tach feedback to provide speed regulation better than 2% and service deviation better than 3%. AC drives typically have less than 1% service deviation. AC drives with slip compensation can provide 0.5% speed regulation or better depending on the nominal slip of the motor.

Also, a particular set of performance requirements can often be provided by more than one drive configuration. The most economical AC drive configuration for a particular set of application requirements often uses an approach to a problem that is somewhat different from the most economical DC drive configuration. For example, to provide sufficient motor cooling for a wide speed range, dc motors are often equipped with a blower and filter or connected to a pipe ventilating system. With AC drives, using a totally enclosed fan cooled (TEFC) motor designed for adjustable-frequency duty can often provide an equivalent speed range.

### 2.2 Variables Affecting Total Life-Cycle Cost

An adequate economic comparison between two types of drives requires an analysis of all of the costs incurred over the entire life-cycle of the equipment. In addition to the purchase price of the drives and related equipment, this includes all of the material and

labor costs required to obtain and install the equipment and put it into operation, plus all of the costs to operate and maintain the equipment during the entire time it is expected to be in service.

The best way to determine which is the most economical system is to perform a detailed analysis. There are no “rules of thumb” that will consistently and accurately predict the outcome of an analysis. Ever since the introduction of AC drives in the late 1960’s they have been slowly proving to be the most economical choice in an increasing variety of applications, but individual application details can often tip the balance either way.

The following is an outline of elements typically included in total life-cycle cost. The items marked (✓) are the most significant items.

Procurement expenses:

- Project engineering expenses of selecting and specifying the equipment
- Purchasing department expenses
- Freight and receiving expenses

Cost of equipment and installation materials:

- Controller, options and accessories
- (✓) Motor, options and accessories
- Operator interface equipment
- Supervisory control equipment
- Machine interface equipment
- (✓) Transformer and other power distribution equipment
- (✓) Power factor and harmonic correction equipment
- (✓) Wire, cable, conduit, etc.
  
- (✓) Installation and commissioning expenses
  
- (✓) Operating expenses:
  - Electric power
  - Periodic maintenance
  - Planned downtime
  - Unplanned downtime
  - Repair
  - Spare and/or replacement parts and equipment

## 2.3 Analysis Method and Base Line Data

The Net Present Value (NPV) method of investment is used for analyzing the life-cycle cost of AC and DC systems for a range of horsepower from 10 to 1500. The NPV method of investment evaluations accounts for the time value of money by discounting all cash flows to present value using the required rate of return. NPV can be presented by the following formula.<sup>[9]</sup>

$$NPV = \sum_{t=0}^n \left[ \frac{A_t}{(1+r)^t} \right]$$

Where

$A_t$  cash flow for the period

$n$  Equipment life in years

$r$  required rate of return

After the cash flow for both the AC and the DC systems have been transformed to NPV, a comparative analysis could be done to assess the life-cycle cost of AC versus DC systems. The following sections describe the base line data used for the analysis.

## 2.4 First Cost for Drives and Motors

The initial purchase cost of the drive and the motor obviously has a major influence on the life-cycle cost. However, these prices may vary considerably depending on the optional features, number of units bought, and other factors. For this analysis prices are the average retail list price based on the ASD equipment suppliers contacted, for quantity one, with open chassis and no optional features. Table 2-1 shows the base line data used for the first cost of drives and motors for different horsepower ratings.

**Table 2-1**  
**First Cost of Drive and Motor at Different Horsepower Ratings**

Drive	Drive Retail Price <sup>{1}</sup> at Rated Horsepower					
Technology	10 HP	50 HP	100 HP	250 HP	500 HP	1500 HP
DC SCR <sup>{2}</sup>	\$4,560	\$7,750	\$8,100	\$14,500	\$21,000	\$39,000
Inverter <sup>{3}</sup>	\$2,400	\$8,000	\$11,900	\$23,500	\$32,000	\$90,000
Vector <sup>{4}</sup>	\$3,500	\$10,000	\$15,800	\$33,750	Note <sup>{5}</sup>	N/A

Motor	Motor Retail Price At Rated Horsepower					
Technology	10 HP	50 HP	100 HP	250 HP	500 HP	1500 HP
DC <sup>{6}</sup>	\$5,010	\$10,500	\$13,000	\$19,550	\$46,000	\$142,000 <sup>{7}</sup>
Induction <sup>{8}</sup>	\$2,800 <sup>{9}</sup>	\$4,900 <sup>{10}</sup>	\$9,700 <sup>{10}</sup>	\$18,800 <sup>{10}</sup>	\$38,500 <sup>{10}</sup>	\$112,500

Notes: {1} Dollars are the average retail list price based on the ASD equipment suppliers contacted, for quantity one, with open chassis and no optional features.

{2} Controller only (non-regenerative non-reversing)

{3} PWM-VSI IGBT technology with Volts/Hz control

{4} Full power from 2 kHz to 8 kHz carrier frequency operation with sensorless control

{5} Off-the-shelf vector drive technology at this horsepower rating will be available in early 1999

{6} DPG-FV (drip-proof guarded TEFC motor 850 rpm base speed)

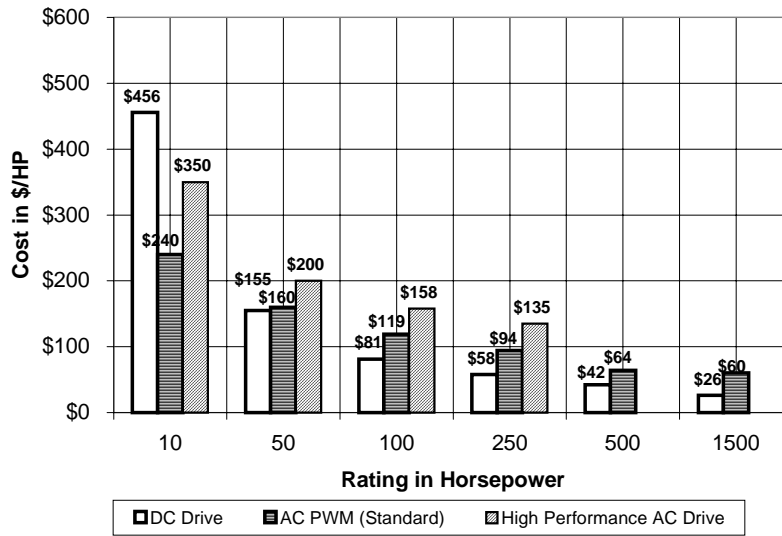
{7} DPG-FV at 850 rpm base speed

{8} Variable speed motor, 10:1 variable/constant torque speed range

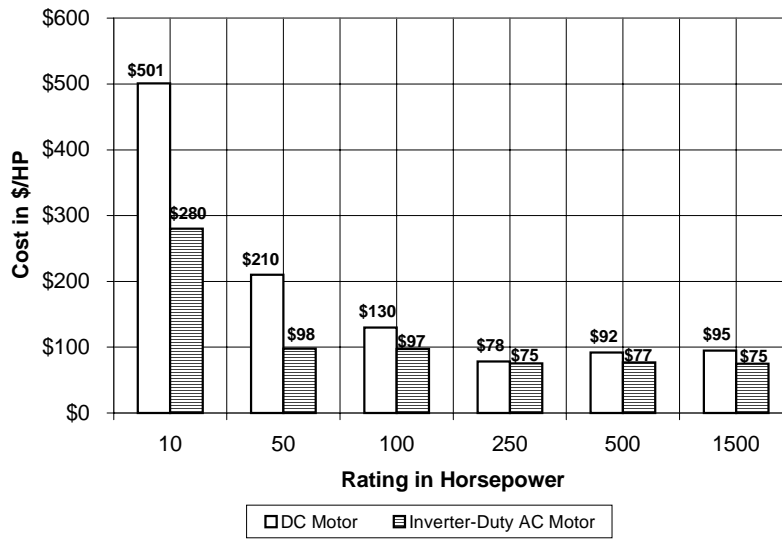
{9} TENV (totaled enclosed non-ventilated) at 1750 rpm base speed

{10} DPG-FV at 1750 rpm base speed

One clear trend that is apparent from the data is that for DC drives the price of the drive per horsepower decreases considerably for higher horsepower drives. Also, on an average, high performance AC drives are 40-60% more expensive than the standard PWM drives. For 500 and 1500 horsepower a representative cost estimate for high performance vector or direct torque control drives could not be obtained since the manufacturers have not started commercially producing these high performance drives at the higher horsepower ratings. This may affect the life-cycle cost analysis for the 500 to 1500 horsepower drive ranges. Figures 2-1 and 2-2 show the base line pricing trend of drives and motors for different horsepower ratings.



**Figure 2-1**  
**First Cost Data for AC and DC Drives**



**Figure 2-2**  
**First Cost Data for AC and DC Motors**

## 2.5 System Maintenance Cost

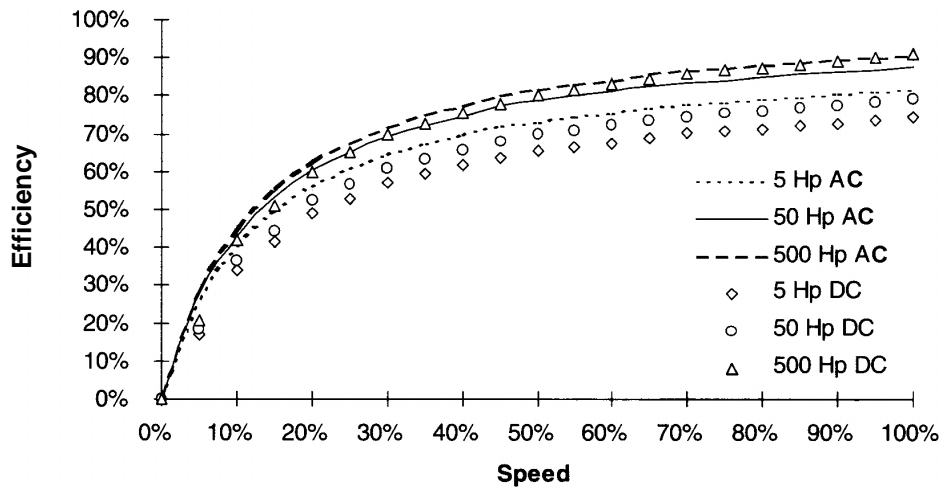
The AC squirrel cage motor is the workhorse of the industry and compared to its DC counterpart it has many advantages considering the maintenance cost. It has no brushes or commutator that require frequent maintenance and also the rewind costs are typically less for ac motors than for dc motors of the same horsepower. These advantages will result in an equivalent annual savings based on reduced maintenance, shorter and fewer motor related outages, and reduced motor rewind cost. However, quantifying this cost is not a trivial job. For this analysis the maintenance cost for a DC drive system is taken as \$7/hp/year compared to \$3/hp/year for an equivalent AC system.<sup>[9,10]</sup>

## 2.6 Other Factors

For the purpose of this analysis the following factors have not been taken into consideration. However, depending on the application these factors may influence the total life-cycle cost. Using the NPV method these costs can be evaluated in the same manner the system maintenance cost has been taken into account for this analysis.

### 2.6.1 Efficiency of Motor and Drive System

As shown in Figure 2-3, the overall efficiency of an AC drive system can be expected to be a little higher than the efficiency of a DC drive system especially at lower speed. DC converters are typically slightly more efficient than AC inverters. Except at higher horsepower, DC motors are typically significantly less efficient than AC motors. In addition, as speed is reduced below 100%, the efficiency of a constant torque DC drive system drops off more rapidly than the efficiency of an AC drive system. The horsepower, the average operating speed and load, and other characteristics of the individual application will determine specific results.



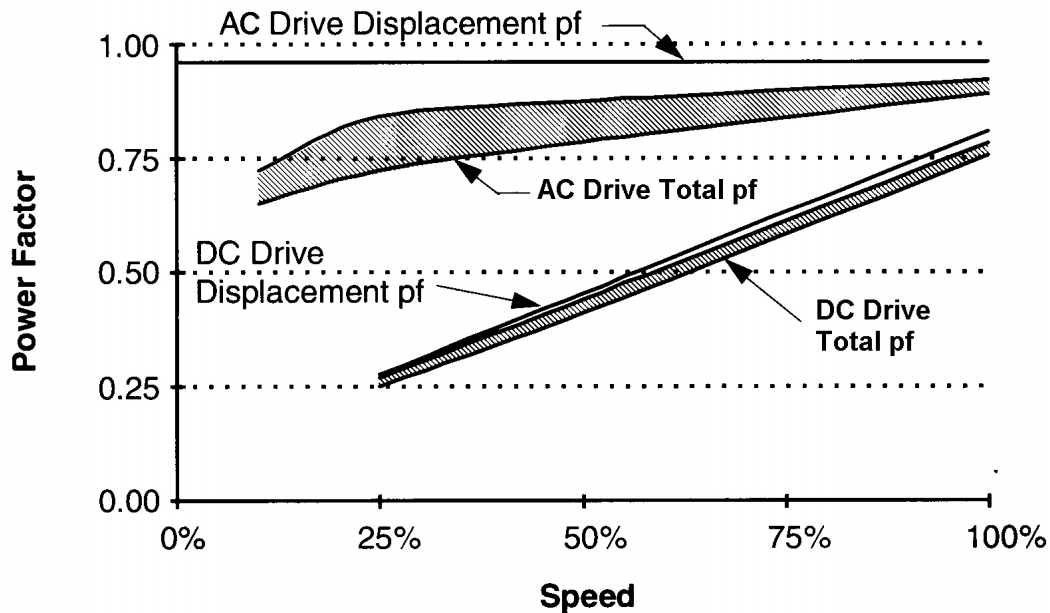
Source: ABB Industrial Systems, Inc.

**Figure 2-3**  
Drive System Efficiency Comparison for Constant Torque Drives

### 2.6.2 Power Factor

With adjustable-speed drives and other electronic power conversion equipment, power factor can be defined in two ways. The displacement power factor is the power factor of the fundamental components of the input line voltage and current. The total power factor includes the effect of harmonic distortion. Depending on the metering equipment used and the billing formula, either a low displacement power factor or a low total power factor can result in higher utility bills.

The displacement power factor of a PWM type AC drive is about 0.95-0.99 at all operating speeds. The displacement power factor of a DC drive is about 0.8 at full speed and decreases towards zero at zero speed. The total resistance, capacitance, and inductance from the source to the load impact the harmonic current distortion. Since the impedance of the power distribution system is an important part of the total circuit, the current distortion can vary widely from one installation to another. Since both displacement power factor and harmonic distortion determine total power factor, the impedance of the power distribution system also affects total power factor. Figure 2-4 shows both displacement power factor and total power factor versus speed for typical PWM drives and typical 6-pulse DC drives. The curves are for full load, constant torque operation. The shaded areas indicate a variation of total power factor for a typical range of installation conditions.



Source: ABB Industrial Systems, Inc.

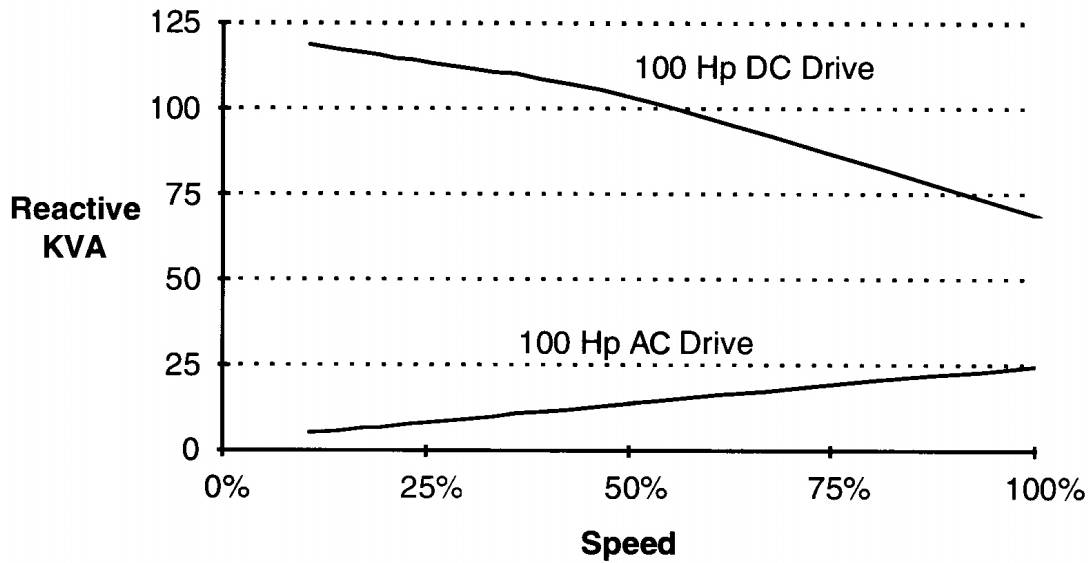
**Figure 2-4**  
**Drive Power Factor Comparison for Constant Torque Drives**

All of the power distribution equipment and wiring that feeds power to a drive must be sized to handle the total RMS current including the harmonic content. Total RMS current can be calculated from:

$$\text{Current} = \frac{\text{Horsepower} \times 746}{\text{Line Voltage} \times \text{Total Power Factor} \times \text{Efficiency} \times \sqrt{3}}$$

As the equation indicates, the input line current for a DC drive is generally higher than for an equivalent AC drive due to lower efficiency and total power factor. For example, at full speed and full load, the efficiency of a typical 100 hp DC drive is 83.3% and the total power factor is 0.77. At 480 volts, the total RMS input current would therefore be 140 amps. Using a high efficiency motor recommended for AC duty, the efficiency of a typical 100 hp AC drive is 80.4% and the total power factor is 0.90. At 480 volts, the total RMS input current would therefore be 124 amps, 11 percent less than the input current for the DC drive.

In considering the impact of a drive's power factor on the power factor of a facility, it is necessary to determine the reactive kVA required by the drive. Figure 2-5 compares the reactive kVA requirements for typical 100 hp AC and DC drives. This comparison does not include the effect of harmonic distortion because the impact of each harmonic must be considered separately.



Source: ABB Industrial Systems, Inc.

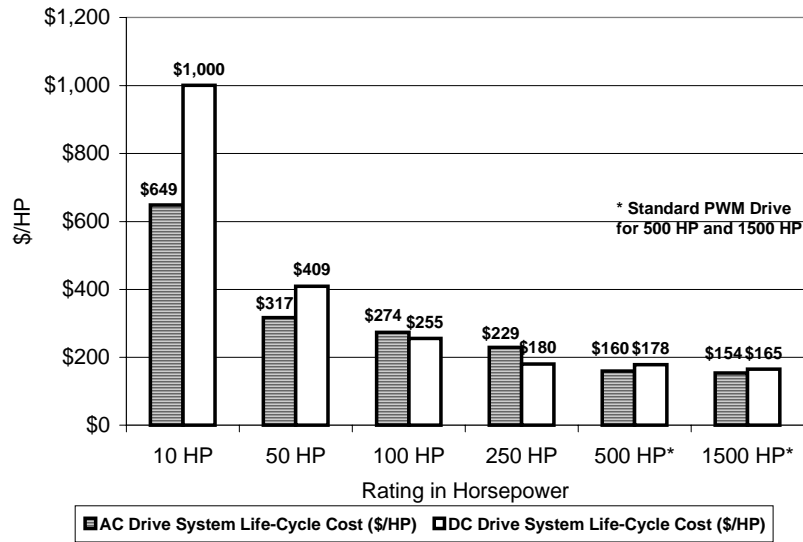
**Figure 2-5**  
Drive Reactive KVA Comparison for Constant Torque Drives

### 2.6.3 Harmonics

With both AC and DC drives, the harmonic content of the input current causes voltage distortion that can effect other equipment that is connected to the same power source. In addition to the harmonic voltage distortion that results from harmonic currents, DC drives introduce harmonic voltage distortion due to “notching” of the voltage waveform caused by the commutation of the controlled rectifiers. The need for harmonic limitation or compensation depends on the acceptable level of harmonic distortion and the size of the power distribution system in comparison to the total kVA of the connected drives. Each specific installation must be individually analyzed to determine the cost of any required harmonic requirements or compensation.

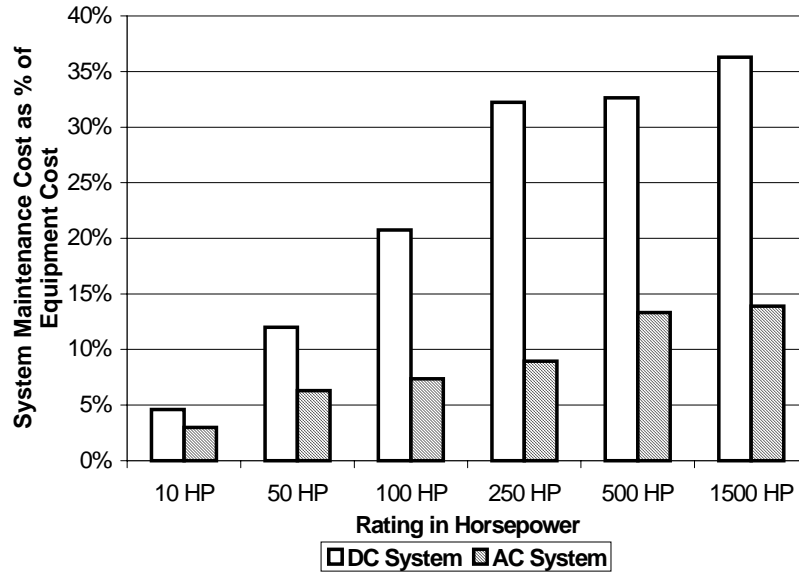
## 2.7 Results of Base Line Life-Cycle Cost Analysis

Using the NPV method, a life-cycle cost analysis was conducted for AC and DC systems with 20 years expected lifetime and 15% required rate of return. The first costs of motors and drives and the yearly maintenance cost of each system were used as the input variables for the analysis. Figure 2-6 illustrates results of the analysis for different horsepower ranges.



**Figure 2-6**  
**Life-Cycle Cost Analysis for AC and DC Drive Systems**

As can be seen from the analysis for the lower horsepower range (< 50 HP), the AC system has a significant advantage over its DC counterpart. This is mainly due to the first costs of the motor and drive systems. However as the horsepower size increases the cost of DC converters becomes attractive compared to high performance AC inverters and the life-cycle differential cost becomes negligible. For 500 and 1500 horsepower ratings, this trend reverses mainly due to the unavailability of high performance AC vector controlled drives in that horsepower range. Traditional PWM AC drives are commercially available in that horsepower range and were used as the baseline cost data. Figure 2-7 shows the Net Present Value for the 20-year maintenance cost of AC and DC systems as a percentage of first cost. For higher horsepower systems the maintenance cost associated with a DC system becomes a significant part of the initial investment for the first cost of the drive system. Often during economic evaluations of AC/DC systems the cumulative effect of the yearly maintenance cost is not factored in the analysis. The following graph clearly shows that the maintenance cost can be a significant portion of the total life-cycle cost of a motor drive system.



**Figure 2-7**  
**Net Present Value of System Maintenance Cost as % of First Cost for AC and DC Drive Systems**

## 2.8 Sensitivity Analysis

A sensitivity analysis was conducted on the baseline data to determine how a change in each of the variables included in the analysis would affect the life-cycle cost. A sensitivity analysis is extremely important in any economic analysis since it shows how changes in the assumptions underlying the base line data could impact the overall result. The life-cycle cost of AC and DC drive systems was recalculated by changing each of the four variables (drive first cost, motor first cost, system maintenance cost, and rate of return) by 20% and then computing the change in the life-cycle cost from the base line data. The results of this sensitivity analysis is shown in Table 2-2.

**Table 2-2**  
**Sensitivity Analysis Result**

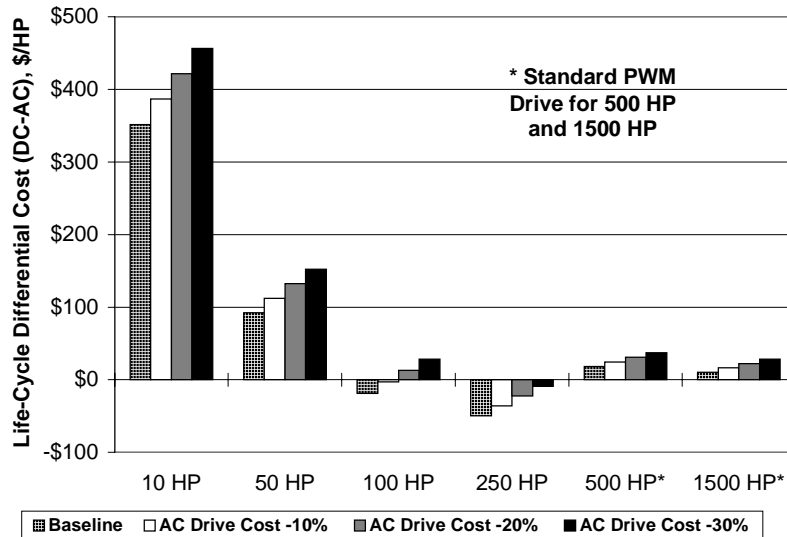
VARIABLE	System Type	% Change in Life-Cycle Cost for 20% Change of each Variable					
		10 HP	50 HP	100 HP	250 HP	500 HP*	1500 HP*
First Cost AC Drive (+20%)	AC	10.8%	12.6%	11.5%	11.8%	8.0%	7.8%
	DC	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
First Cost DC Drive (+20%)	AC	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	DC	9.1%	7.6%	6.4%	6.4%	4.7%	3.2%
First Cost AC Motor (+20%)	AC	8.6%	6.2%	7.1%	6.6%	9.6%	9.7%
	DC	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
First Cost DC Motor (+20%)	AC	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	DC	10.0%	10.3%	10.2%	8.7%	10.3%	11.5%
DC Maintenance Cost (+20%)	AC	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	DC	0.9%	2.1%	3.4%	4.9%	4.9%	5.3%
AC Maintenance Cost (+20%)	AC	0.6%	1.2%	1.4%	1.6%	2.4%	2.4%
	DC	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Rate of Return (+20%)	AC	-0.4%	-0.9%	-1.0%	-1.2%	-1.7%	-1.8%
	DC	-0.6%	-1.6%	-2.5%	-3.5%	-3.6%	-3.9%

\* Standard PWM Drive for 500 HP and 1500 HP

A close look at the results of the sensitivity analysis shows that the first cost of the AC drive and the DC motor are the most critical variable affecting the life-cycle cost (shaded areas in Table 2-2). Next in significance are the DC drive and AC motor first cost. It is anticipated that the price of the DC motor and drive, and AC motor will remain pretty stable in the future. However, the price of AC drive systems, especially the high performance drives may decline as these drives gain more market penetration.

In order to determine how that would impact the life-cycle cost analysis, the first cost of the AC drive was varied from base line to 30% less than base line in steps of 10%. The result of that analysis as a differential cost between the AC and DC systems is shown in

Figure 2-8. A positive differential cost means the DC system life-cycle cost is more than its AC counterpart and vice versa for a negative differential cost. Clearly as the AC drive price starts coming down the difference between AC and DC systems for lower horsepower drives increases and for higher horsepower drives the AC system starts to look attractive compared to its DC counterpart.



**Figure 2-8**  
**Impact of AC Drive First Cost on Life-Cycle Cost Differential to DC Drive Systems**

## 2.9 Conclusions

With advancements in AC drive technology, opportunities now exist for either AC or DC technology to be applied for many processes. While the initial decision depends on the application requirement, a life-cycle cost analysis provides useful data to compare the two alternatives as an investment decision. In this section we have provided a sample life-cycle analysis cost and identified key variables that may need to be accounted for in such an analysis. A sensitivity analysis is conducted to identify how changing one or more of the key variables will impact the system life-cycle cost.

# 3

## SYSTEM COMPATIBILITY ISSUES FOR AC AND DC DRIVES

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In addition to the background research information provided, approximately thirteen evaluation tests were performed on three adjustable-speed drive (ASD) systems: a DC drive, an AC drive with sensorless vector control, and an AC drive with Volts/Hz control. These tests were broken down into system compatibility and performance evaluations. The drives chosen for these tests are representative examples of the most common 5 HP AC and DC drive topologies. Therefore, the test results should not be viewed as standard results for all AC and DC drives. The system compatibility tests were designed to characterize the interactions of typical AC and DC drive topologies with the electric power system and the motors. There were nine system compatibility tests conducted on the three ASD systems. The system compatibility tests can be grouped into two categories: the effects of the electric power system on ASDs and the effects of ASDs on the electric power system and motors.

The effects of the electric power system on ASDs:

1. Steady-state Voltage Unbalance
2. Steady-state Undervoltage/Overvoltage
3. Voltage Sag Response
4. Capacitor Switching Transient Response

The effects of ASDs on the electric power system and motors:

1. Electro-Magnetic/Radio Frequency Interference (EMI/RFI)
2. Input Characteristics
3. Output Characteristics
4. Power Factor
5. Voltage Notching

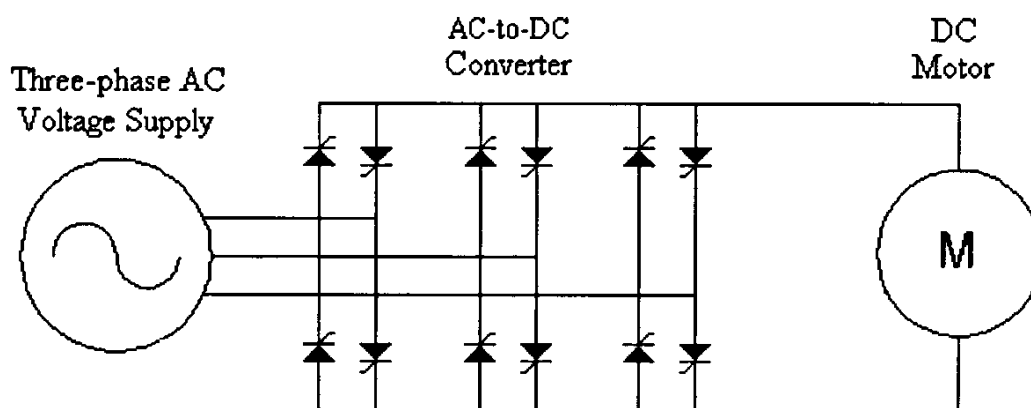
In the past, DC drive systems were chosen over AC drive systems due to wide speed range and precise process torque control requirements. These performance tests were designed to characterize the performance of three representative ASD systems under specific loading conditions. The performance tests included:

1. Starting Torque
2. Speed Regulation
3. Low-Speed High-Torque Control
4. System Efficiency

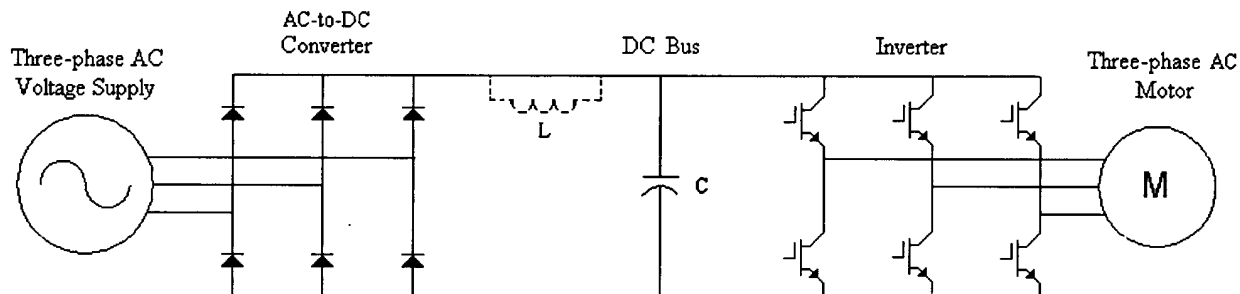
The three ASD systems chosen for the system compatibility and performance evaluation tests were:

1. DC drive system (digital control technology) with encoder feedback.
2. AC PWM voltage source inverter (VSI) drive system (digital Volts per Hertz control technology) without encoder feedback.
3. AC PWM-VSI drive system (digital sensorless vector control technology) without encoder feedback.

These three drive systems are considered suitable for general applications and are representative of industrial ASD applications. A diagram of typical DC and VSI AC drive systems are illustrated in Figures 3-1 and 3-2.



**Figure 3-1**  
**DC Drive (typical)**  
**(field circuit not shown)**

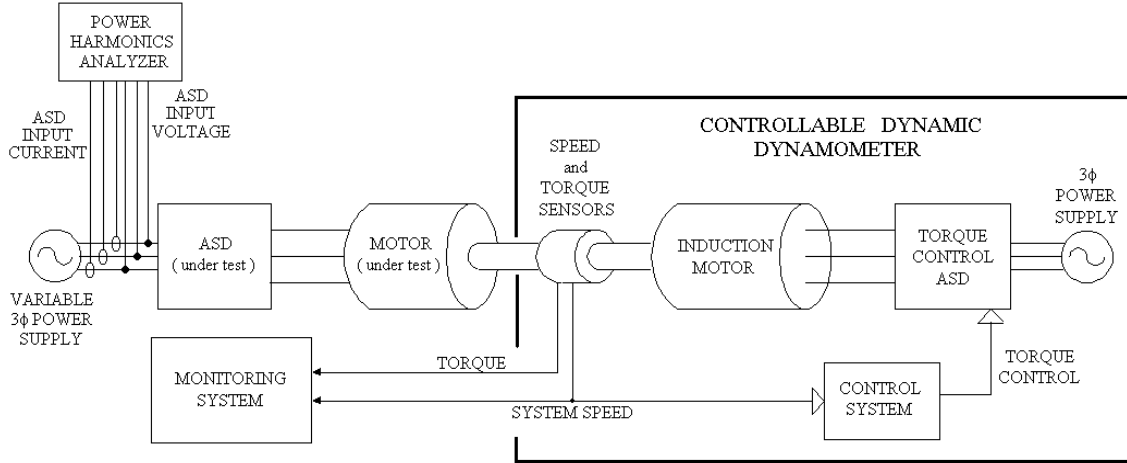


**Figure 3-2**  
VSI AC Drive (typical)

### 3.1 The effects of the electric power system on ASDs

*Steady-State Voltage Unbalance* – The ANSI recommended practice suggest maintaining the voltage unbalance at the point of delivery below 3%. The voltage unbalance of the electric service supply significantly affects the input current of most ASDs. For a given percent voltage unbalance, the resulting percent current unbalance can be much higher. Overcurrent conditions may be exacerbated by sources with high short-circuit capacity. Steady-state voltage conditions can lead to overcurrent conditions in rectifiers (AC-to-DC converters) of ASDs. Sustained voltage unbalance conditions may significantly reduce the life of rectifiers and lead to rectifier failures. Brief unbalanced input voltage conditions occur during unbalanced voltage sags.

The test setup for the steady-state voltage unbalance evaluation can be seen in Figure 3-3. The Power Harmonics Analyzer was used to measure the input current and voltage of each ASD. The dynamometer was set to apply a constant torque load to the motor and drive under test. The Monitoring System was used to monitor the load torque of the dynamometer and the speed of the rotating system. Appendix A describes the controllable dynamic dynamometer test system.



**Figure 3-3**  
**Test Setup for the ASD Steady-State Voltage Unbalance Evaluation**

The dynamometer was set to produce a constant load torque to the motor and drive under test. The ASDs and the dynamometer were programmed to produce the following steady-state load conditions:

- Speed = 1800 rpm
- Load Torque = 19.8 N-m
- Load Power = 5 hp

Table 3-1 contains the data for the steady-state voltage unbalance evaluation test for the DC drive system. The data shows that the voltage unbalance does not cause high current unbalance between the phase currents for the DC drive system. For all test points, there was no change in the speed or torque of the driven system. **Note:** The field current for the DC motor was derived from phases A and C.

**Table 3-1**  
**DC Drive Steady-State Voltage Unbalance Test Results**

$V_{ub}$ (%)	$V_{ab}$ (V)	$V_{bc}$ (V)	$V_{ca}$ (V)	$I_a$ (A)	$I_b$ (A)	$I_c$ (A)	$I_{ub}$ (%)
0	460	460	460	7.5	6.7	7.2	6.0
1.5	450	460	450	7.3	6.7	7.5	6.6
3.0	440	460	440	7.0	6.7	7.7	8.1
5.0	427	460	427	6.4	6.9	8.0	12.7

Table 3-2 contains the test results for the AC sensorless vector control drive. The data shows that low levels of input voltage unbalance can lead to significant input current unbalance for ASDs with uncontrolled rectifiers. The input current unbalance was reduced due to the input line reactors of this ASD. Input line reactors are often recommended for ASDs with uncontrolled rectifiers, among other things, to reduce the adverse effects of input voltage unbalance. For all test points, the speed and torque of the system decreased by less than 0.5%.

**Table 3-2**  
**AC Drive – Sensorless Vector Control**  
**Steady-State Voltage Unbalance Test Results**

$V_{ub}$ (%)	$V_{ab}$ (V)	$V_{bc}$ (V)	$V_{ca}$ (V)	$I_a$ (A)	$I_b$ (A)	$I_c$ (A)	$I_{ub}$ (%)
0	460	460	460	6.5	6.3	6.5	2.1
1.5	450	460	449	5.5	7.0	8.0	19.5
3.0	439	460	438	4.7	8.7	9.9	39.5
5.0	428	460	427	3.1	11.0	11.3	63.4

Table 3-3 contains the test results for the AC Volts/Hz control drive. The data shows that low levels of input voltage unbalance can lead to high input current unbalance for ASDs with uncontrolled rectifiers without input line reactors. During the 5% input voltage unbalance condition, the input line current of the low voltage phase reduced to 4% of the other two phases while the other two phase currents increased to 190% of the nominal current during balanced voltage conditions. The input current unbalance could be reduced by adding input line reactors to this ASD. For all test points, the speed and torque of the system decreased by less than 0.5%.

**Table 3-3**  
**AC Drive – Volts/Hz Control**  
**Steady-State Voltage Unbalance Test Results**

$V_{ub}$ (%)	$V_a$ (V)	$V_b$ (V)	$V_c$ (V)	$I_a$ (A)	$I_b$ (A)	$I_c$ (A)	$I_{ub}$ (%)
0	460	460	460	9.3	9.3	8.9	2.9
1.5	450	460	450	8.4	9.2	11.9	21.0
3.0	440	460	440	6.1	12.4	13.8	43.3
5.0	427	460	427	0.8	17.3	17.3	93.0

**Steady-State Undervoltage/Overvoltage** – Electric supply systems and user systems are designed and operated so that the steady-state supply voltage and utilization voltages normally remain within the expected voltage range. During peak load, electric service companies may lower their distribution line voltages in order to reduce the system power consumption. The under and overvoltage tests were designed to show the effects of low and high steady-state voltage conditions on the three ASD systems.

The test setup for the steady-state undervoltage and overvoltage evaluations was the same as the one shown previously in Figure 3-3. The Power Harmonics Analyzer was used to measure and calculate the input current harmonics of each ASD. The Monitoring System was used to monitor the load torque of the dynamometer and the speed of the rotating system. The dynamometer was set to produce a constant load torque to the motor and drive under test. The ASDs and the dynamometer was set to produce the following load conditions:

- Speed = 1800 rpm
- Load Torque = 19.8 N-m
- Load Power = 5 hp

Table 3-4 lists the test results for the DC drive system. As expected, the results show that the fundamental and rms current values do not increase as the input voltage varies between +10% down to -10% because the DC drive has a controlled rectifier. The DC drive operates in continuous current mode and continuously monitors the motor current. The DC drive compensates the control of the SCRs in the rectifier to sustain the motor current at the required level. For all test points, there was no change in the speed or torque of the system.

**Table 3-4**  
**DC Drive Steady-State Undervoltage/Overvoltage Test Results**

Voltage (V)	* $\Delta$ Voltage (%)	$I_{rms}$ (A)	$I_f$ (A)	$I_{THDf}$ (%)	Speed (rpm)	Torque (N-m)	$V_A$ (V)	$I_{Field}$ (A)
414	-10	7.05	6.78	26.7	1741	20.3	502	0.86
437	-5	7.07	6.81	26.0	1741	20.3	500	0.94
460	0	7.13	6.87	27.0	1741	20.3	498	0.99
483	+5	7.17	6.88	27.7	1741	20.3	499	1.00
506	+10	7.15	6.88	28.0	1741	20.3	498	0.94

\*  $\Delta$  = change in

Table 3-5 contains the test results for the AC sensorless vector control drive. The results show that the fundamental and rms current values increase as the input voltage decreases from +10% down to -10%. As expected, the DC bus voltage increases and decreases with the input voltage. The speed only decreased by 1.2% as the voltage was decreased by 10%. The speed increased by less than 0.5% as the input voltage was increased by 10%. There was no significant change in the torque of the system.

**Table 3-5**  
**AC Drive – Sensorless Vector Control**  
**Steady-State Undervoltage/Overvoltage Test Results**

Voltage (V)	$\Delta$ Voltage (%)	$I_{rms}$ (A)	$I_f$ (A)	$I_{THDf}$ (%)	Speed (rpm)	Torque (N-m)	DC Bus (V)
414	-10	7.06	6.27	45.2	1718	20.3	547
437	-5	6.72	5.80	50.2	1730	20.3	580
460	0	6.44	5.60	54.8	1739	20.3	611
483	+5	6.30	5.23	58.9	1742	20.3	643
506	+10	5.13	5.03	61.1	1747	20.4	675

Table 3-6 contains the test results for the AC Volts/Hz control drive. The results show that the fundamental current values increased as the input voltage decreased from +10% down to -10%. However, the rms value of the input current did not follow the same trend. These test results show that the impedance of the source significantly affects the rms input current and the THD values. The addition of input line reactors would lower the rms input current and improve the THD.

**Table 3-6**  
**AC Drive – Volts/Hz Control**  
**Steady-State Undervoltage/Overvoltage Test Results**

Voltage (V)	$\Delta$ Voltage (%)	$I_{rms}$ (A)	$I_f$ (A)	$I_{THDf}$ (%)	Speed (rpm)	Torque (N-m)	DC Bus (V)
414	-10	8.90	6.17	102.7	1728	20.3	577
437	-5	8.90	5.77	115.7	1736	20.3	614
460	0	9.17	5.53	130.3	1737	20.3	649
483	+5	9.00	5.20	138.7	1739	20.3	682
506	+10	8.23	5.10	121.3	1740	20.4	713

As expected, the DC bus voltage increases and decreases with the input voltage. The speed only decreased by 0.5% as the voltage was decreased by 10%. The speed increased by less than 0.2% as the input voltage was increased by 10%. There was no significant change in the torque of the system.

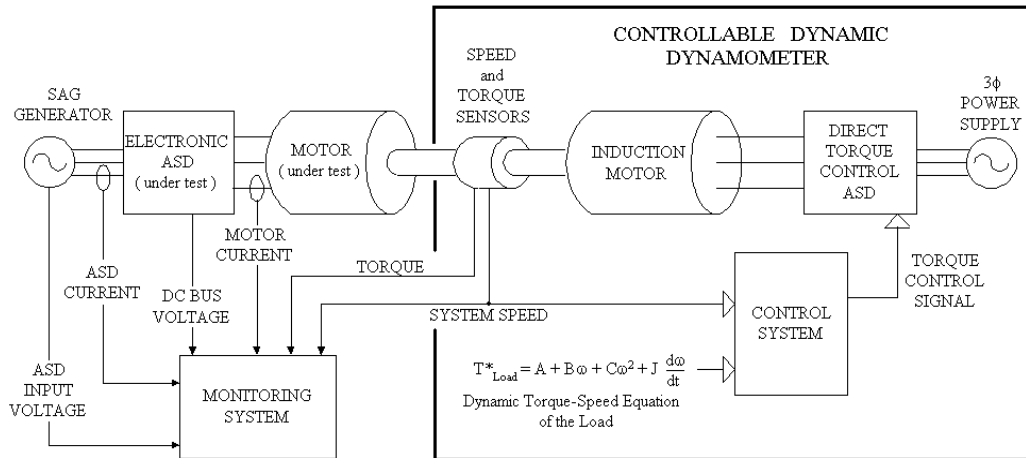
**Voltage Sag Response** – Voltage sags and momentary interruptions are common occurrences in low voltage distribution systems. Voltage sag conditions can cause voltage-sensitive equipment, such as AC and DC drives, to trip off-line. When ASDs trip, safe operation of the process can be comprised and costly situations often result. Industrial and commercial ASD users can experience significant losses when ASDs or ASD-driven processes trip during voltage sag conditions.

With the emergence of concerns for power quality and improving customer power, the voltage sag response of ASDs and other voltage-sensitive equipment has become increasingly important. Ongoing ASD voltage sag evaluation tests are moving some of the burden of ASD trips from the utilities to the ASD end-users and manufacturers. As a result, ASD manufacturers have begun adding multiple ASD programming options that can mitigate and improve the ride-through of an ASD application during voltage sag conditions. Even with the added programming options and improved voltage sag ride-through, it is important for ASD users to understand which options are appropriate for their process applications.

AC VSI (Voltage Source Inverter) drives have DC link capacitors, which provide some energy storage, however, the main purpose of the DC link capacitors is to filter the output of the rectifier. Thus, the energy storage is usually low when compared to the rated power of the drive. Thus, the DC link voltage will drop quickly during voltage sag conditions. Drive manufacturers set lower limits for the DC link voltage, called the undervoltage trip point. When the DC link voltage drops to the undervoltage trip point, the drive reacts according to the restart and ride-through programming options. The undervoltage trip point, the sag depth, the sag duration, the restart and ride-through options, the load type, and the load inertia directly influence the impact of the voltage sag on the ASD-driven process.

Older generation DC drives tend to be more susceptible to voltage sag conditions, especially when voltage sags involve phase shifts, frequency shifts, or multiple zero crossings. However, advances in DC drive control technology may make them somewhat less susceptible. DC drives do not have DC link capacitors. SCR-controlled DC drives use controlled rectifiers to apply voltage to DC motors. DC drives may adjust firing angles in the rectifier to compensate during reduced input voltage conditions. However, adjusting firing angles may cause overcurrent conditions once the input voltage recovers from the sag. Again, the restart and ride-through programming options determine how the drive reacts during voltage sag conditions.

The test setup for the voltage sag response evaluation can be seen in Figure 3-4.



**Figure 3-4**  
Test Setup for ASD Voltage Sag Response Evaluation

The Monitoring System was used to monitor the output torque of the motor and the speed of the rotating system. The sag generator was set to apply symmetrical three-phase voltage sags down to 60% of nominal for 6 and 30 cycles. The controllable dynamic dynamometer was set to produce a variable torque load (industrial fan load) to the motor and drive under test. The ASDs were evaluated with and without restart and ride-through parameters enabled.

ASD and Motor:

- Speed or Output Frequency (under load) = 1200 rpm or 40 Hz

Dynamometer Load (Nominal Setpoint):

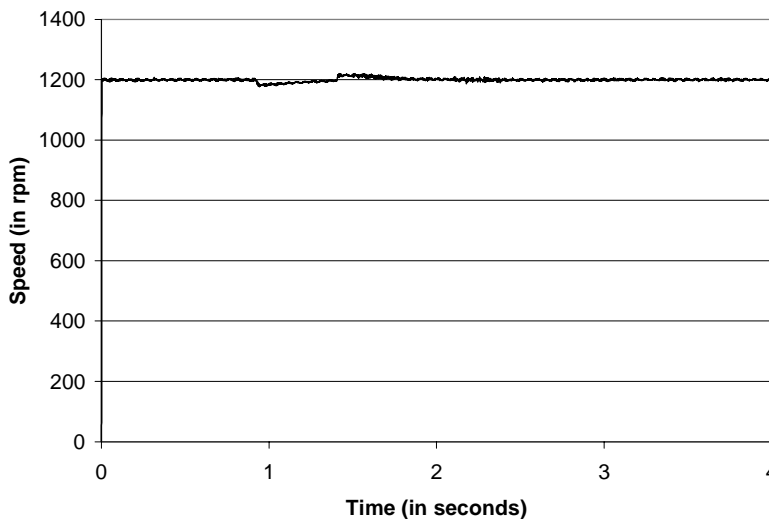
- Variable Torque Load
- Load Torque = 10 N-m (50% full-load torque)
- Load Inertia = 3.7 x Motor Under Test
- Load Power = 1.67 hp (33% full-load power)

Many industrial processes require precise and accurate control over process system parameters such as pressure, torque, temperature, flow, and speed. These processes are often driven by electric motors under ASD control. The ASD controls the torque and speed of the motor, which, in turn, controls the selected process parameters. The response of ASDs to voltage sag conditions directly impacts the torque and speed of the

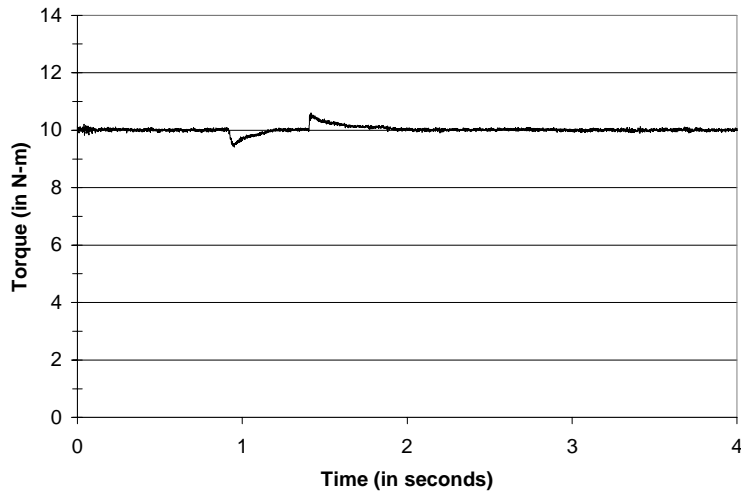
motor. Thus, the response of the ASD directly impacts the process parameters. It is not only important to determine whether or not the drive restarts after a voltage sag, but it is extremely important for some industries to know how the ASD controls the motor during and after the voltage sag. Therefore, it is necessary to monitor the torque and speed of the motor during voltage sag conditions. By monitoring the torque and speed, ASD users can observe the response of an ASD and the impact of the response on the mechanical process. The voltage sag response evaluation test results for each ASD/motor combination are listed in Tables 3-7, 3-8, and 3-9, and Figures 3-5 through 3-10. The tables indicate the ASD restart and ride-through parameter setups and the effect of the ASD response on the torque and the speed of the system. The figures show graphical representations of the ASD response to a 30 cycle, symmetrical three-phase, voltage sag down to 60% of nominal.

**Table 3-7**  
**DC Drive Voltage Sag Response Evaluation Test Results**  
 (with ride-through parameters disabled and enabled)

Restart/Ride-through	Voltage Sag (%)	Duration (cycles)	$\Delta$ Speed (rpm)	$\Delta$ Torque (N-m)
Disabled	60	6	-34	-0.8
Disabled	60	30	-1200	-9.9
Enabled	60	6	-28	-0.7
Enabled	60	30	-24 to +20	-0.5 to +0.7



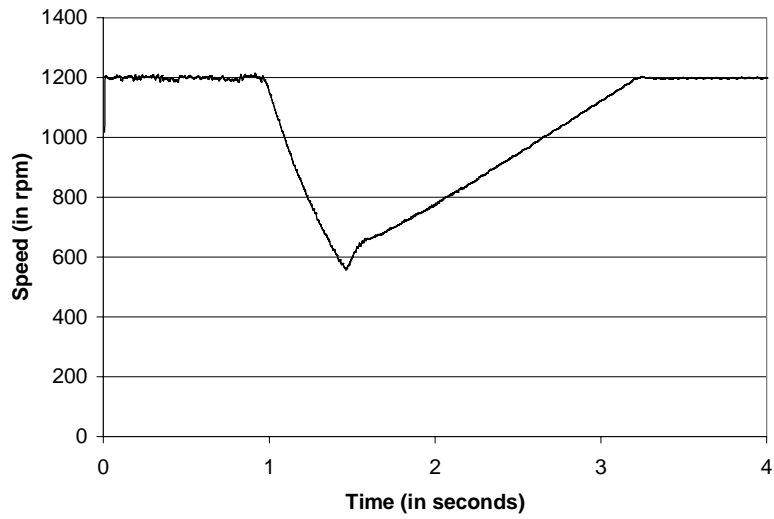
**Figure 3-5**  
**DC Drive Voltage Sag Response @ 30 Cycles Versus System Speed**  
 (with restart and ride-through parameters enabled)



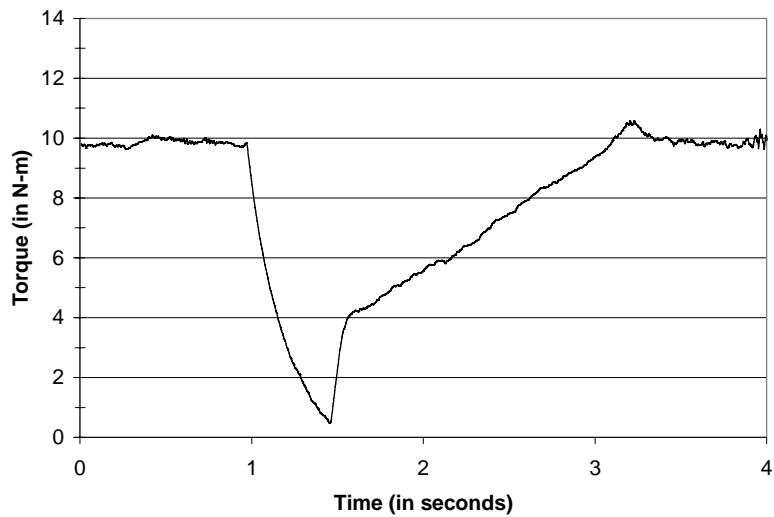
**Figure 3-6**  
**DC Drive Voltage Sag Response @ 30 Cycles Versus Torque**  
**(with restart and ride-through parameters enabled)**

**Table 3-8**  
**AC Drive Sensorless Vector Control Voltage**  
**Sag Response @ 30 Cycles Evaluation Test Results**  
**(with ride-through parameters disabled and enabled)**

Restart/Ride-through	Voltage Sag (%)	Duration (cycles)	$\Delta$ Speed (rpm)	$\Delta$ Torque (N-m)
Disabled	60	6	-1200	-9.9
Disabled	60	30	-1200	-9.9
Enabled	60	6	-140	-9.9 to +0.5
Enabled	60	30	-649	-9.9 to +0.5



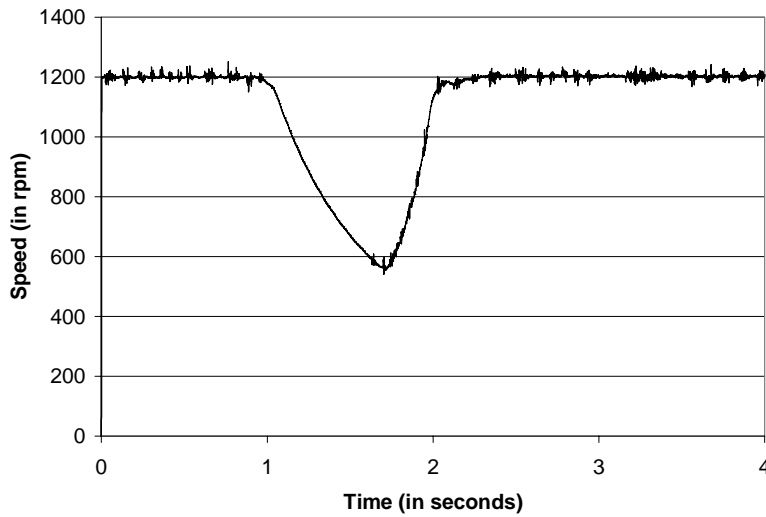
**Figure 3-7**  
**AC Drive – Sensorless Vector Control**  
**Voltage Sag Response @ 30 Cycles Versus System Speed**  
**(with restart and ride-through parameters enabled)**



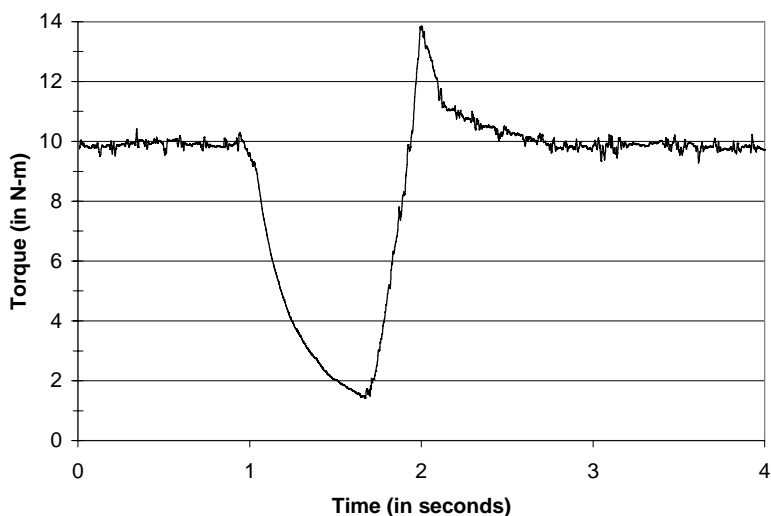
**Figure 3-8**  
**AC Drive – Sensorless Vector Control**  
**Voltage Sag Response @ 30 Cycles Versus System Torque**  
**(with restart and ride-through parameters enabled)**

**Table 3-9**  
**AC Drive Volts/Hz Control**  
**Voltage Sag Response @ 30 Cycles Evaluation Test Results**  
**(with ride-through parameters disabled and enabled)**

Restart/Ride-through	Voltage Sag (%)	Duration (cycles)	$\Delta$ Speed (rpm)	$\Delta$ Torque (N-m)
Disabled	60	6	-1200	-9.9
Disabled	60	30	-1200	-9.9
Enabled	60	6	-623	-9.9 to +3.7
Enabled	60	30	-644	-9.9 to +4.0



**Figure 3-9**  
**AC Drive – Volts/Hz Control**  
**Voltage Sag Response @ 30 Cycles Versus System Speed**



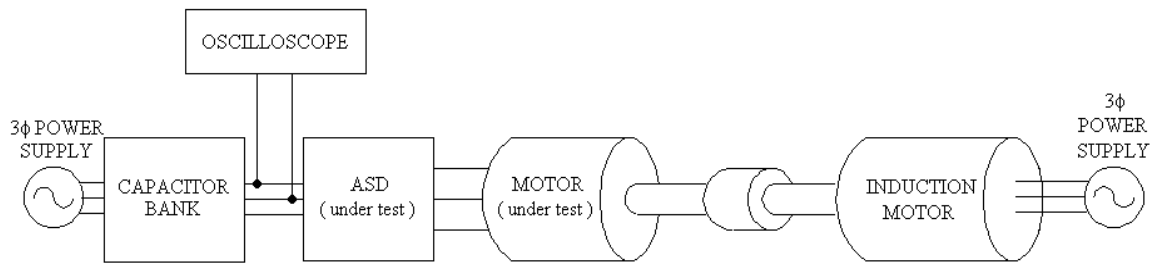
**Figure 3-10**  
**AC Drive – Volts/Hz Control**  
**Voltage Sag Response @ 30 Cycles Versus Torque**

**Capacitor Switching Transient Response** – Utilities use capacitor banks for displacement power factor correction. The capacitors reduce the reactive power demand on the source and reduce system losses. The banks may be switched onto the system (energized) as needed or they may be connected at all times. When capacitor banks are energized, a transient voltage oscillation occurs between the capacitor and the inductance of the distribution system. The result is a transient overvoltage that can be as high as 2.0 per-unit (above nominal peak voltage) at the capacitor location. The majority of the transients have frequencies in the range of 300 to 800 Hz, with the typical maximum magnitude of 1.2 to 1.5 per-unit (measured line-to-line).

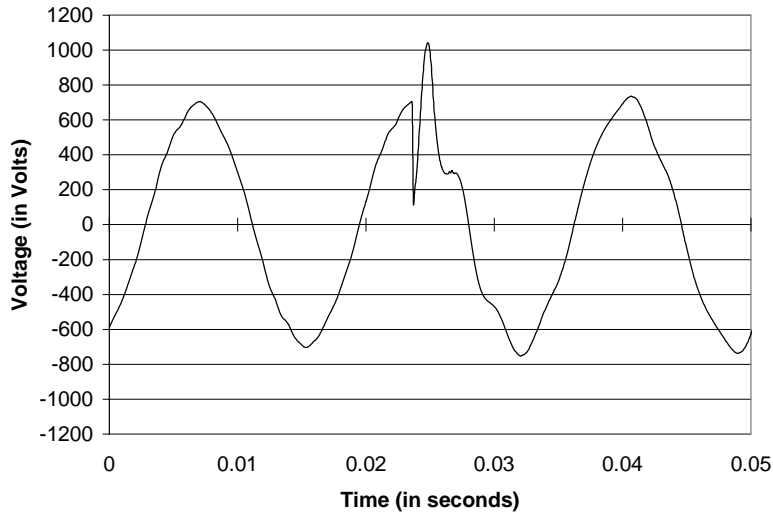
AC drives, with DC link capacitors and uncontrolled rectifiers, are particularly vulnerable to capacitor switching transients. These transients may cause failure of protective devices and electronic components in ASDs. The failures may result from overcurrent conditions of the rectifier or overvoltage conditions on the dc link capacitors. Often, the results are nuisance trips when the voltage on the DC link exceeds a predetermined upper threshold. The drive usually requires the involvement of an operator to reset the drive. These nuisance trips can create costly production delays when capacitor banks are energized to meet load demand.

The rating of the ASD, the ASD load level, and the impedance between the capacitor banks and the ASD are all factors that determine the magnitude of the transient at the terminals of the drive. Input line reactors are often recommended for reducing the affects of the transient's magnitude on the drive's overvoltage tripping circuit. The test setup for the capacitor switching transient evaluation test can be seen in Figure 3-11.

The test was conducted at two load conditions. One test was conducted for the ASD systems at idle conditions (ASD is energized but is not operating the motor) and the other test was conducted at full-load conditions. The dynamometer was used to apply a constant load torque to the motor under test. The oscilloscope was used to monitor the capacitor transient voltage. The capacitor bank was switched onto the power system to create the transients. The ASD systems were subjected to transients of increasing magnitude (starting at 1.1 per-unit) until the ASDs tripped or the magnitude reached 1.5 per-unit. The per-unit values of the transients were based on the nominal voltage ratings of the drives, 460 V. Figure 3-12 shows the transient applied to each ASD system. The results of the tests are presented in Tables 3-10, 3-11 and 3-12. The tables list the load torque and speed setpoints, the capacitor transient magnitudes (in per-unit), and the response of the ASDs.



**Figure 3-11**  
Test Setup for the Capacitor Switching Transient Evaluation



**Figure 3-12**  
Capacitor Switching Transient

Table 3-10 contains test results for the DC drive. The drive did not trip at either load point for transient voltages up to 1.5 per-unit. There were no increases in load torque or speed.

**Table 3-10**  
**DC Drive Capacitor Switching Transient Test Results**

Speed (rpm)	Load Torque (N-m)	Load Power (hp)	Capacitor Transient Magnitude (pu)	ASD Response
1800	19.9	5	1.5	No Trip
idle	idle	0	1.5	No Trip

Table 3-11 contains the test results for the AC sensorless vector control ASD. This drive has programming features that allow the dc bus to rise significantly above the nominal peak bus voltage. The drive did not trip at either load point for transient voltages up to 1.5 per-unit. There were no increases in load torque or speed. As mentioned previously, this drive has internal input line reactors. Input line reactors decrease the magnitude of the transient seen by the rectifier and DC link capacitors of the drive. Input line reactors are often recommended as mitigation tools for capacitor switching transients in both AC and DC drive applications.

**Table 3-11**  
**AC Drive – Sensorless Vector Control**  
**Capacitor Switching Transient Test Results**

Speed (rpm)	Load Torque (N-m)	Load Power (hp)	Capacitor Transient Magnitude (pu)	ASD Response
1800	19.9	5	1.5	No Trip
idle	idle	0	1.5	No Trip

**Table 3-12**  
**AC Drive – Volts/Hz Control**  
**Capacitor Switching Transient Test Results**

Speed (rpm)	Load Torque (N-m)	Load Power (hp)	Capacitor Transient Magnitude (pu)	ASD Response
1800	19.9	5	1.26	Trip; Auto-reset
idle	idle	0	1.26	Trip; Auto-reset

Table 3-12 contains the test results for the AC Volts/Hz control ASD. When the drive was operating at full-load, the overvoltage control for this drive caused the drive to trip and stop the load when the DC bus voltage exceeded 820 V (1.26 per unit). Once the DC bus voltage dropped below the overvoltage threshold, the drive automatically restarted the motor and load, and returned to the operating setpoint. When the ASD was in the idle state, the ASD display flashed an overvoltage fault condition for a 1.26 per unit transient. The drive automatically reset itself when the bus voltage dropped below the overvoltage threshold. As mentioned previously, input line reactors are often recommended for ASD applications for mitigating the effects of capacitor switching transients. The addition of input line reactors would have likely increased the transient voltage magnitude required to trip this drive.

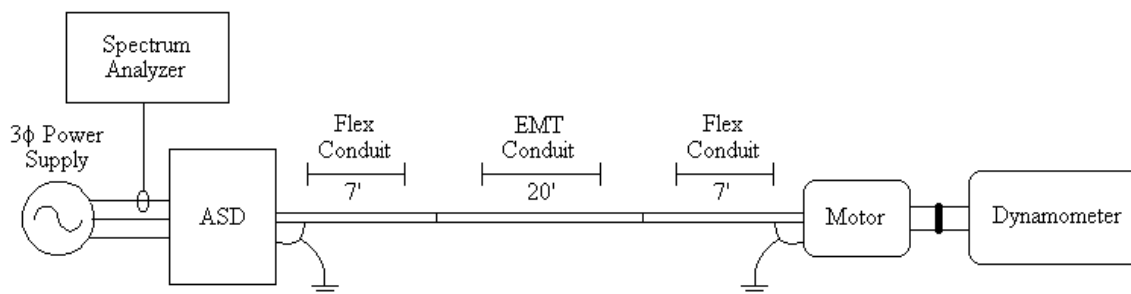
### 3.2 The Effects of ASDs on the Electric Power System and Motors

*EMI/RFI Interference* – In the 1990s, many ASD manufacturers began to replace bipolar junction transistors (BJTs) with insulated gate bipolar transistors (IGBTs) in AC drive inverters. IGBTs provided manufacturers with several advantages over BJTs such as faster switch times from off-state to on-state and vice versa. This decreased the switching losses and improved the efficiency of the drive. Other advantages included decreased drive package cost and increased carrier or switching frequencies. Higher switching frequencies paved the way PWM inverters. PWM inverters with high switching frequencies have reduced harmonic heating of the motor, improved torque performance at low operating frequencies, and reduced audible noise from motor laminations.

IGBTs provided ASD manufacturers with the improvements in motor control and efficiencies, but they also created application issues in other areas as well. Electro Magnetic Interference (EMI) is a common source of concern in PWM-ASD applications. The concerns are created by the fast transition of the AC drive output voltage. The fast transitions are sources of radiated and conducted noise. These interfere with other sensitive equipment, which is connected to the same distribution bus. EMI, both

radiated and conducted, can interfere with communication links, encoder feedback, ultrasonic sensors, temperature sensors, computers, AM radio, TV, CAT scanners, security alarms, and many other sensitive electronic devices.

The EMI evaluation tests were designed to show conducted and radiated EMI measurements for the three ASD systems at rated load torque and speed conditions. The test setup can be seen in Figure 3-13. The test instruments and measurements used for these tests are typically used by field engineers for acquiring EMI data. A current transformer (CT) and a spectrum analyzer were used for the conducted EMI evaluation. The CT was connected to one of the input phases of the ASD under test. The CT output was connected to the spectrum analyzer. A baseline measurement was taken with all devices in the off-state for comparison to the measurements operating under load. An Isotropic Electric Field Probe (10 kHz – 1 GHz, X-Y-Z combined) was used for the radiated electric field data. The test results can be seen in Tables 3-13, 3-14, and 3-15, and Figures 3-14, 3-15, and 3-16. The tables contain the radiated electric field measurements. The measurements were taken at four equally spaced locations around the motors and the drives at one meter from the motors and the drives. The figures contain the conducted EMI measurements.



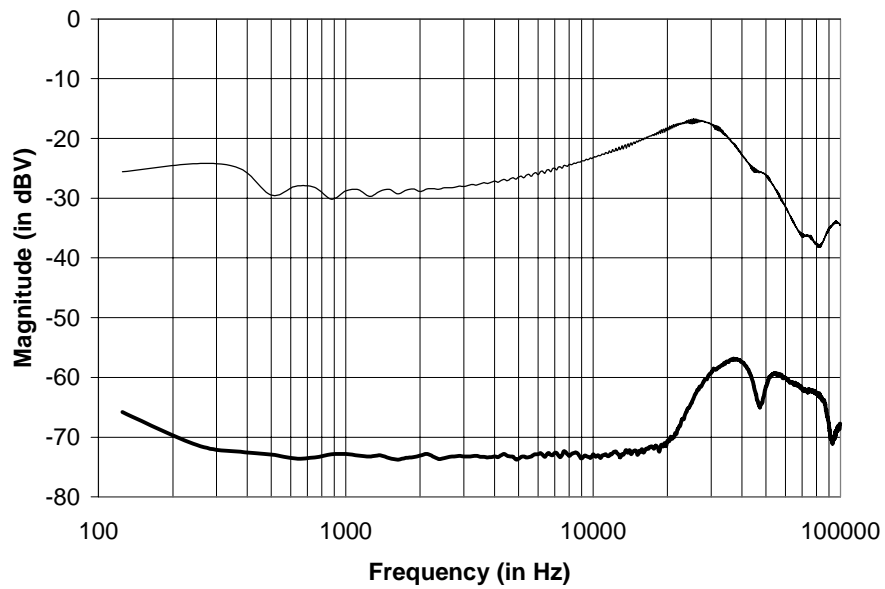
**Figure 3-13**  
**Test Setup for Radiated Electro Magnetic Interference**

Table 3-13 shows that the electric field measurements taken on both the DC drive and motor were near zero Volts/meter. Most drive suppliers indicate that radiated EMI emissions become a significant concern when levels reach 0.1V/m to 3.0V/m. Figure 3-14 is a preliminary step towards establishing a conducted emissions signature for drives. At this writing there are no conducted emission limits<sup>1</sup> from 10 kHz to 150 kHz for drives. The darker line in Figure 3-14 is the base line measurement with the DC drive off.

<sup>1</sup> The European Union has enforced basic Electro Magnetic Compatibility (EMC) standards applied to drives i.e. EN55011 *Limits and Methods of Measurements of Electromagnetic Disturbance Characteristics of Industrial, Scientific and Medical Radiofrequency Equipment*, and EN50081-2 *Electromagnetics Compatibility Generic Emission Standard, Part 2 --- Industry*

**Table 3-13**  
**DC Drive Electric Field Evaluation**  
 (electric field measurements in Volts/meter)

	0				0	
0	ASD	0		0	Motor	0
	0				0	



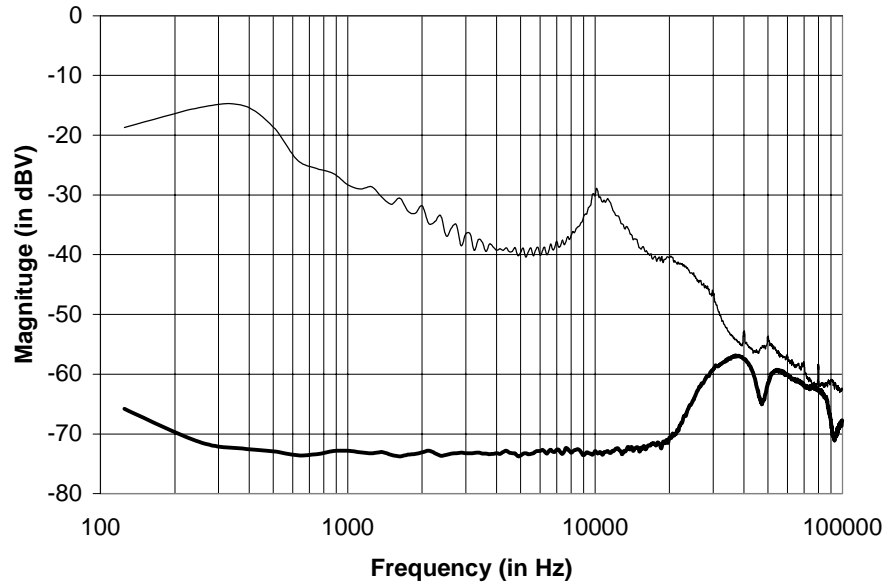
**Figure 3-14**  
**DC Drive Conducted EMI**

Table 3-14 shows that the electric field measurements taken on both the AC drive with sensorless vector control and motor varied between 0.41V/m to 1.8V/m. As previously mentioned, most drive suppliers would acknowledge that radiated EMI emissions become a significant concern when levels reach 0.1V/m to 3.0v/m. This is why ASD suppliers provide specific EMI/RFI motor leads shielding instructions in their ASD installation manuals.<sup>2</sup> Figure 3-15 is a preliminary step to establish a conducted emissions signature for this drive. The darker line in Figure 3-15 is the base line measurement with the AC drive off.

**Table 3-14**  
**AC Drive – Sensorless Vector Control**  
**Electric Field Interference Test Results**  
**(electric field measurements in Volts/meter)**

	0.74				0.49	
1.20	ASD	0.61		1.80	Motor	1.63
	0.41				0.67	

<sup>2</sup> In the same way that a transmitting antenna converts electrical energy into RF energy, the inverter-to-motor cable can act as an antenna that radiates electrical energy into space. If the field strength of any radiated energy is higher than can be tolerated by nearby equipment, electromagnetic interference (EMI), leading to malfunction or failure of sensitive electronics, is possible. The more automated the facility, i.e. the more electronic equipment present, the greater the risk of interference. As with RF transmission lines, the RF energy can be easily confined to the cable with a continuous corrugated aluminum shield/armor.

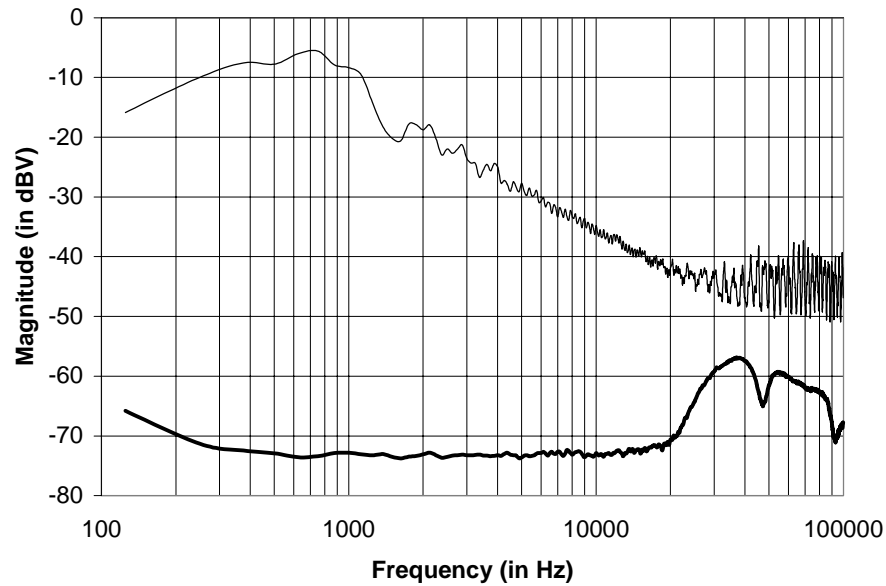


**Figure 3-15**  
**AC Drive – Sensorless Vector Control**  
**Conducted EMI**

Table 3-15 shows that the electric field measurements taken on both the AC drive with Volts/Hz control and motor varied between 0.15 V/m to 1.30 V/m. As previously mentioned, this could be indicative of emerging radiated EMI emissions because the levels are between 0.1V/m to 3.0V/m. Again, AC drive manufacturers strongly recommend in their ASD installation manuals that to protect against EMI/RFI that the user provides motor leads shielding and/or placing drive motor cables in EMT conduit. Figure 3-16 is a preliminary step to establish a conducted emissions signature for this drive. The darker line in Figure 3-16 is the base line measurement with this AC drive off.

**Table 3-15**  
**AC Drive – Volts/Hz Control**  
**Electric Field Interference Test Results**  
**(electric field measurements in Volts/meter)**

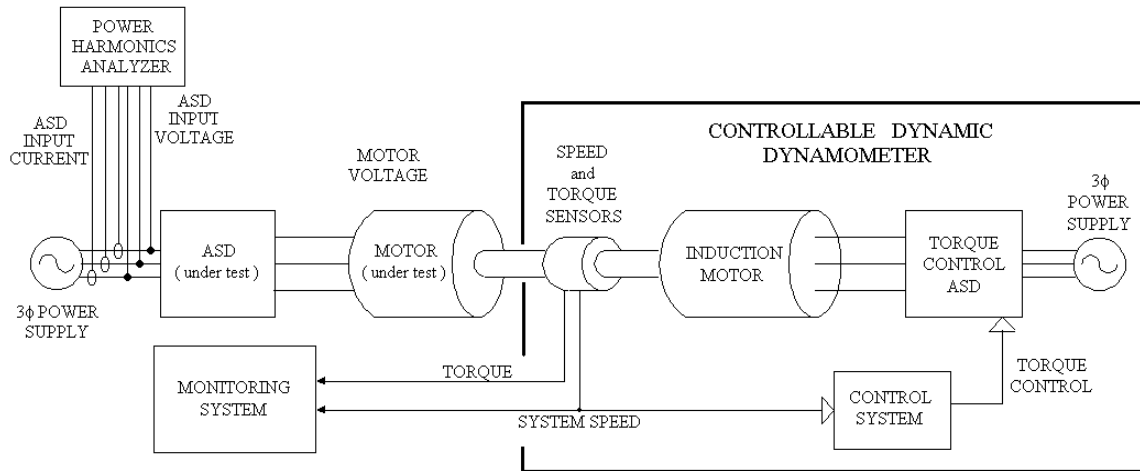
	0.31				0.15	
1.03	ASD	0.44		1.19	Motor	1.30
	0.63				0.55	



**Figure 3-16**  
**AC Drive – Volts/Hz Control Conducted EMI**

**Input Characteristics** – The input rectifiers (AC-to-DC converters) for the AC and DC drives shown in Figures 3-1 and 3-2 are quite different. The DC drive has a three-phase controlled rectifier with the firing angle of the SCRs being the controlled variable. The AC drive has a three-phase uncontrolled rectifier. The diodes conduct when the input voltage exceeds the voltage of the DC link. The differences between controlled and uncontrolled rectifiers produce very different input current waveforms. The currents injected back into the electric service system by each converter produce different harmonic spectrum, current harmonic distortion levels, and power factor measurements. Significant current harmonic distortion can increase system voltage distortion, increase system losses, decrease distribution system equipment life, and increase the likelihood of resonance conditions. Therefore, it is important to understand the effect of ASD loads on the electric service system.

The test setup for the input current harmonics evaluation is shown in Figure 3-17. The Power Harmonics Analyzer was used to measure and calculate the input current harmonics of each ASD. The dynamometer was set to apply a constant torque load to the motor and drive under test. The Monitoring System was used to monitor the load torque of the dynamometer and the speed of the rotating system.



**Figure 3-17**  
**Test Setup for the ASD Input Current Harmonics Measurements**

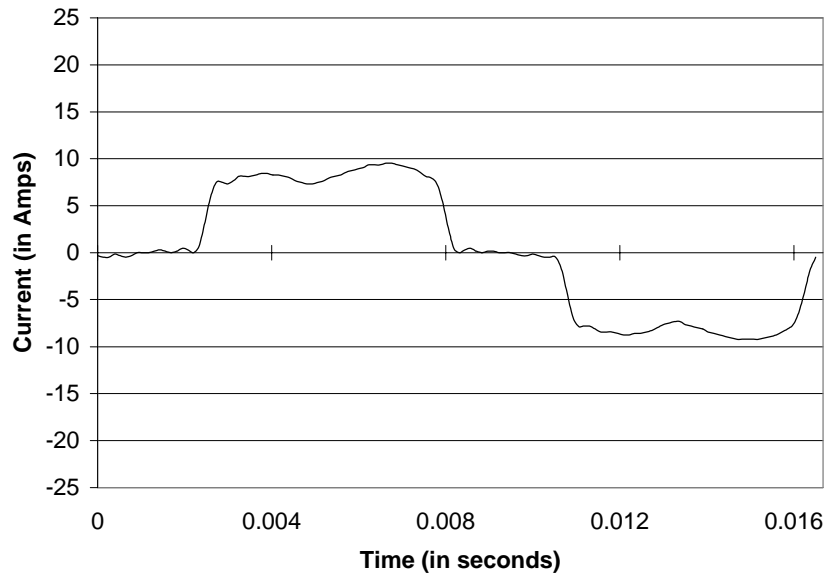
The ASD input current harmonics were recorded at various speed and load torque setpoints. The input current levels, harmonic spectrum, and test data are shown below in Figures 3-18 through 3-25, and Tables 3-16 through 3-19. The figures show the input current waveforms and harmonic spectrum for each drive under the following load conditions:

- Speed = 1800 rpm
- Load Torque = 19.8 N-m
- Load Power = 5 hp

**Table 3-16**  
**DC Drive Input Current Harmonic Test Results**  
**(current measurements shown as rms values)**

Speed (rpm)	Load Torque (N-m)	Load Power (hp)	$I_{rms}$ (Amps)	$I_{THDf}$ (%)	$I_f$ (Amps)	3 <sup>rd</sup> (Amps)	5 <sup>th</sup> (Amps)	7 <sup>th</sup> (Amps)
1800	19.8	5.0	6.91	26.4	6.65	0.25	1.49	0.51
1800	9.9	2.5	3.90	28.0	3.74	0.24	0.95	0.08
900	19.8	2.5	6.85	28.7	6.58	0.31	1.70	0.31
900	9.9	1.25	3.91	33.6	3.69	0.24	1.17	0.15

The data in Table 3-16 shows that the total harmonic distortion (THD) of the input current (based on the fundamental input current,  $I_f$ ) for the DC drive remains relatively constant (i.e. 26.4 to 33.6%) for the four speed, torque, and load power setpoints. The DC drive operates in continuous current mode. This significantly reduces the 5<sup>th</sup> and 7<sup>th</sup> harmonic currents and decreases the THD values.



**Figure 3-18**  
**DC Drive Input Current @ 1800 RPM and 5 HP Load**

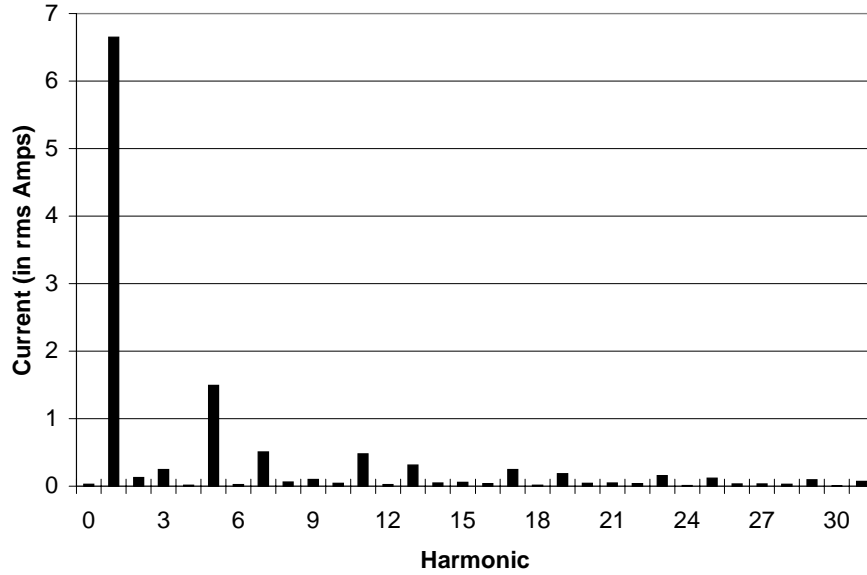
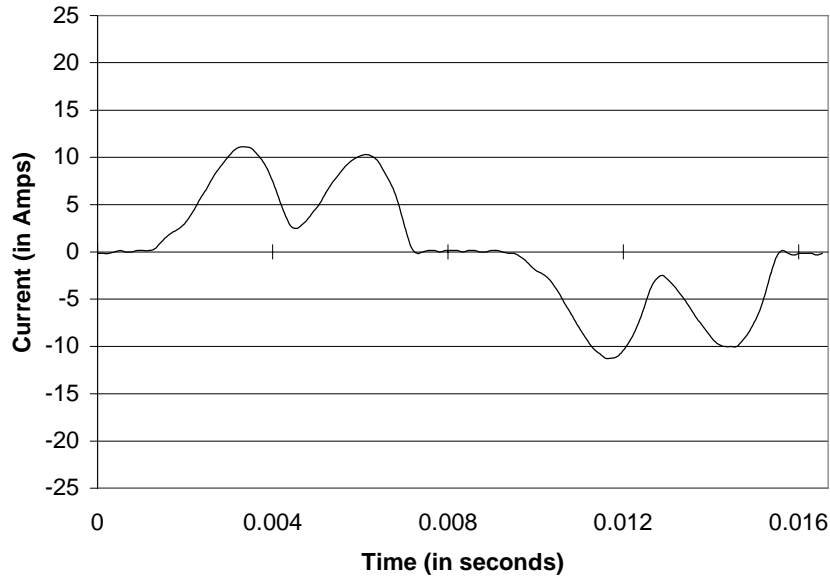


Figure 3-19  
DC Drive Input Current Harmonic Spectrum @ 1800 RPM and 5 HP Load

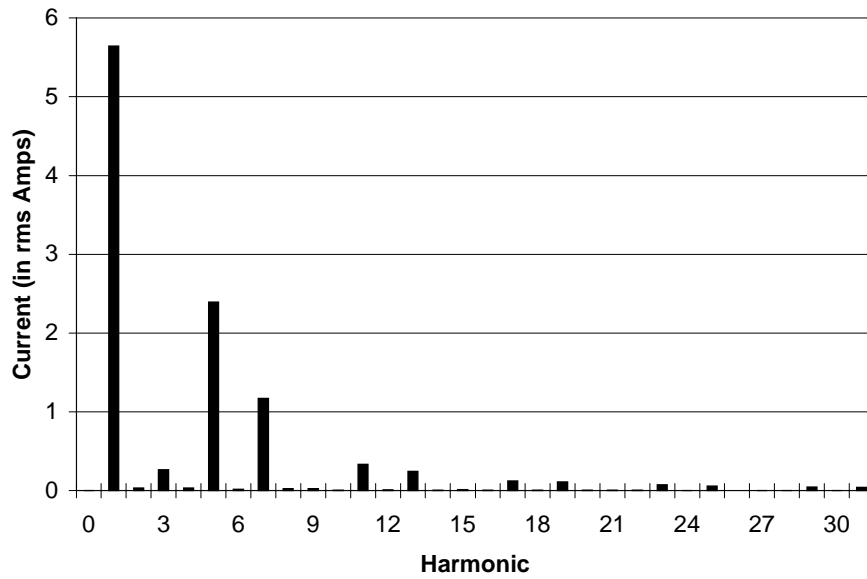
Table 3-17  
AC Drive – Sensorless Vector Control  
Input Current Harmonic Test Results  
(current measurements shown as rms values)

Speed (rpm)	Load Torque (N-m)	Load Power (hp)	$I_{rms}$ (Amps)	$I_{THDf}$ (%)	$I_f$ (Amps)	3 <sup>rd</sup> (Amps)	5 <sup>th</sup> (Amps)	7 <sup>th</sup> (Amps)
1800	19.8	5.0	6.27	48.2	5.64	0.27	2.39	1.17
1800	9.9	2.5	3.34	70.1	2.73	0.25	1.57	1.02
900	19.8	2.5	3.49	68.1	2.72	0.23	1.62	1.03
900	9.9	1.25	1.95	78.6	1.53	0.22	0.93	0.69

The input current waveform of Figure 3-20 suggests that the AC drive with sensorless vector control has input line reactors installed between the input voltage connections and the rectifier. The presence of the input line reactors significantly reduced the 5<sup>th</sup> and 7<sup>th</sup> harmonic currents and the total harmonic current distortion (without the reactors the THD is estimated to be near 120%). From the data in Table 3-17, the total harmonic current distortion increased and the fundamental current ( $I_f$ ) decreased as the load power decreased. The 5<sup>th</sup> and 7<sup>th</sup> harmonic currents decreased as well, but they did not decrease as much as the fundamental current. Thus, the THD percentage of the fundamental current increased. **Note:** The ASD output frequency was adjusted so that the speed of the system was 1800 or 900 rpm to compensate for motor slip.



**Figure 3-20**  
**AC Drive Input Current – Sensorless Vector Control @ 1800 RPM and 5 HP Load**

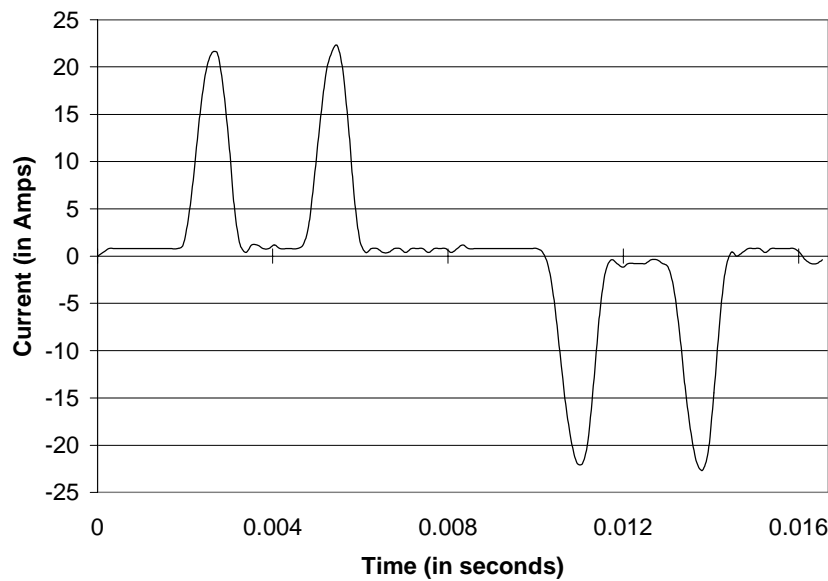


**Figure 3-21**  
**AC Drive Input Current Harmonic Spectrum –**  
**Sensorless Vector Control @ 1800 RPM and 5 HP Load**

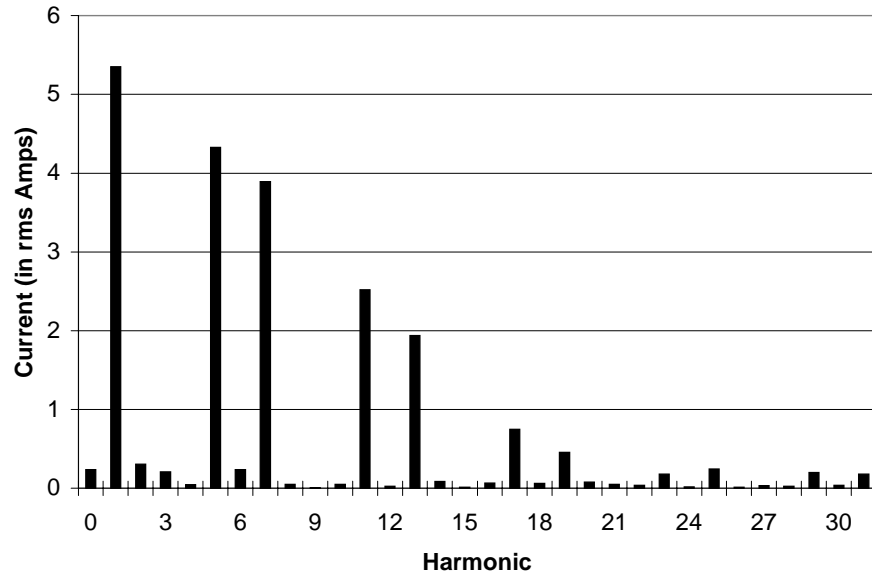
**Table 3-18**  
**AC Drive – Volts/Hz Control**  
**Input Current Harmonic Test Results**  
 (current measurements shown as rms values)

Speed (rpm)	Load Torque (N-m)	Load Power (hp)	$I_{rms}$ (Amps)	$I_{THDf}$ (%)	$I_f$ (Amps)	3 <sup>rd</sup> (Amps)	5 <sup>th</sup> (Amps)	7 <sup>th</sup> (Amps)
1800	19.8	5.0	8.64	125.6	5.35	0.21	4.33	3.89
1800	9.9	2.5	4.80	141.6	2.75	0.01	2.28	2.13
900	19.8	2.5	4.77	139.1	2.76	0.11	2.26	2.10
900	9.9	1.25	2.72	146.5	1.52	0.05	1.22	1.16

The waveform of Figure 3-22 shows the typical input current waveform for an AC drive with an uncontrolled rectifier and without a DC link reactor or input line reactors. Figure 3-23 represents this drive’s input current harmonic spectrum. From the data in Table 3-18, one can see that the total harmonic current distortion increased and the fundamental current ( $I_f$ ) decreased as the load power decreased. The addition of a DC link reactor or input line reactors would significantly decrease the current distortion of the 5<sup>th</sup> and 7<sup>th</sup> harmonic currents. A 3% line reactor was installed at the input terminals of the drive. Figures 3-24 and 3-25, and Table 3-19 show the results of the 100% speed and load torque setpoint. **Note:** The ASD output frequency was adjusted so that the speed of the system was 1800 or 900 rpm to compensate for the motor slip.



**Figure 3-22 AC Drive Input Current – Volts/Hz Control @ 1800 RPM and 5HP Load**

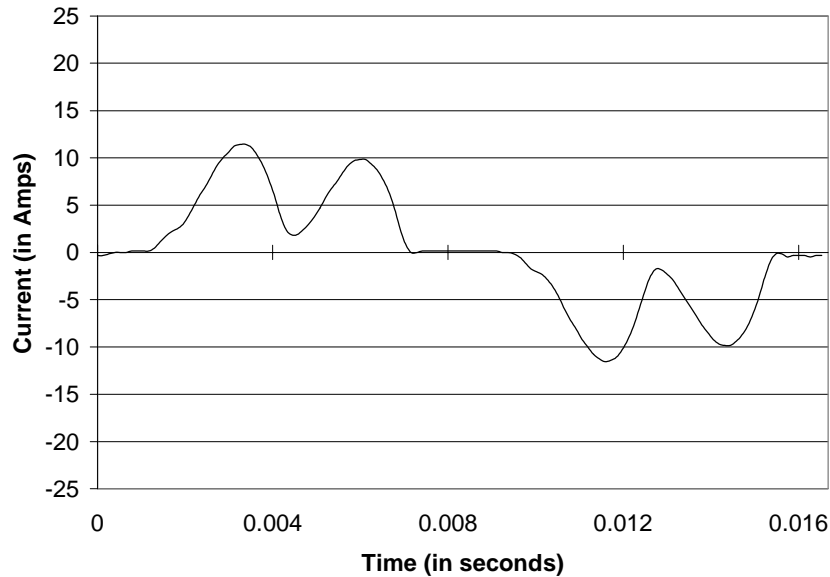


**Figure 3-23**  
**AC Drive Input Current Harmonic Spectrum – Volts/Hz Control @ 1800 RPM and 5 HP Load**

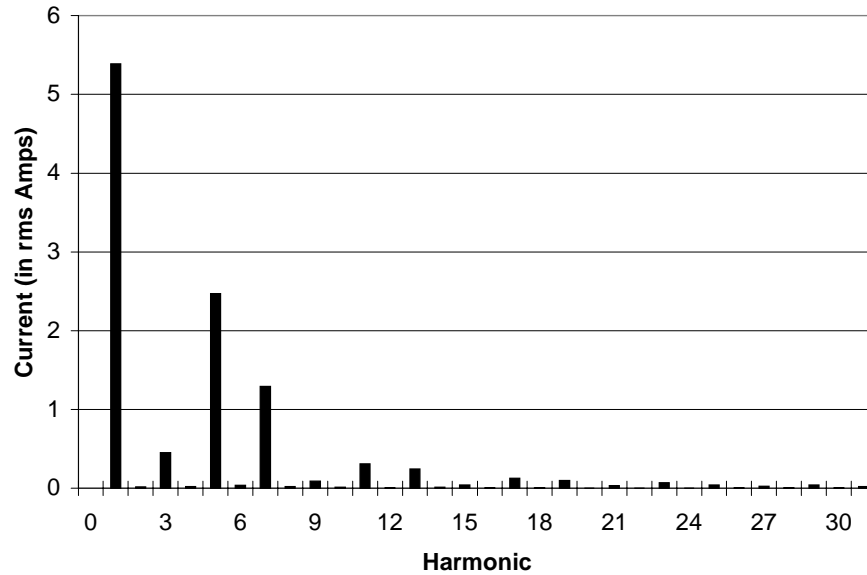
**Table 3-19**  
**AC Drive – Volts/Hz Control (with 3% line reactor)**  
**Input Current Harmonic Test Results**  
 (current measurements shown as rms values)

Speed (rpm)	Load Torque (N-m)	Load Power (hp)	$I_{rms}$ (Amps)	$I_{THDf}$ (%)	$I_f$ (Amps)	3 <sup>rd</sup> (Amps)	5 <sup>th</sup> (Amps)	7 <sup>th</sup> (Amps)
1800	19.8	5.0	6.11	53.14	5.39	0.45	2.47	1.29

With the addition of the 3% line reactor, the THD of the input RMS current and the 5<sup>th</sup> and 7<sup>th</sup> harmonic currents were significantly reduced. These results were similar to the sensorless vector control AC drive (see Figures 3-20 and 3-21, and Table 3-17).



**Figure 3-24**  
**AC Drive Input Current – Volts/Hz Control**  
**@ 1800 RPM and 5 HP Load (with 3% line reactor)**



**Figure 3-25**  
**AC Drive Input Current Harmonic Spectrum – Volts/Hz Control**  
**@ 1800 RPM and 5 HP Load (with 3% line reactor)**

**Output Characteristics** – In the early days of AC drives, motor control techniques employed by AC drive manufacturers were not as sophisticated as they are today. With improvement in power semiconductor switch capabilities, namely IGBTs, and improvement in microprocessor speeds, advanced motor control techniques are possible. PWM is the most common type of inverter used in low-voltage (<600V) AC drive applications. The ultra-fast switch capabilities of the IGBT make PWM inverters possible. With PWM inverters, motors can be made to operate with higher efficiency and lower torque pulsations.

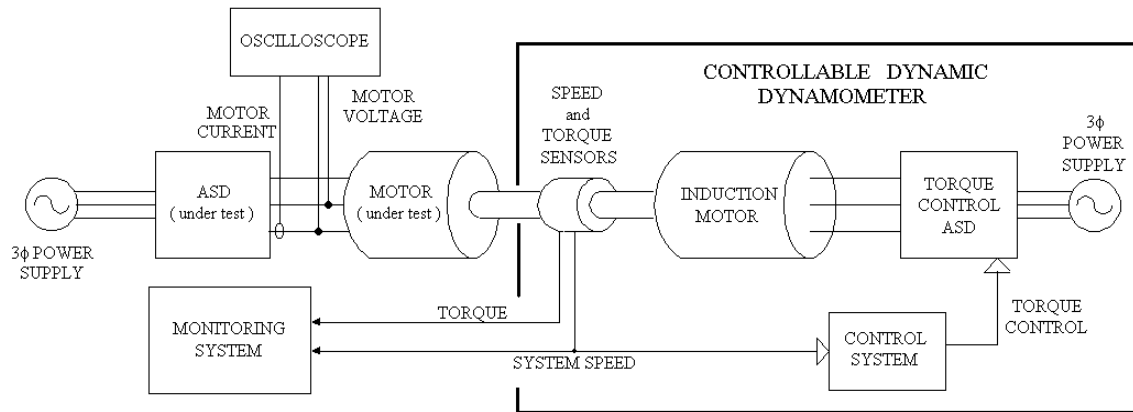
Motor insulation requirements, motor temperature, resonance conditions, stator winding requirements, and motor bearing life are all functions of the output characteristics of AC drives. The output characteristics depend on several factors:

1. Control Technique (Volts/Hz, vector control, etc.)
2. Inverter Control (six-step, pulse-width modulation, etc.)
3. Modulation Index
4. Modulation Waveform (sinusoidal, space vector, etc.)

## 5. Switching Frequency

## 6. Motor Reactances

The test setup for the output characterization of the three drive topologies is shown in Figure 3-26.



**Figure 3-26**  
**Test Setup for the ASD Output Current Harmonics Evaluation**

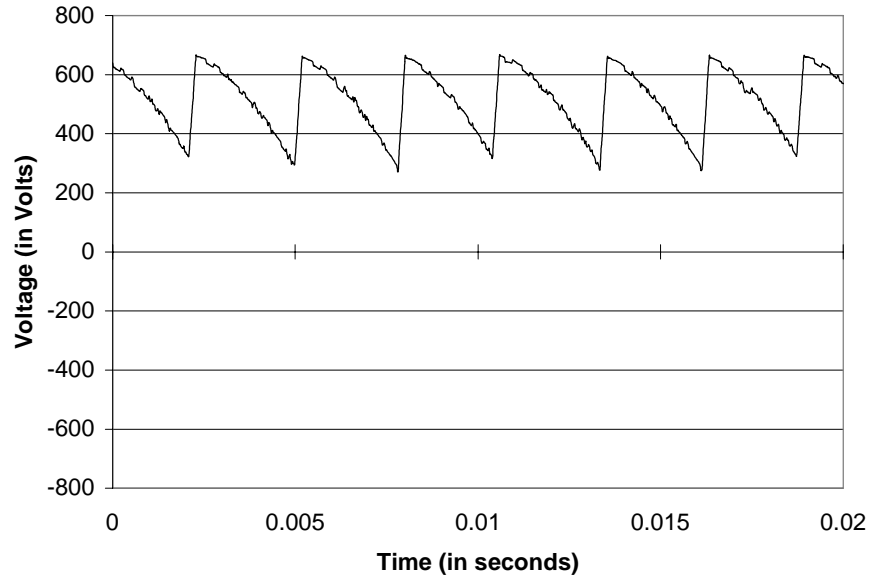
For the three drive systems tested, output current harmonics were documented at various speed and load torque setpoints. The output voltage and current waveforms, current harmonic spectrum, and test data are shown below in Figures 3-27 through 3-34, and Tables 3-20 through 3-22. The figures show the output voltage and current waveforms and current harmonic spectrum for each drive under the following load conditions:

- Speed = 1800 rpm
- Load Torque = 19.8 N-m
- Load Power = 5 hp

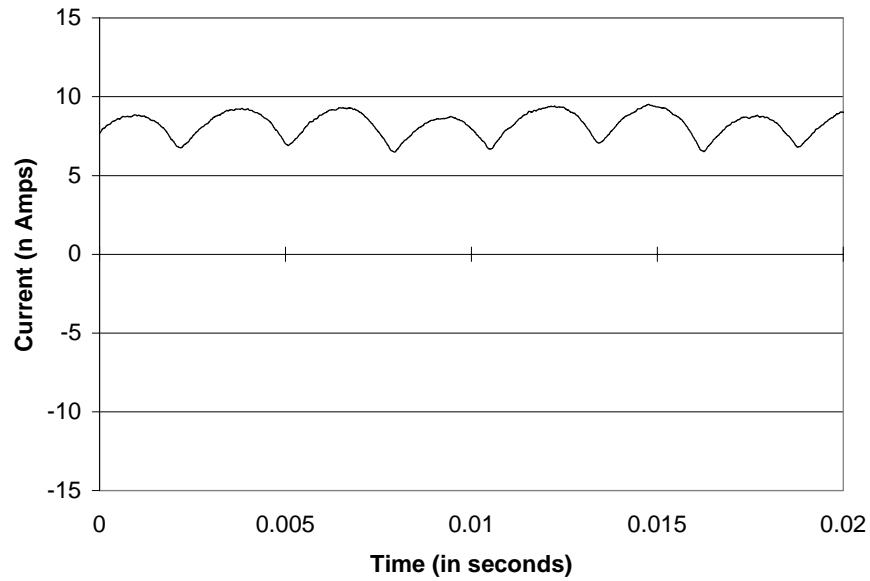
**Table 3-20**  
**DC Drive Output Current Harmonic Test Results**  
 (current measurements shown as rms values)

Speed (RPM)	Load Torque (N-m)	Load Power (HP)	V <sub>A</sub> (RMS)	V <sub>A</sub> (DC)	I <sub>A</sub> (RMS)	I <sub>A</sub> (DC)	FF <sub>V</sub>	RF <sub>A</sub>	FF <sub>A</sub>	RF <sub>A</sub>
1800	19.8	5.0	525	510	8.34	8.30	1.03	0.24	1.01	0.10
1800	9.9	2.5	514	497	4.61	4.51	1.03	0.26	1.02	0.26
900	19.8	2.5	333	279	8.28	8.18	1.19	0.65	1.01	0.16
900	9.9	1.25	318	258	4.42	4.22	1.23	0.72	1.05	0.31

Unlike AC drives, DC drives do not have inverters. The output current and voltage of DC drives is quite different. Thus, the same terminology cannot be applied to both when describing their output parameters. The form factor (FF) and the ripple factor (RF) are measurement quantities used to describe the output voltage and current of the DC drive. The form factor is a measurement of the shape of the output current and voltage. FF is computed by dividing the rms value of the current or voltage by the dc value of the current or voltage, respectively. The ripple factor is a measure of the ripple content of the waveform. The ripple factor is computed by taking the square root of the FF squared minus one. Table 3-20 contains the test results for the DC drive. As expected, the FF and RF data for the motor current was lower for the high load torque conditions compared to the low torque conditions for the same speed setpoints.



**Figure 3-27**  
**DC Drive Output Voltage @ 1800 RPM and 5 HP Load**

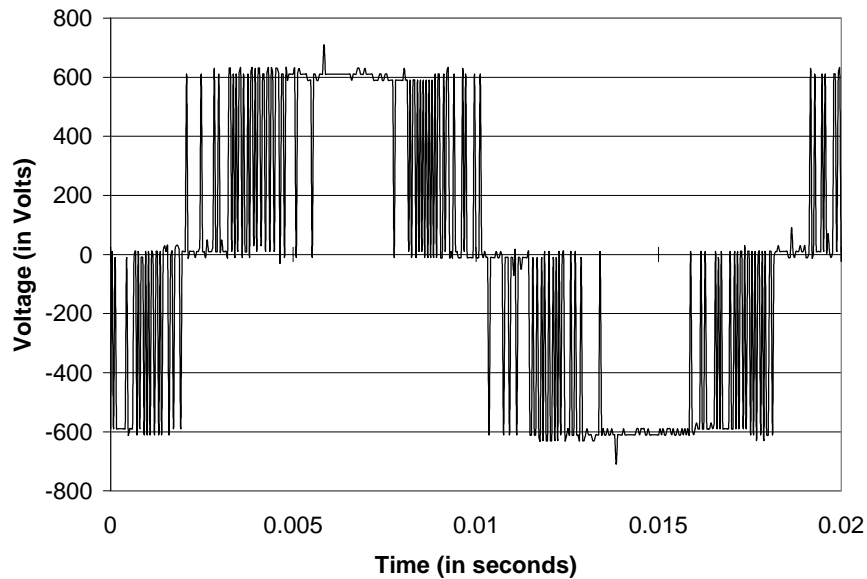


**Figure 3-28**  
**DC Drive Output Current @ 1800 RPM and 5 HP Load**

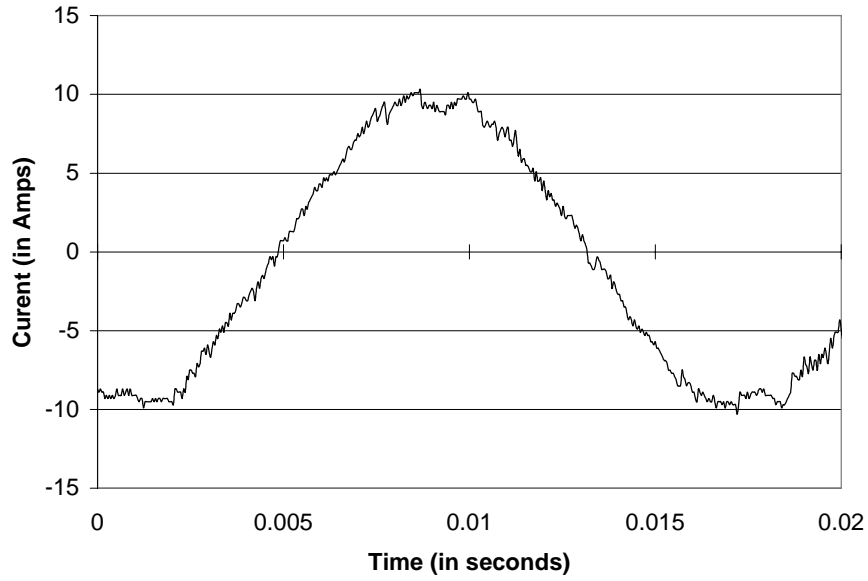
**Table 3-21**  
**AC Drive – Sensorless Vector Control**  
**Output Current Harmonic Test Results**  
 (current measurements shown as rms values)

Speed (RPM)	Load Torque (N-m)	Load Power (hp)	$I_{rms}$ (Amps)	$I_{THDf}$ (%)	$I_f$ (Amps)	3 <sup>rd</sup> (Amps)	5 <sup>th</sup> (Amps)	7 <sup>th</sup> (Amps)
1800	19.8	5.0	6.92	3.45	6.86	0.06	0.1	0.15
1800	9.9	2.5	4.3	3.87	4.21	0.03	0.05	0.09
900	19.8	2.5	6.45	1.45	6.45	0.04	0.02	0.02
900	9.9	1.25	4.2	1.89	4.20	0.02	0.01	0.01

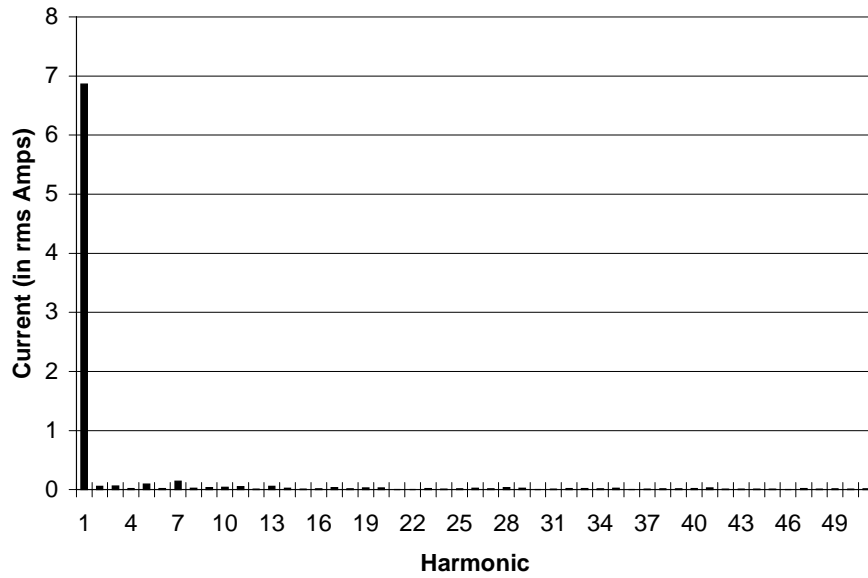
Table 3-21 contains the test results for the AC sensorless vector control drive. The data shows low levels of current harmonic distortion at all load levels tested. Low level harmonic content at the 5<sup>th</sup> and 7<sup>th</sup> harmonics suggest that torque pulsation produced by these harmonics will have little effect on the system. In addition, the harmonic spectrum of Figure 3-29 shows low harmonic content at integer frequencies through the 50<sup>th</sup> harmonic. **Note:** The switching frequency of this ASD was listed as 3 kHz (average).



**Figure 3-29**  
**AC Drive Output Voltage – Sensorless Vector Control**  
**@ 1800 RPM and 5 HP Load**



**Figure 3-30**  
**AC Drive Output Current – Sensorless Vector Control**  
**@ 1800 RPM and 5 HP Load**

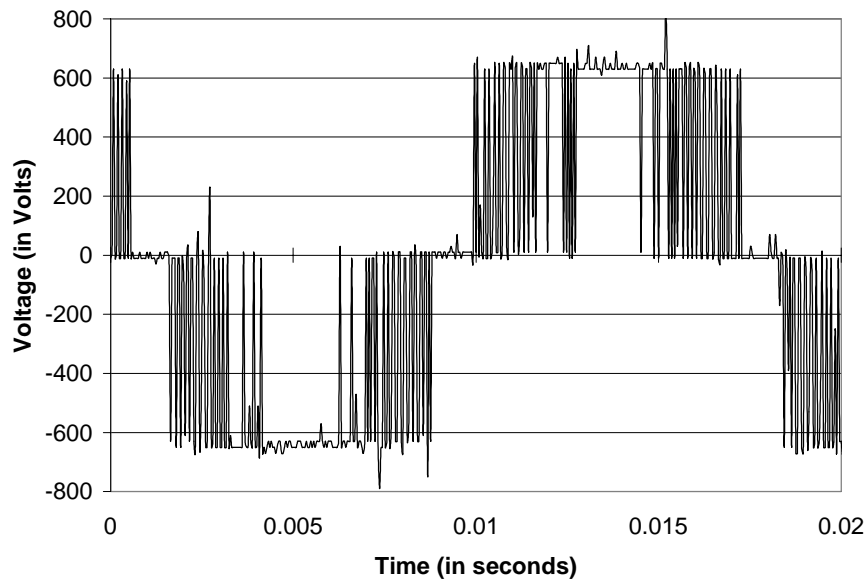


**Figure 3-31**  
**AC Drive Output Current Harmonic Spectrum –**  
**Sensorless Vector Control @ 1800 RPM and 5 HP Load**

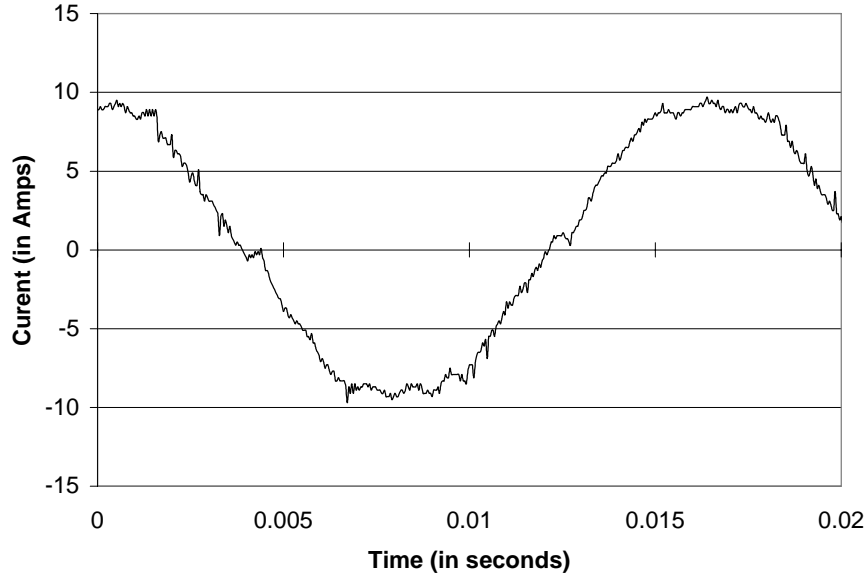
Table 3-22 contains the test results for the AC Volts/Hz control drive. The data shows low levels of current harmonic distortion at all load levels tested. Low level harmonic content at the 5<sup>th</sup> and 7<sup>th</sup> harmonics suggest that torque pulsation produced by these harmonics will have little effect on the system. In addition, the harmonic spectrum of Figure 3-32 shows low harmonic content at integer frequencies through the 50<sup>th</sup> harmonic. **Note:** The switching frequency of this ASD was set at 3 kHz.

**Table 3-22**  
**AC Drive – Volts/Hz Control**  
**Output Current Harmonic Test Results**  
**(current measurements shown as rms values)**

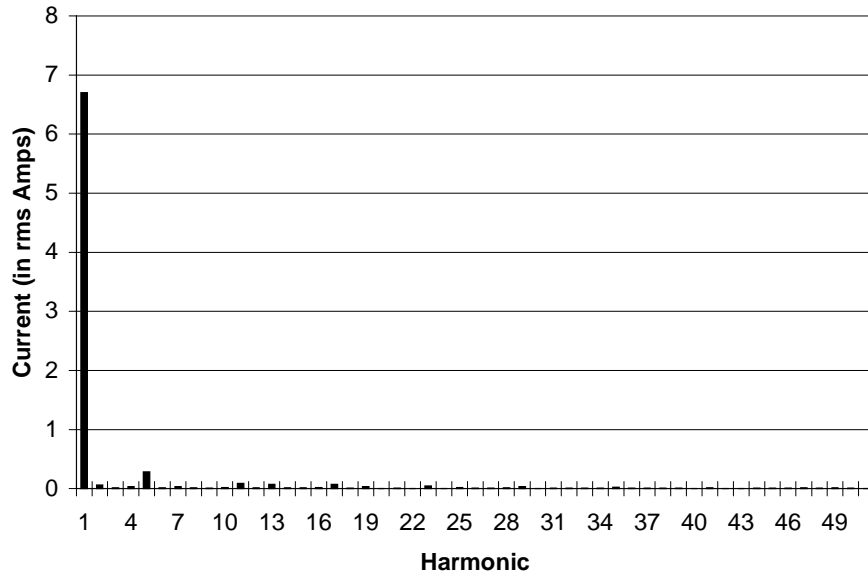
Speed (RPM)	Load Torque (N-m)	Load Power (HP)	$I_{rms}$ (Amps)	$I_{THD f}$ (%)	$I_f$ (Amps)	3 <sup>rd</sup> (Amps)	5 <sup>th</sup> (Amps)	7 <sup>th</sup> (Amps)
1800	19.8	5.0	6.70	5.02	6.65	0.01	0.28	0.04
1800	9.9	2.5	4.16	7.71	4.14	0.04	0.25	0.07
900	19.8	2.5	6.89	3.83	6.89	0.05	0.17	0.05
900	9.9	1.25	4.03	5.07	4.30	0.03	0.14	0.04



**Figure 3-32**  
**AC Drive Output Voltage – Volts/Hz Control @ 1800 RPM and 5 HP Load**



**Figure 3-33**  
**AC Drive Output Current – Volts/Hz Control @ 1800 RPM and 5 HP Load**



**Figure 3-34**  
**AC Drive Output Current Harmonic Spectrum – Volts/Hz Control @ 1800 RPM and 5 HP Load**

**Power Factor** – The typical ASD, with 6-pulse input rectifier, is considered a nonlinear load. Nonlinear loads draw non-linear current from the electric service system. The nonlinear current waveforms may cause significant voltage distortion in “soft” electric service sources. Generally, voltage distortion and nonlinear currents increase system losses and reduce power factor.

Power factor can be described by three quantities: displacement power factor, distortion power factor, and true power factor. The displacement power factor is the ratio of the total fundamental power (in kW) divided by the product of the fundamental voltage and fundamental current. The distortion power factor is the inverse of the square root of the current total harmonic distortion ( $I_{\text{THD}}$  based on the fundamental current) squared plus one. The true power factor is the displacement power factor times the distortion power factor.

The displacement power factor for AC drives with uncontrolled rectifiers is near unity when fed from a “stiff” electricity source. This is not the case for DC drives with controlled rectifiers. The displacement power factor for DC drives varies with the speed of the motor. At reduced speed, the displacement power factor is quite low. The opposite is true at higher motor speed.

DC drives often operate in continuous current mode because of the ac line and/or dc link reactances that are inherent in their application. One advantage of continuous current mode is the reduction of harmonic currents drawn by the drive. This reduces the harmonic distortion of the current and increases the distortion power factor. DC drives operate with significantly higher distortion power factor levels than AC drives with uncontrolled rectifiers at reduced load torque conditions. However, for DC drives the true power factor is low because a low displacement power factor offsets a high distortion power factor at reduced speed conditions regardless of load torque.

The test setup for the power factor evaluations was the same setup used for the steady-state voltage unbalance evaluations. It can be seen in Figure 3-3. The Power Harmonics Analyzer was used to measure total harmonic current distortion and the displacement power factor for each ASD at four load points. The Monitoring System was used to monitor the load torque of the dynamometer and the speed of the rotating system. The dynamometer was set to produce a constant load torque to the motor and drive under test. The test results can be found in Tables 3-23, 3-24, and 3-25. The tables contain the load torque (in N-m) and speed (in rpm) setpoints, the load power (in horsepower), the current harmonic distortion ( $I_{\text{THD}}$  as a percent of the fundamental), the displacement power factor (dpf), and the true power factor (pf).

**Table 3-23**  
**DC Drive Power Factor Test Results**

Speed (rpm)	Load Torque (N-m)	Load Power (hp)	$I_{THDf}$ (%)	d <sub>pf</sub>	pf
1800	19.9	5	26.4	0.82	0.79
1800	9.9	2.5	28.0	0.78	0.75
900	19.9	2.5	28.7	0.48	0.46
900	9.9	1.25	33.6	0.46	0.44

Table 3-23 contains the test results for the DC drive. As expected, the current distortion remains relatively constant for all load torque and speed setpoints. The displacement power factor decreases as the speed of the system decreases. The true power factor follows the same trend since it is a function of the displacement power factor.

The addition of power factor correction capacitors is a method often used to correct the displacement power factor at facilities with large numbers of DC drives. Since the DC drives are non-linear loads, the power factor correction capacitors must be configured as harmonic filters. Properly designed and applied, the harmonic filters can reduce the effects of harmonic resonance, voltage distortion, and transient voltage magnification.

**Table 3-24**  
**AC Drive – Sensorless Vector Control**  
**Power Factor Test Results**

Speed (rpm)	Load Torque (N-m)	Load Power (hp)	$I_{THD}$ (%)	d <sub>pf</sub>	pf
1800	19.9	5	48.2	0.98	0.88
1800	9.9	2.5	70.1	0.96	0.79
900	19.9	2.5	68.1	0.95	0.79
900	9.9	1.25	78.6	0.96	0.75

Table 3-24 contains the test results for the AC sensorless vector control drive. The effect of the input line reactors in this drive can be seen in the displacement and true power factor data. Normally, the displacement power factor for AC drives fed from “stiff” electric service supplies is near unity. For this AC drive, the displacement power factor was less than unity. The input line reactors shifted the fundamental current slightly out

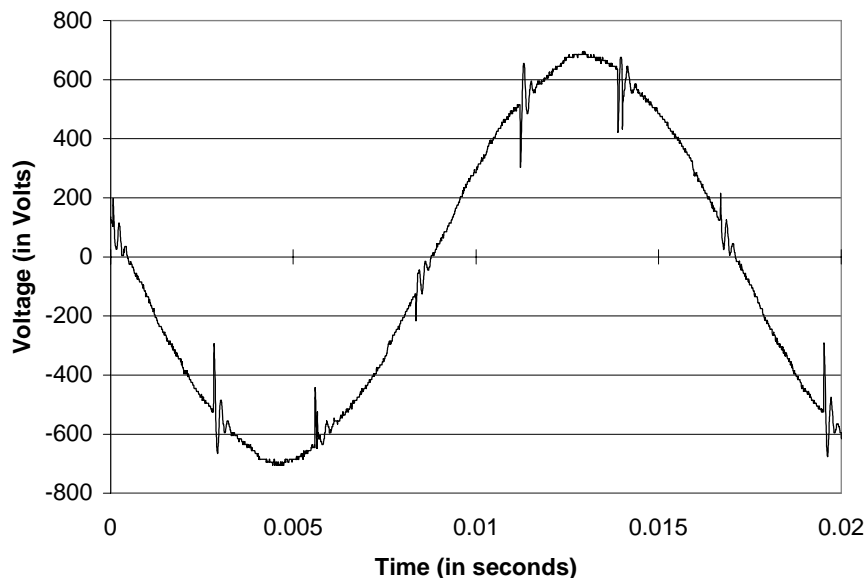
of phase with fundamental voltage. At higher load power conditions, the current distortion was significantly reduced, which improved the true power factor. At low load power conditions, the input line reactors had a reduced effect on true power factor.

**Table 3-25**  
**AC Drive – Volts/Hz Control Power Factor Test Results**

Speed (rpm)	Load Torque (N-m)	Load Power (hp)	$I_{THD}$ (%)	d <sub>pf</sub>	pf
1800	19.9	5	125.6	1.00	0.67
1800	9.9	2.5	141.6	0.99	0.65
900	19.9	2.5	139.1	0.98	0.64
900	9.9	1.25	146.5	0.99	0.64

Table 3-25 contains the test results for the AC Volts/Hz control drive. As mentioned previously, this drive had no input line reactors and its input AC to DC converter was an uncontrolled rectifier. As expected, the current distortion was high and the true power factor was low for all load power conditions. The displacement power factor was near unity for all load conditions. The addition of input line reactors would improve the true power factor of this drive.

**Voltage Notching** – Large DC drives, with SCR-controlled rectifiers, may interfere with other electronic loads, which are connected to the same distribution system. The cause of the problem, voltage notching, occurs when the DC drive begins to transfer current from one phase to another phase. The source reactance prevents instantaneous transfer. As an SCR in an adjacent phase begins to conduct, the commutation time (angle) causes a shorting action across two phases when two SCRs are conducting simultaneously. There is period of reduced voltage until one SCR successfully commutates. Once the SCR commutates, there is a subsequent voltage overshoot due to any circuit stray inductance. The voltage notches can create multiple zero crossings, which can interfere with clocks, phase-angle control welders, and other equipment with controls that utilize zero cross timing circuits. The repetitive overshoots can shorten the life of surge protection devices such as MOVs. Figure 3-35 is an oscilloscope snapshot taken of the voltage notching created by the DC drive system under no-load conditions.



**Figure 3-35**  
**Voltage Notching of the DC Drive**

The depth and overshoot of the voltage notch seen by other loads connected to the same distribution service is a function of the impedance of the connected system between the DC drive and the load. The depth and overshoot will be significantly less when there is sufficient impedance to dampen the effects. Other means for mitigating “notching and overshooting” voltages may be required for “stiff” systems. The addition of input line reactors to the DC drive may have reduced the notch depth and overshoot. Sometimes, even the impedance of line reactors is not sufficient. A simple low-pass RC filter, connected between each of the phases and upstream of the line reactor, may be needed to reduce the notch depth and overshoot to meet the specific application’s requirements.<sup>3</sup>

This chapter presented the system compatibility tests and results, which serve as a means to characterize some of the utility and motor interface compatibility issues often faced by application, utility, and process engineers in new and existing ASD applications. The next chapter presents the performance evaluation tests and results, which serve to document the control performance characteristics of the three representative ASD systems.

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<sup>3</sup> Refer to IEEE 519-1992 *Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems* for guidelines and limits on “notching” in low-voltage systems.



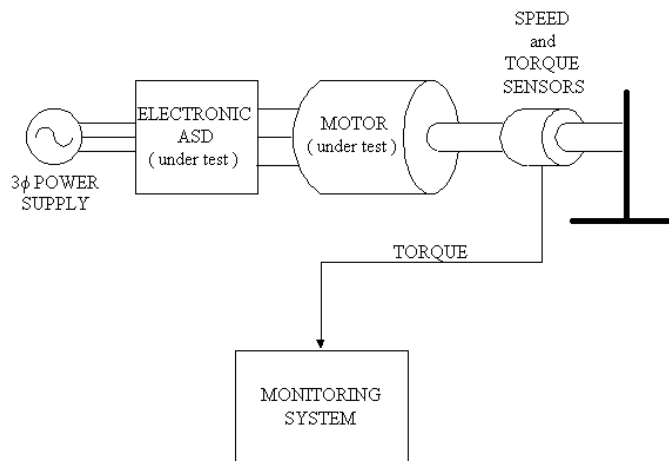
# 4

## PERFORMANCE ISSUES FOR AC AND DC DRIVES

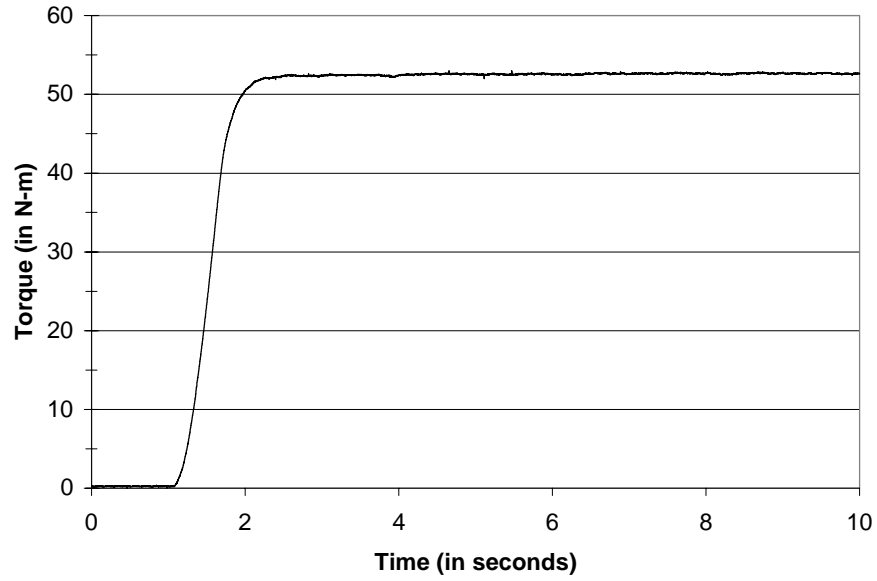
In the past, DC drive systems were chosen over AC drive systems for applications requiring high starting torque, precise speed regulation, or high torque at low speeds. AC drive systems are now being used in many of these applications due to the evolution of the high-performance AC drive. The new generation AC drives systems can achieve many of the same performance characteristics of DC drives systems. The following performance evaluation tests characterize the starting torque, speed regulation, low-speed high-torque control, and the system efficiencies of the three ASD/motor combinations.

### 4.1 Starting Torque

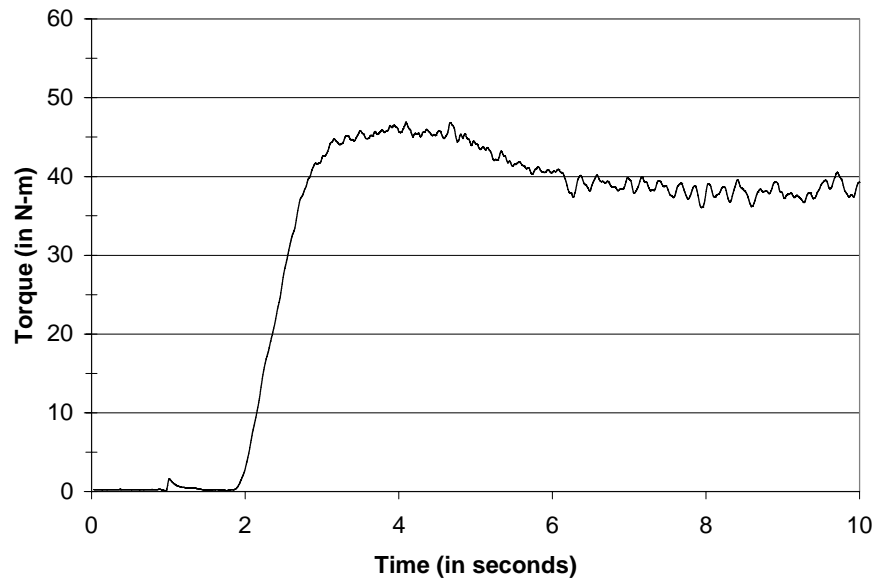
The test setup for the starting torque evaluation test can be seen in Figure 4.1. A rigid steel plate was inserted between the dynamometer and the torque sensor. The steel plate was designed to lock the rotor of the motor under test. The ASDs were programmed to allow maximum motor current and starting torque. The ASDs were started and the torque was measured. The test results for the three ASD systems can be seen in Figures 4-2, 4-3, and 4-4.



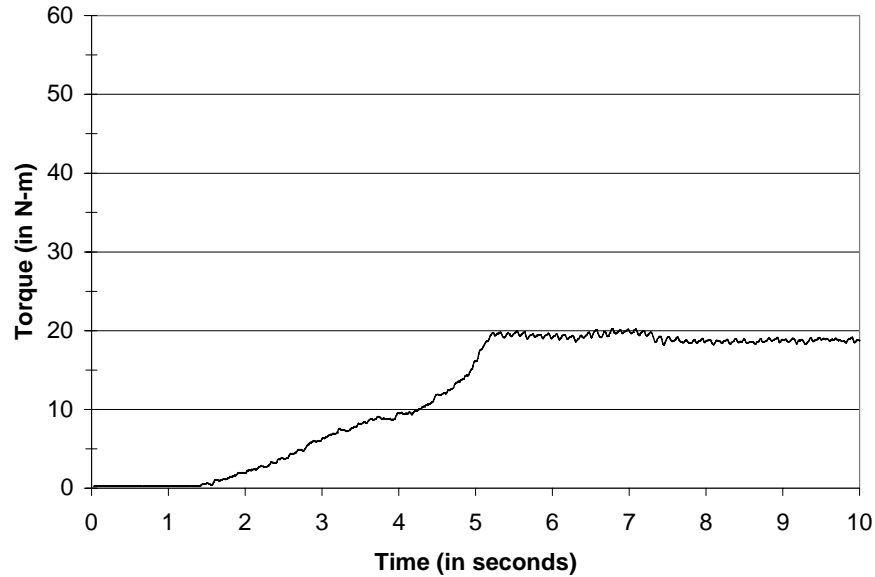
**Figure 4-1**  
**Test Setup for the Starting Torque Evaluation**



**Figure 4-2**  
**DC Drive Starting Torque**  
**Maximum Starting Torque = 52.4 N-m (256% of full-load torque)**



**Figure 4-3**  
**AC Drive – Sensorless Vector Control Starting Torque**  
**Maximum Starting Torque = 47.4 N-m (231% of full-load torque)**



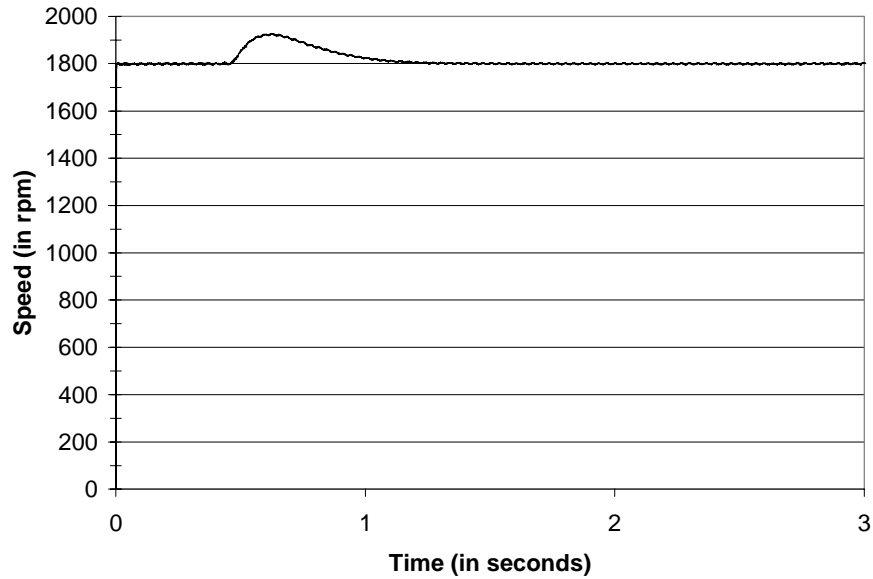
**Figure 4-4**  
**AC Drive – Volts/Hz Control Starting Torque**  
**Maximum Starting Torque = 20.1 N-m (98% of full-load torque)**

## 4.2 Speed Regulation

The test setup for the speed regulation evaluation test was the same setup that was used in the ASD voltage sag response evaluation tests. That setup was pictured in Figure 3-4. The speed regulation was broken down into four separate tests. Two tests were performed at 1800 rpm while the other two were performed at 450 rpm. The tests were designed to characterize the ability of each drive system to maintain a constant system speed during load step changes. At each speed, the load stepped from no-load to full-load for one test and from full-load to no-load for another test. The test results for the three ASD systems can be seen in Tables 4-1, 4-2, and 4-3 and Figures 4-5, 4-6, and 4-7. The figures depict the test results for a step load change from full-load to no-load at 1800 rpm. **Note:** The Volts/Hz control ASD had no programming features that permit operation of the load at constant speed during step load changes.

**Table 4-1**  
**DC Drive Speed Regulation Test Results**

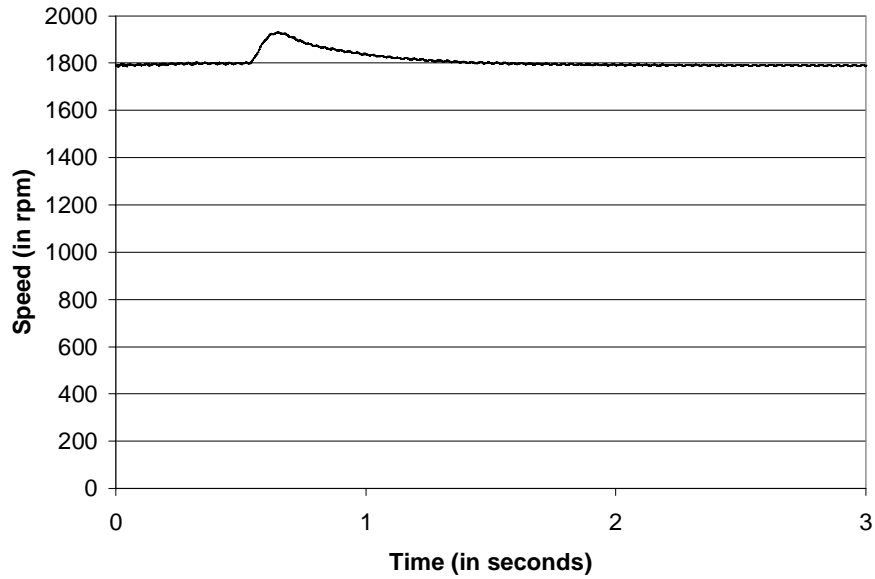
$\Delta$ Load		Constant Speed Setpoint (RPM)	$\Delta$ Speed (RPM)
From	To		
100%	0%	1800	+125
0%	100%	1800	-131
100%	0%	450	+133
0%	100%	450	-132



**Figure 4-5**  
**DC Drive Speed Regulation @  $\Delta$ 100% to 0%**

**Table 4-2**  
**AC Drive – Sensorless Vector Control**  
**Speed Regulation Test Results**

$\Delta$ Load		Constant Speed Setpoint (RPM)	$\Delta$ Speed (RPM)
From	To		
100%	0%	1800	+ 132
0%	100%	1800	- 131
100%	0%	450	+ 126
0%	100%	450	- 123



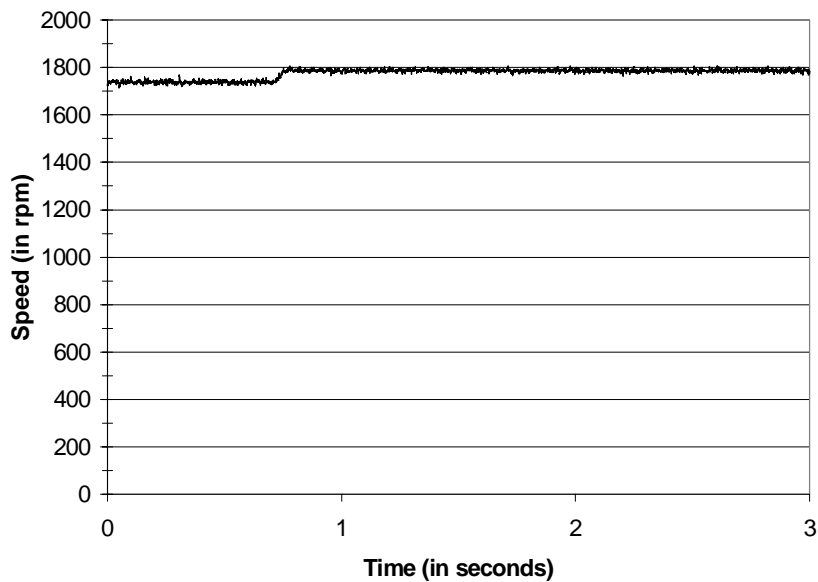
**Figure 4-6**  
**AC Drive Speed Regulation – Sensorless Vector Control @  $\Delta$  Load 100% to 0%**

**Table 4-3**  
**AC Drive – Volts/Hz Control**  
**Speed Regulation Test Results**

Δ Load		Frequency Setpoint (Hz)	Δ Speed (rpm)
From	To		
100%	0%	60 <sup>(2)</sup>	+ 47 <sup>(1)</sup>
0%	100%	60 <sup>(2)</sup>	- 46 <sup>(1)</sup>
100%	0%	15 <sup>(2)</sup>	+ 82 <sup>(1)</sup>
0%	100%	15 <sup>(2)</sup>	- 85 <sup>(1)</sup>

Notes: <sup>(1)</sup> The Volts/Hz control ASD had no programming features that permit operation of the load at constant speed during step load changes.

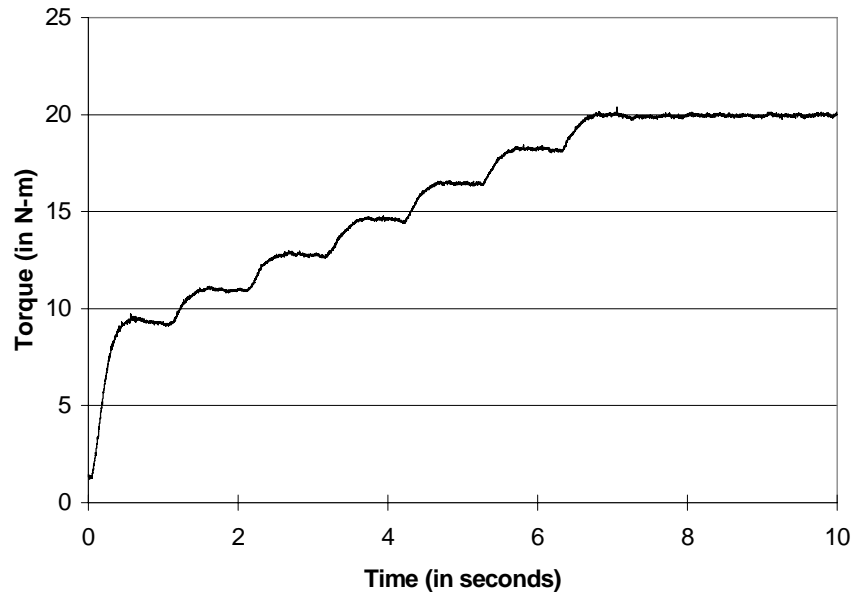
<sup>(2)</sup> Frequency setpoint in cycles per second.



**Figure 4-7**  
**AC Drive Speed Regulation – Volts/Hz Control @ Δ Load 100% to 0%**

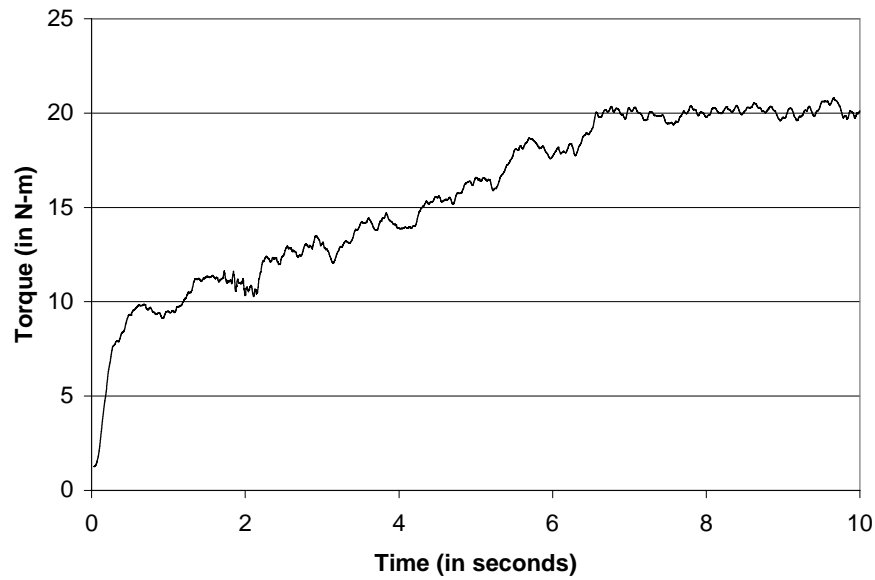
### 4.3 Low-Speed High-Torque Control

The test setup for the low-speed high-torque evaluation test was the same setup that was used in the ASD voltage sag response evaluation tests. That setup was pictured in Figure 3-4. This test was designed to characterize the output torque capability of each ASD at low operating speeds. The minimum (continuous) operating output frequency of the Volts/Hz control ASD was 6 Hz ( $\approx$  180 rpm). Thus, each ASD was started and set to operate at 6 Hz or 180 RPM. The controllable dynamic dynamometer was programmed to increase the load torque on the motor by 10% every second until the load torque reached full-load. The test results for the three ASD systems can be seen in Figures 4-8, 4-9, and 4-10.



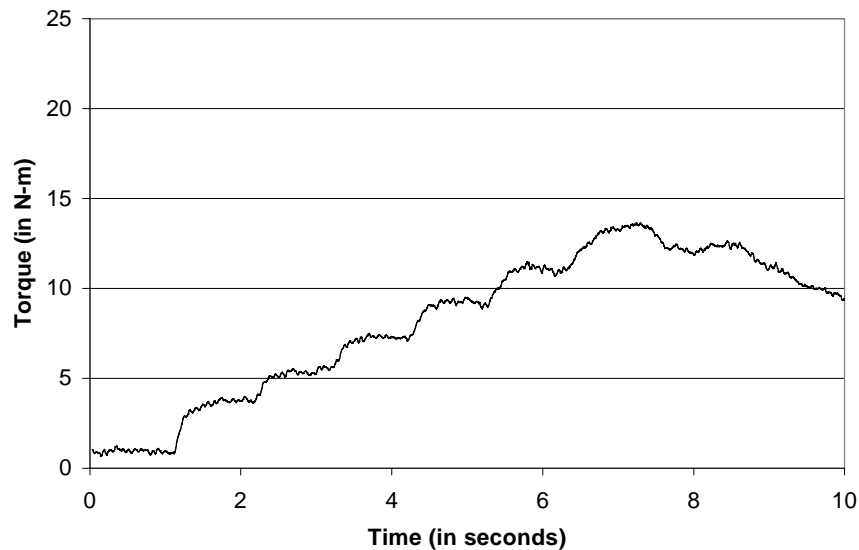
**Figure 4-8**  
**DC Drive - Low-speed Torque Control @ 10% Steps per Second**

Figure 4-8 shows the results of the low-speed high-torque control capability of the DC drive system. These results indicate that the ASD/motor combination was able to deliver continuous full-load torque to the load at 180 rpm. **Note:** The initial load torque was 40% of full-load torque and increased by 10% to the full-load torque setpoint.



**Figure 4-9**  
**AC Drive – Sensorless Vector Control**  
**Low-speed Torque Control @ 10% Steps per Second**

Figure 4-9 shows the results of the low-speed high-torque control capability of the AC sensorless control drive system. These results show that the ASD/motor combination was able to deliver continuous full-load torque to the load at 180 rpm. **Note:** The initial load torque was 40% of full-load torque and increased by 10% to the full-load torque setpoint.



**Figure 4-10**  
**AC Drive – Volts/Hz Control**  
**Low-speed Torque Control @ 10% Steps per Second**

Figure 4-10 shows the results of the low-speed high-torque control capability of the AC Volts/Hz control drive system. These results show that the ASD/motor combination was **not** able to deliver continuous full-load torque to the load at 180 rpm. The Volts/Hz control ASD was only able to apply 60% of full-load torque to the load. As the load torque increased beyond 60%, the motor began to spin in the opposite direction. **Note:** The initial load torque was 0% of full-load torque and increased by 10% to the full-load torque setpoint.

#### 4.4 System Efficiency

Industrial and commercial facilities are continually searching for ways to reduce costs while increasing revenues. One way of accomplishing this objective is to reduce energy consumption costs. Industrial and commercial facilities, in their heavy reliance on electric motors, are by far the largest consumers of electric power. In fact, electric motor driven processes consume more than fifty percent of all generated electric energy. The use of energy efficient motors and electronic adjustable-speed drives can provide industries with a means for significantly controlling energy costs.

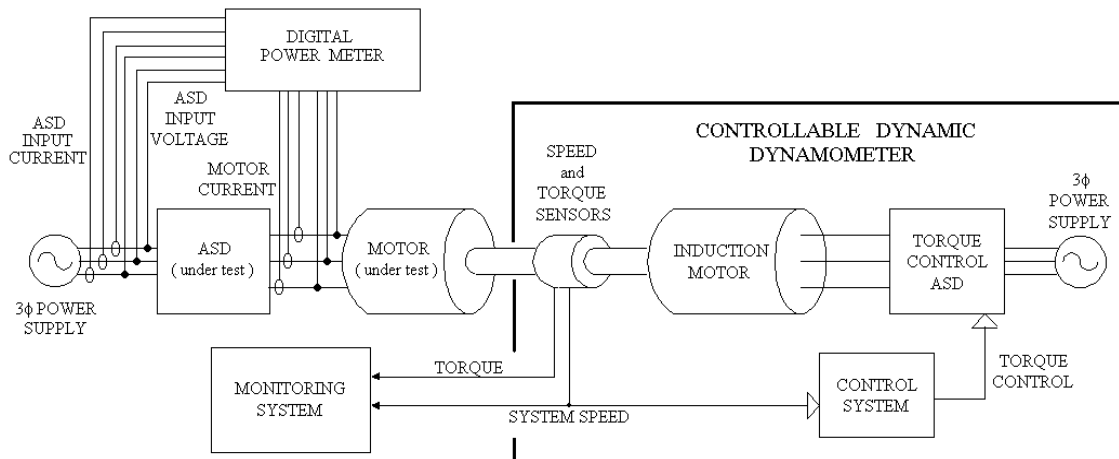
ASDs are being applied in increasing numbers to improve the efficiency and flexibility of customer operations. By controlling the speed of a motor electronically, the losses associated with mechanical controls such as dampers and throttles are nearly eliminated. While electronic motor control increases the overall energy efficiency of the

process, ASD losses and additional motor losses resulting from ASD operation should be considered when evaluating the total energy savings potential for an ASD application.

Currently, there are no published standards for determining the efficiency of an ASD or an ASD/motor combination. The only existing standard, the IEC-1800, calls for ASD manufacturers to report the efficiency of the ASD or the ASD/motor combination at rated speed and load torque conditions. For ASD-driven motors, both the motor speed and the load torque can change over the entire operating range of the application. Because of this, the efficiency of an ASD and ASD/motor combination needs to be evaluated throughout the entire operating range.

The efficiency test results presented in this report were not meant to be a complete evaluation of ASD/motor combination efficiency for the three ASD topologies. The efficiency test data was measured at two load points only. A complete evaluation of the ASD/motor combination efficiency would require measurements over the full range of load torque and speed setpoints.

The test setup for the system efficiency evaluation tests can be seen in Figure 4-11. The digital power meter was used to measure total input power to the ASD and the motor under test. The speed and torque sensors were used to measure the load torque and speed of the system for calculating the total load power. The controllable dynamic dynamometer was used to apply a constant load torque to the motor under test. The ASD/motor combinations were operated at two load setpoints. The test results for the three ASD systems can be seen in Tables 4-4, 4-5, and 4-6.



**Figure 4-11**  
Test Setup for the System Efficiency Evaluation

**Table 4-4**  
**DC Drive System Efficiency Test Results**

Speed (RPM)	Load Torque (N-m)	Load Power (HP)	$P_{ASD}$ (kW)	$P_M$ (kW)	$\eta_{ASD}$ (%)	$P_L$ (kW)	$\eta_M$ (%)	$\eta_{SYS}$ (%)
1800	19.9	5	4.66	4.47	95.9	3.75	83.9	80.5
900	9.9	2.5	1.43	1.18	82.5	0.933	79.1	65.2

**Table 4-5**  
**AC Drive – Sensorless Vector Control System Efficiency Test Results**

Speed (RPM)	Load Torque (N-m)	Load Power (HP)	$P_{ASD}$ (kW)	$P_M$ (kW)	$\eta_{ASD}$ (%)	$P_L$ (kW)	$\eta_M$ (%)	$\eta_{SYS}$ (%)
1800	19.9	5	4.45	4.40	98.9	3.75	85.2	84.3
900	9.9	2.5	1.24	1.13	91.1	0.933	82.6	75.2

**Table 4-6**  
**AC Drive – Volts/Hz Control System Efficiency Test Results**

Speed (RPM)	Load Torque (N-m)	Load Power (HP)	$P_{ASD}$ (kW)	$P_M$ (kW)	$\eta_{ASD}$ (%)	$P_L$ (kW)	$\eta_M$ (%)	$\eta_{SYS}$ (%)
1800	19.9	5	4.55	4.33	95.2	3.75	86.6	82.4
900	9.9	2.5	1.23	1.11	90.2	0.933	84.0	75.9



# 5

## GLOBAL TRENDS IN AC AND DC DRIVE MARKETS

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### 5.1 The Evolving Market Place

In today's rapid changing market place drive users are applying AC and DC drives in applications that require more demanding speed and torque performance.<sup>[11]</sup> Drive technology has had to keep pace with these ever more demanding expectations. Additionally, today's market place is more focused than ever on unit cost and cost reduction. Thus eliminating the tendency towards over applying technology to a process. Properly matching the drives' size and unit characteristic to the application are two very effective ways of managing these costs. In the competition between AC and DC electric motor drive technology, especially DC drives, would seem to have reached maturation. Yet DC and AC developments keep rolling along, and according to drive manufacturers, drives have a long way to go in North America before they reach saturation.<sup>[12]</sup>

To identify and define their new position in the market, personnel from drive manufacturers are soliciting feedback from their customers to determine how the customer bought their motors, drives, and process control systems. What they are finding is that the world of drives is divided into two groups — motor/drive focused customers and process controller focused customers. The first group sees the motor/drive as sitting in the middle of the control scheme, between the motor and the process controller, and is concerned with horsepower, torque, and speed. The second group sees the motor/drive as an *element* of an automated network, and is concerned with processing speeds, protocols, and ladder logic.

A number of motor/drive manufacturers are utilizing this information and are making strides toward integrating process control with drive systems.<sup>[13]</sup> Also, motor suppliers are making breakthroughs on another front by integrating drives with motors. In an attempt to make the controls and motors more compatible, some motor suppliers have begun physically mounting a low-end drive to the motor chassis. This technology piggybacks one of the supplier's own drive controllers on the housing of an industrial AC motor to deliver a minimal-footprint drive system. The key to this packaging concept is the development of a new microchip that permits IGBTs to offer higher frequency switching with less heat output. The lower heat levels permit the power and logic circuitry to be mounted together to save space. Keeping the interconnecting

wiring short makes for more accurate speed control and contributes to extended motor life. Motor mounted drive packages offer other advantages to the user including: compact design for tight space applications, guaranteed compatibility between the drive and motor, and reduced installation costs.

Motor/drive suppliers are learning that most users care less about the insides of drive technology, they are more concerned with what the drive can do for them and how to cost-optimize the technology. On the DC side, customers are interested in replacing old drives with newer, more efficient controls that will interface to existing and still useful DC motors. As with AC drives, networking, easy set-up, and diagnostics are key components in making the ultimate decision. These growing market insights suggest that to be a global leader in motor/drives, an equipment manufacturer needs to go to market with strategies compatible with these findings.

## 5.2 Forecasts of the U.S. Motor Drive Market

In 1996, Frost & Sullivan compiled a major industrial report on the *U.S. Motor Drive, Feedback Element, and Variable Speed Drive Market*. The report emphasized the growing importance of motor control components as critical products in industrial manufacturing processes. They divided the U.S. motor control market into three important segment level components of motion control systems: —motor drives<sup>4</sup>, —feedback elements<sup>5</sup>, and —mechanical variable-speed drives.<sup>6</sup> Frost & Sullivan characterized each market segment as follows:

***Motor Drives Market Segment*** — is a growth market segment, with AC drives, servo drives, and stepper drives all forecasted to experience double-digit revenue growth throughout the 1995-2002 forecast period. The sole exception is the DC drive market, which is projected to contract over the same time period.

***Feedback Market Segment*** — is one of the most dynamic market segments in the motor controller market, with all subsegments experiencing substantial revenue growth, and with the rotary encoder and Hall-effect sensor markets experiencing double-digit revenue growth over most of the 1995-2002 forecast period.

***Mechanical Variable-Speed Drives Segment*** — is forecasted to see negative revenue growth after 1997 as the markets for these products begin to shrink. Most of the fall in the mechanical variable-speed drive market is directly attributable to growth in the

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<sup>4</sup> Includes AC and DC drives, stepper motor controls, and servos

<sup>5</sup> Includes rotary encoders, linear encoders, resolvers, and Hall-effect sensors

<sup>6</sup> Includes mechanical variable-speed drives (with open pulley drives, enclosed belt/motor drives, and traction motor drives), and hydrostatic drives

hydrostatic drive market, which is projected to grow at an annual rate of over 5 percent during the 1995-2002 forecast period.

The total market for motor drives, feedback elements, and variable-speed drives was estimated at over \$2.36 billion in 1995. With relatively steady annual growth anticipated over the forecast period, revenues are anticipated to reach approximately \$4.04 billion in 2002. This market growth is being driven by numerous factors including continued demand for motor drives and feedback elements within factory automation applications.

In addition to this increased demand, the motor control components market is a relatively cyclical market and growth is being spurred on by a generally growing economy and growth in capital expenditures. A compound annual growth rate over the 1995-2002 forecast period is projected to be 8 percent for the total market, representing growth in motor drives, feedback elements, and variable-speed drives.

The motor drive segment is the largest of the motor drive, feedback element, and variable-speed drive market, accounting for 68 percent of total market revenues in 1995 (the latest year with accurate market figures). Table 5-1 shows the total motor drive market for unit shipments, revenues, and forecasted revenues in the U.S. for 1992-2002. An estimated 920,000 motor drives were shipped in 1995, up from 726,000 in 1992, with shipments expected to top 1 million in 1996. This upward trend should continue to grow through the end of the century, with an anticipated 1.8 million units shipped in 2002. In 1995 the motor drive market experienced revenue growth of approximately 7 percent and unit growth of 9 percent.

**Table 5-1**  
**Total Motor Drive Market:<sup>7</sup>**  
**Unit Shipments and Revenue Forecasts (U.S.), 1992-2002**

Year	Units (Million)	Revenues (\$ Billion)	Revenue Growth Rate (%)
1992.....	0.73	2.33	---
1993.....	0.78	1.42	6.5
1994.....	0.85	1.51	6.5
1995.....	0.92	1.62	7.0
1996.....	1.01	1.73	7.5
1997.....	1.11	1.87	7.5
1998.....	1.22	2.01	8.0
1999.....	1.36	2.18	8.5
2000.....	1.51	2.37	8.5
2001.....	1.68	2.56	8.5
2002.....	1.87	2.77	8.0
Compound Annual Growth Rate (1995-2002): 8.0%			

Source: Frost & Sullivan

Currently, there is a high level of consolidation within the electronic drive industry. When electric drives were first developed, they were very specialized and used for specific purposes. This allowed manufacturers to carve out a niche within the industry. However, the specialized nature of the drives began to fade because of advances in microprocessors, logic chips, and power semiconductors. Over the past 20 years electric drives have become increasingly standardized. Because of this standardization of electric drives, traditional niche markets began dissolving into one another, thereby creating fewer but larger niches. To compensate for lost market share or to secure new market share, mergers and acquisitions have become common and have proceeded at a fairly rapid pace.

At present, there is still some conflict between the supporters of AC drives and the supporters of DC drives, although its intensity has been somewhat diminished. AC

<sup>7</sup> All figures are rounded; the base year is 1995. The market for motor drives consists of alternating current (AC), direct current (DC), stepper motor drives, and servo motor drives. It is inherently difficult to assess the motor drive market because many of the drives are combined with other offerings to provide complete solutions to customers. AC motor drives are defined as being both the standard inverter drives and vector AC drives. DC motor drives are defined as both thyristor DC drives and brushless DC drives. Servo motor drives<sup>{2}</sup> are defined as both AC and DC servo motor drives, and they include the sequence logic and the power driver. Stepper motor controls are defined as single stepper controllers that include the sequence logic, the amplifier, and the power driver.

Servo motor drives are included for completeness in reporting the motor drive market segment, but will not be elaborated on because they are outside the present scope of work.

drives and motors are now almost on par with DC drives and motors because of improvements in technology. AC is now almost completely able to mimic DC, with the added advantage of being replaceable and less expensive in some cases. Manufacturers of AC drives are taking advantage of the higher maintenance costs associated with DC drives and motors in order to increase sales. As noted in Table 5-2, end-users for motor drives can be divided into six different categories. Table 5-2 lists the total motor drive market in percent of revenues by U.S. end-user type for 1992-2002.

**Table 5-2**  
**Total Motor Drive Market:**  
**Percent of Revenues by End-User Type (U.S.) 1992-2002**

Year	Industrial (%)	Other (%)	Computer (%)	HVAC (%)	Medical (%)	Special (%)
1992.....	33.5	26.0	14.7	9.5	1.6	14.7
1993.....	33.8	24.6	14.9	10.2	1.7	14.8
1994.....	34.4	23.2	15.0	10.7	1.8	14.9
1995.....	34.9	21.8	15.2	11.2	1.9	15.0
1996.....	35.5	20.4	15.3	11.6	2.0	15.2
1997.....	36.1	19.3	15.3	11.9	2.1	15.3
1998.....	36.5	18.5	15.2	12.2	2.2	15.4
1999.....	36.8	17.9	15.0	12.4	2.3	15.6
2000.....	37.2	17.3	14.8	12.6	2.4	15.7
2001.....	37.4	17.0	14.6	12.7	2.5	15.8
2002.....	37.9	16.4	14.4	12.8	2.6	15.9

All figures are rounded; the base year is 1995.

\* Source: Frost & Sullivan

Each end-user category listed in Table 5-2 is described in the following paragraphs:

**Industrial Manufacturing** — includes machine tools packaging and materials handling equipment, in 1995 comprised an estimated 34.9 percent of the motor drive market. This segment is forecasted to grow to 37.9 percent of the motor drive market in 2002. This growth is being spurred on by demands in the packaging, material handling, and machine tool markets.

**Computer and Peripheral Equipment** — this segment accounted for an estimated 15.2 percent of the motor drive market in 1995. It is anticipated that this market will remain stable throughout the forecast period. It is estimated that the computer and peripheral segment will have a market share of 14.4 percent in 2002.

**HVAC Equipment** — in 1995 this segment accounted for 11.2 percent of the motor drive market. Because of increasing energy conservation measures and awareness, the HVAC market continues to grow. It is forecasted that the HVAC market will account for 12.8 percent of the motor drive market in 2002.

**Medical Equipment** — this segment is the smallest segment of the motor drive market and accounted for an estimated 1.9 percent of the market in 1995. Stepper motor controls are the most popular motor drive for the medical segment. The medical segment is expected to grow at approximately the same rate as the motor drive market, within an anticipated market share of 2.6 percent in 2002.

**Special Industrial Equipment** — this segment, which includes printing, paper, metals, textiles, and food processing applications, in 1995 accounted for an estimated 15 percent of the motor drive market. The special industrial segment is anticipated to grow slightly over the forecast period (1995-2002) to 15.9 percent of the motor drive market in 2002. This growth is due to the continued upgrade of equipment that requires motor drives.

Several issues are of concern within the motor drive market. These issues are common concerns with each market segment. Customers are concerned about reliability, service and support, and, of course, price. The number one issue manufacturers have to cope with is reliability. They have to provide a motor drive that continually performs its functions and does not break down — resulting in minimal downtime. Service and support of motor drives is very important to end-users. Some drives are very difficult to install and program. Therefore it is imperative to make the installation process as painless as possible. Finally, in an increasingly cost-conscious corporate environment, customers are always concerned about getting the best price.

The AC drive market is forecasted to increase through the year 2002 by an average of more than 12% as shown in Table 5-3. The DC drive market, however, is expected to decrease by an average of more than 1.4% over the same period. The forecast trends indicate that AC drives will be used increasingly over the next few years in new and retrofit applications. Therefore, most ASD manufacturers focus on developing and improving existing AC drive technologies.

**Table 5-3**  
**AC and DC Motor Drive Market:**  
**Unit Shipment, Growth Rate, and Forecast (U.S.) 1992-2002**

Year	*AC (Thousand)	AC Growth Rate (%)	*DC (Thousand)	DC Growth Rate (%)
1992.....	357.6	-	222.6	-
1993.....	397.4	11.1	221.5	-0.5
1994.....	442.9	11.4	219.8	-0.8
1995.....	496.0	12.0	218.0	-0.8
1996.....	558.0	12.5	216.5	-0.7
1997.....	628.9	12.7	214.5	-0.9
1998.....	710.0	12.9	211.5	-1.4
1999.....	802.9	13.1	207.5	-1.9
2000.....	910.0	13.3	203.3	-2.0
2001.....	1029.8	13.2	198.4	-2.4
2002.....	1164.8	13.1	192.6	-2.9
Compound Annual Growth Rate (1995-2002):				<b>12.5%</b>
				<b>-1.4%</b>

All figures are rounded; the base year is 1995.

\* Source: Frost & Sullivan

### 5.3 Motor Drive Market and Technology Trends

The motor drive, feedback element, and variable-speed drive markets are being spurred on by numerous market factors. One of the main factors driving the overall market is a continued realization of cost reductions associated with the proper implementation of motor control components. These cost reductions are made possible by three main factors: improved productivity, energy savings, and increased efficiencies. Energy savings are best realized in heating, venting, and air conditioning (HVAC) systems that use variable-speed drives. Increased productivity and operating efficiencies may be achieved by using motor control components to efficiently manage a machine or motion control system. The biggest cost reduction and energy savings are realized by using electronic motor drives to mitigate mechanical process losses. This is one reason why the motor drive segment is growing at an estimated 8 percent over the forecast period (1995-2002), while the mechanical variable-speed drive segment is anticipated to see negative growth over much of the same period.

Continued technological advances also help to enlarge the motor drive and feedback element markets by improving products for current markets and creating new end-user markets. Many companies are in the plant modernization process of updating equipment and switching to more automated applications that require motor drives and feedback elements. While this trend towards new technologies is good for many

motor control market segments and essential for a healthy market, it is having an adverse effect on some of the more mature market segments. The continual advancement of product technologies and capabilities is having less of an impact, even a negative impact on the mechanical variable-speed drives segment. This negative effect arises because the mechanical variable-speed drives segment employs a much simpler and sometimes less efficient technology than the electronics-based technologies offered in other segments such as the motor drive and feedback element segments. However, the variable-speed drive market is not collapsing and is experiencing some growth because of the continued demand for hydrostatic drives used in off-road applications.

Motor drives, feedback elements, and mechanical variable-speed drives play an integral role in the continued modernization of various motor driven systems. In general, the markets for motor drives continue to grow in terms of revenues and units shipped. The market for feedback devices continues to grow at a rapid rate, and the mechanical variable-speed drive market's growth is lead by hydrostatic drives. Motor control components have become an integral portion of motion control systems, increasing the productivity and efficiency of manufacturing processes. With the continued use of and demand for more efficient and technologically advanced motors and components, the motor control components market is projected to remain a positive growth market well into the next century.

Also, customer support continues to be a major factor that influences the buying decisions of end-users. Although end-users are always concerned about price, they are often more concerned about minimizing potential production downtime. To minimize downtime, customers require the support of manufacturers in troubleshooting problems and getting machines up and running again after problems have been solved. In addition to minimal downtime once a drive has been installed, customer support groups provide information to end-users to make sure they purchase the right solution for their particular needs. Once the correct product is purchased, the manufacturers' customer support groups also typically provide assistance with end-user installation of products.

In essence, manufacturers' customer support groups are designed to minimize the potential headaches of end-users and to allow manufacturers to develop a friendly and mutually beneficial relationship with their customers. Companies that have excellent customer support centers have a distinct advantage over their competitors in this extremely competitive market.

#### **5.4 Emerging and/or Applicable Standards**

Most new standards are related to the general characteristics of electric power supply, such as harmonics or surges, and to the electromagnetic compatibility (EMC) of end-use

electronic appliances, including immunity and emissions limits. The current interest in EMC is being fueled by increasing applications of micro and power electronics equipment, especially in commercial and industrial sectors, where customers need both the uniformity and protection afforded by standards.

For those involved in the selection and applications of drives and motors, a thorough understanding of the relevant standards is important. The following is a summary of the principal standards for controls, motors and drives.

- **NEMA Standards Publication No. ICS7**, *Industrial Control and Systems Adjustable-Speed Drives*. This document reviews general standards for drive converters, drives and drive systems. Included are sections on:
  - loop position and tension control systems,
  - wind and unwind drive systems,
  - adjustable-frequency converters rated not more than 600 Volts,
  - general purpose adjustable-voltage DC packaged-drive systems,
  - adjustable-frequency drive systems rated not more than 600 Volts using semiconductor power conversion,
  - adjustable-frequency drive systems rated 601 to 7200 Volts,
  - an application guide for line reactors and input transformers.
- **IEEE Standard 112-1991**, *Test procedure for Polyphase Induction Motors and Generators*. The standard describes general type of motor tests, measurements, types of losses, determination of efficiency, temperature tests, and other performance tests.
- NEMA Standards Publication No. MG1-1993, *Motors and Generators*.
  1. A new Part 30 has been added, titled “Application Considerations for Constant Speed Motors Used on a Sinusoidal Bus with Harmonic Content and General Purpose Motors used with Variable Voltage or Variable Frequency Controls or Both.” Typical application information includes:
    - a) Derating curve for harmonic content of a constant frequency power supply.
    - b) Maximum safe operating speeds.
    - c) Typical derating curves for loss of cooling at reduced speeds.

- d) Examples of derating curves for operations with inverter power supply.
  - e) Limiting values of peak voltage and maximum rate-of-change of voltage (dv/dt) when operated from inverter power supplies.
- 2. A new Part 31 has been added, titled "Definite-Purpose Inverter-Fed Motors." Typical information includes:
  - a) Definition for basis of rating.
  - b) Preferred speed and speed ranges.
  - c) Limits for maximum intermittent and relative equivalent temperature rise for defined load/speed cycles.
  - d) Limiting values of peak voltage and maximum rate-of-change of voltage (dv/dt).
- **NEMA Standard Publication No. MG10-1994**, *Energy Management Guide for Selection and Use of Fixed Frequency Medium AC Squirrel-Cage Polyphase Induction Motors*. Typical application information in this standard includes:
  - a) Evaluation of efficiency economics.
  - b) Applications involving load cycling.
  - c) Applications involving extended periods of light load operation (power factor controllers).
  - d) Applications of pumps and fans involving throttling of bypass control.
- **IEEE 519-1992**, *Recommended Practices and Requirements for Harmonic control in Electrical Power Systems*. This guide applies to all types of static power converters (i.e. ASDs) used in industrial and commercial power systems. The problems involved in the harmonic control and reactive compensation of such converters are addressed, and an application guide is provided. Limits of disturbances to the AC power distribution system that affect other equipment and communications are recommended. This guide is not intended to cover the effect of radio frequency interference.
- **EN55081-2**, **European Union Generic EMC Standard Applied to Drives**, *Electromagnetic Compatibility Generic Emission Standard, Part 2 – Industry*. This document summarizes allowable emission levels in industrial and commercial facilities for Class A, group 1 equipment from 150 kHz to 1 GHz.

- **EN 55011, European Union Basic EMC Standard Applied to Drives, Limits and Methods of Measurements of Electromagnetic Disturbance Characteristics of Industrial, Scientific, and Medical Radiofrequency Equipment, Class A – Industry, Class B – Residential, Commercial, and Light Industry**

## 5.5 Review & Analysis of Drive Power Electronics Trends

New technology trends<sup>[14]</sup> are developing in all of the market segments; however, the most important technology trend is occurring in power semiconductors for the motor drive segment. Internally, an AC drive's power electronic circuits consist of semiconductor switches for both AC/DC rectification and DC/AC inversion. The AC/DC rectifier switches of the AC drive controls the DC voltage to the inverter section, and the DC/AC inverter section of the AC drive consists of power switching devices and logic circuits to control the motor's voltage and frequency level for the desired speed. Internally, the DC drive's power electronic circuit consists of semiconductor switches for AC/DC rectification.

The state-of-the-art in industrial and commercial power conversion technology is moving very rapidly due to dramatic improvements in semiconductor power device technology. Present power semiconductors that are already available in the marketplace include the insulated-gate bipolar transistor (IGBT) for power electronic applications up to 750kW at 480VAC, and the gate turn-off thyristor for power conversion applications above 750kW. Both higher voltage and higher current devices such as the integrated gate commutated thyristor (IGCT) are on the horizon and promise even greater performance at MW-level applications.

A majority of the power electronic devices being developed are gate-controlled switches that address the issues of increased semiconductor device switching speed, power handling, reliability, ruggedness, and power gain. Ease of use through simpler gate drive requirements and innovative packaging is expected to lower the cost of product development and commercialization, thus making it possible to incorporate enhanced power converters in an even larger number of applications for both AC and DC drives.

While both AC and DC drives provide considerable advantages in terms of reduced process energy losses and improved productivity, harmonic current generation and power quality disturbance issues remain and they are often costly to solve. AC and DC drives can benefit from evolutionary semiconductor devices with extremely low losses, snubberless control capabilities and fast switching designs.



# 6

## CASE STUDIES COMPARING AC AND DC DRIVE APPLICATIONS

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Case studies are intended to draw on past experiences in various critical industrial process industries to identify and to define the diversity of AC and DC drive applications for improving productivity and efficiency in motor driven systems. Today's access to high speed, highly reliable AC and DC power electronics has made drives a practical and cost effective alternative to conventional fixed-speed control with mechanical variable-speed schemes.

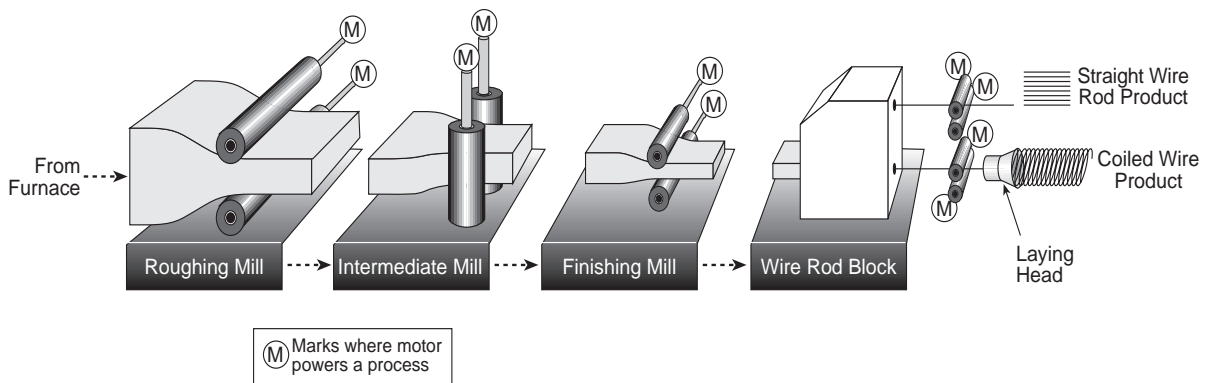
A growing number of industrial manufacturers and process equipment suppliers are becoming keenly aware of the improved production and efficiency opportunities provided by drives. Typical examples of applying drives for process productivity enhancements include:

- shortening the non-productive time and thus improving the working duty cycle,
- controlling process speed and thus improving productivity,
- shortening or eliminating set-up time between various batches,
- tightening end-product tolerances,
- compensating for variations in process parameters or input raw materials in order to yield a consistent product,
- reducing maintenance costs and improving process reliability.

Following are four (4) case studies illustrative of applying drives for increased process performance.

## 6.1 Case Study #1 — Advanced Wire Rod Mills

**Background** — One of the world's largest producers of top grade stainless steel products for automotive and medical applications is now using AC vector controlled drives in its wire rod mills.<sup>[15]</sup> The primary market for their rod products are a variety of companies in the demanding automotive industry. Individual wire rod order quantities are usually relatively small but the variety of product shapes and materials is very large. This puts extreme demands on the flexibility of the rolling mill operation. Figure 6-1 is a schematic representation of the wire rod mill layout.



**Figure 6-1**  
Schematic Representation of the Wire Rod Mill Layout

**Drive Selection Rationale** — As far as the electrical and automation equipment was concerned, this corporation opted for advanced, yet proven solutions to each rolling mill task. For the first time, three-phase squirrel cage induction motors were being used throughout the rolling mill, and the finishing mill was equipped with voltage source frequency converters as the speed adjusting element. The corporation committed to this approach because their experience confirmed that induction motors were both robust and reliable, and their maintenance requirements were restricted to the bearings. Since no cooling water was required, both their installation and the plant maintenance were significantly simplified. In addition, these AC drives were more efficient, reducing the energy bill, and the heat load of the buildings at the same time.

Main motors on the 16 horizontal and vertical stands of the roughing, intermediate and finishing mills are 6-pole, totally-enclosed, fan cooled, low-voltage motors in ratings from 350 to 1200 kW each. The motors are fed in groups of six via individual voltage-source PWM inverters from three 1000V DC busbars that in turn are supplied from controlled SCR bridges. This concept has the advantage that the load-peaks that occur when the billet enters each stand do not overload the DC bus and its associated feeder.

In contrast to comparably sized DC drives, the vector-controlled adjustable-speed AC drives offer better dynamic performance, lower losses, and equal torque quality. Since all stands operate in a continuous mode, dynamic braking is only provided centrally at each DC busbar for bringing the empty mill to a standstill.

The dynamic and reliable speed and torque control of all the drives is achieved by digital controllers with comprehensive communications and diagnostic capabilities. These controllers communicate with each other and with the basic plant automation system via a 2-wire field bus protocol.

**Summary of Benefits** – The chosen AC drive approach provided the following advantages:

- lower costs for hardware
- uniform hardware and programming language for the entire basic automation system
- no computer specialists required
- online parameter changes for time-critical process values
- low dimensional tolerances of the finished product were achieved through minimal-tension controls

## 6.2 Case Study #2 --- Winding Operations<sup>[16]</sup>

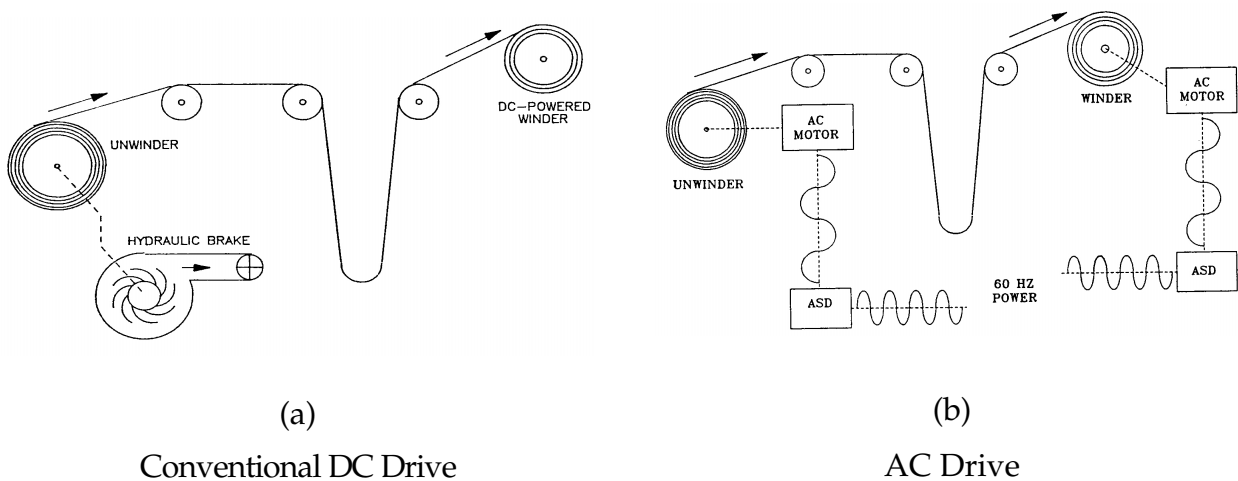
**Background** — Winding operations are found largely in the paper, steel, and aluminum industries. Speed regulation, which is necessary to maintain proper tension on the material, is often furnished by a brake on the unwinding roll. Traditional means of speed control are hydraulic brakes and dc regenerative motors acting as brakes. Winding and unwinding basically requires a constant horsepower control scheme. Since the tension remains the same over a varying diameter, the torque decreases as the diameter increases. To obtain precise tension control it is necessary to simultaneously obtain the correct torque and the correct slip at the correct speed. In this case study, the industrial operations manager sought to replace the existing winding-unwinding conventional DC approach with an AC drive for improved tension control.

**Drive Selection Rationale** — The conventional winder drive was a DC drive controller set to a closed loop speed operation during threading. Lead speed is added to the winder thread and winding speed. When the strip begins to wrap, the control scheme transfers to tension control and the speed reference is ignored. The tension reference begins to direct the speed in order to control the winding torque requirements. As the material diameter builds, the tension reference lessens, since less torque is required for

the same pounds of pull. Changes in machine speed are made by adjusting the master speed reference to all drives. As the diameter of the product builds up, its inertia increases. The control scheme must take this change into account.

Unwinding is similar to winding, except the tension reference is negative which is equivalent to drag. Figure 6-2(a) illustrates a paper unrolling operation with conventional DC drive. Down-line from the unwinder is a dc motor-powered winder running the paper at, or near, constant speed. Back tension is maintained by a hydraulic brake, mounted onto the unwinder shaft. Acting as an inefficient centrifugal pump, the hydraulic brake converts energy into waste heat. The heat is then removed by a heat exchanger. The resistance to the pumping action is determined by the position of a valve, which is controlled automatically.

**Summary of Benefits** – With the help of high performance AC drives (see Figure 6-2(b)), proper tension can be maintained by varying the speed of the winding roll, the unwinding roll, or both. In the paper unrolling operation shown, an AC drive is used in place of the constant speed-constant torque dc motor to drive the winder, as illustrated. The desired tension is maintained by varying the motor speed and/or torque continuously. With the AC drive controlling the winder, the use of the hydraulic brake as well as the associated energy losses and cooling requirements are eliminated. This results in higher efficiency, less maintenance and better accuracy.



**Figure 6-2**  
**Comparison of Winding – Unwinding Application**  
**(a) with DC Drive, and (b) with AC Drive**

### 6.3 Case Study #3 --- Precise Control for Pressure-Sensitive Labels<sup>[17]</sup>

**Background** — To produce laminated, pressure-sensitive labels, a silicone film needs to be applied to 3.4 ft wide, 30,000 ft long rolls of 2.5 – 5.0 mil paper used to line the labels. Several years ago, a major mid-western company's plant was at peak capacity with more than \$35 million in revenues, so the company asked its engineers to achieve faster, better production using newer coating processes and control systems. The company's engineers chose to replace a former water-based, 500 ft/min, emulsion process with a method that could triple production speed. It uses ultraviolet light to trigger a photo-initiator on solid silicone film.

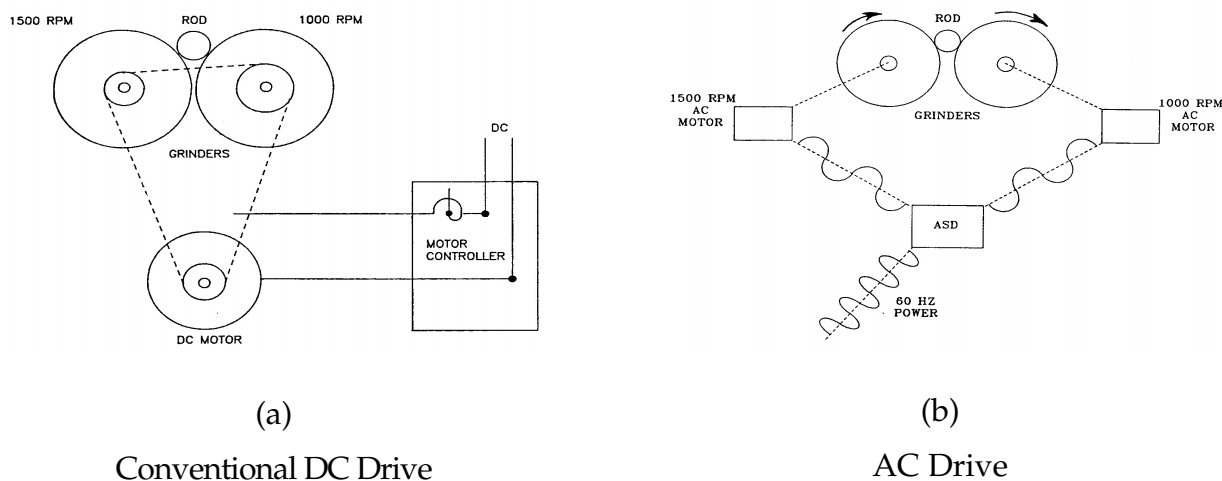
**Drive Selection Rationale** — Precise control and roller coordination were critical to this new process because an improperly cured liner could stick to the rollers or itself. Poor control might cause sticky coating imperfections, and uneven roller speeds could create liner web sags, which leads to wrinkles, jams, and tears. To cut dc motor downtime by replacing them with AC motors, the plant's operations engineers settled on a system that combined field-oriented controlled AC drives, intuitive operator interface terminals, programmable controllers, and single-source engineering and integration support. In the past, the company's engineers had been accustomed to using only dc motors and drives because only they were able to deliver the precise speed control and handle the high torque loads needed to produce a quality product.

**Summary of Benefits** — The new system manages rollers with 16 AC drives that directly control torque and reportedly meet or exceed dc motor and drive performance. The drives communicate with a programmable controller through a data highway network for information management and via a remote I/O network for normal control functions. Drive-to-drive communication is also available at high speeds. Machine operators found their new system provided greater flexibility to coordinate varying roller speeds at either end of the process because the new drives could be programmed to run at set speeds or at percentages or ratios of line speed. The drives also have enhanced regenerative braking and web tension maintenance down to zero speed, which allow faster and more accurate adjustments. Likewise, controllers can download process parameters to the system more quickly, which means faster converting and order filling.

### 6.4 Case Study #4 — Speed Regulation for Quality and Precision<sup>[16]</sup>

**Background** — Quality and precision are very important in finishing operations such as grinding, polishing, and honing. Equipment commonly used are lapping machines, as well as centerless and cylindrical grinders. Speed control is necessary to regulate the grinding rate versus the feed rate.

**Drive Selection Rationale** — DC shunt motors are generally used in these applications because their speed is adjustable and varies only slightly with load. To regulate the speed, the field current of the dc shunt motor is controlled. The conventional DC controller of a centerless grinder is shown below in Figure 6-3(a), machining a long steel rod. A dc shunt-wound motor drives the two grinding wheels at their respective speeds. Variation of the shunt-field current provides the speed control; field current is increased to lower motor speed and decreased to raise motor speed. Disadvantages of this drive are: maintenance of the motor — especially the commutator and brushes, and the high initial cost of a conventional precision motor controller.



**Figure 6-3**  
**Comparison of Centerless Grinder Application**  
**(a) with DC Drive, and (b) with AC Drive**

**Summary of Benefits** — The stringent quality and precision requirements rendered by high performance AC drives is especially suited to finishing operations, particularly when speed regulation of multidrives is required. For the centerless grinder shown in Figure 6-3(b), precise speed regulation can be accomplished by the use of a AC drive system, consisting of separate motors for each grinding wheel, supplied by a common converter. The motors may be low slip induction motors. Since each grinding wheel speed is proportional to the motor supply frequency, both grinding wheels can be controlled simultaneously by regulating the common converter frequency. Note: *Special attention must be paid to closely coupled multiple motors fed from a common AC drive. It is important to take into account relative speed variations if the torques differ. Low slip induction motors must be used in such cases. Consideration should also be given to drastically unequal load sharing which may result in pushing an individual motor to breakdown torque. For this reason, individual motor overload protection is usually necessary.*

# 7

## CONCLUSIONS

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Advances in both AC drive and DC drive technologies will continue to play an integral role in the continued modernization of motor driven systems. But most drive users could care less about the “insides” of drive technology. They are more concerned about what the drive can do for them and how to cost-optimize the technology. While the industry trend is showing that AC drives are growing at a faster rate than DC drives, the growth of AC drives is in new applications rather than encroaching on DC drives in great numbers.

In order to make an economic comparison between AC drives and DC drives, it is first necessary to confirm that either type of drive can meet the performance requirements of the application. It is also necessary to determine what optional features are required. It is best to review the fundamental requirements of the application rather than specify an AC drive equipped with features equivalent to a particular DC drive configuration that was used in the past. Nominally comparable features do not always provide equivalent performance when applied with either type of drive.

An adequate economic comparison between two types of drives requires an analysis of all of the costs incurred over the entire life-cycle of the equipment. In addition to the purchase price of the drives and related equipment, this includes all of the material and labor costs required to obtain and install the equipment and put it into operation, plus all of the costs to operate and maintain the equipment during the entire time it is expected to be in service.

The life-cycle cost analysis showed for the lower horsepower range (< 50 HP), the AC drive system has a significant advantage over the DC drive system. This is mainly due to the first costs of the motor and drive systems. However, as the drive system ratings increase, the lower cost of the DC drive converters becomes attractive compared to the high performance AC drive inverters. For 500 and 1500 horsepower ratings, this trend reverses mainly due to the unavailability of high performance AC vector controlled drives in this horsepower range.

One clear trend that is apparent from this research is that for DC drives the price per horsepower decreases considerably for higher horsepower ratings. Also, on an average, high performance AC drives are 40 to 60% more expensive than the standard PWM

*Conclusions*

Volts/Hz controlled drives. It appears from present ASD equipment supplier feedback, that both AC and DC drive prices will remain stable for the foreseeable future.

The system compatibility test results, while only representative, confirm the need for documented electrical and mechanical drive system performance on different ASD technologies. This information illustrates the ASD's response to both the steady-state and active process dynamics in real time to the ASD electric supply input voltage conditions. Comprehensive technical data regarding the power quality impacts on both the electric service and mechanical process can benefit utilities and their customers to maximize drive system productivity and reliability.

In the context of the above conclusions, it is noteworthy to mention that first-cut comparisons of individual features and characteristics of AC and DC motors/drives are frequently confusing. Both AC and DC drive systems enjoy technology advantages that can, however, be offset by details of the specific application, economics, or user preference. For instance, AC drives are relatively easier to interface with the electric service source while DC drives are easier to interface with their motors. Said another way, AC drives can create significant EMI/RFI interference on its motor circuit, while DC drives can create significant EMI/RFI interference on the electric service source. There are no "rules of thumb" that will consistently and accurately predict the outcome of the drive selection process.

## 8

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# A

## DESCRIPTION OF CONTROLLABLE DYNAMIC DYNAMOMETER TEST SYSTEM

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### Background

Testing of electric motors and adjustable-speed drives (ASDs) during power system voltage sags has become important. The response of the ASD and motors to a sag is shown to be a function of the load type and the inertia of the load, as well as the programming parameters of the drive. Because of its limited steady-state and dynamic characteristics, the typical dynamometer is not suitable for conducting evaluation tests that induce dynamic responses from electric motors and ASDs. A controllable dynamometer is needed that can mimic the behavior of actual industrial-type loads during steady-state and dynamic conditions, with user-selectable load characteristics and load inertia. The following information has been excerpted from a comprehensive 1998 paper<sup>8</sup> on this subject which discusses the significance of evaluation tests conducted with the controllable dynamic dynamometer.

### Introduction

Many industrial processes require precise and accurate control over process system parameters such as pressure, torque, temperature, flow, and speed. Since most of these processes are driven by an electric motor, the torque and speed of the motor directly impacts process variables. Many industrial applications use adjustable-speed drives to control the speed and/or torque of electric motors. Any upset of the normal operating conditions of the motor and load can have adverse effects on production including lost production time, lost product, and lost revenue. These upsets can be caused by power system transient events such as voltage sags. In order to evaluate the effects of power system disturbances on electric motors, dynamometers are used for loading the electric motor and ASD while the ASD is subjected to a disturbance.

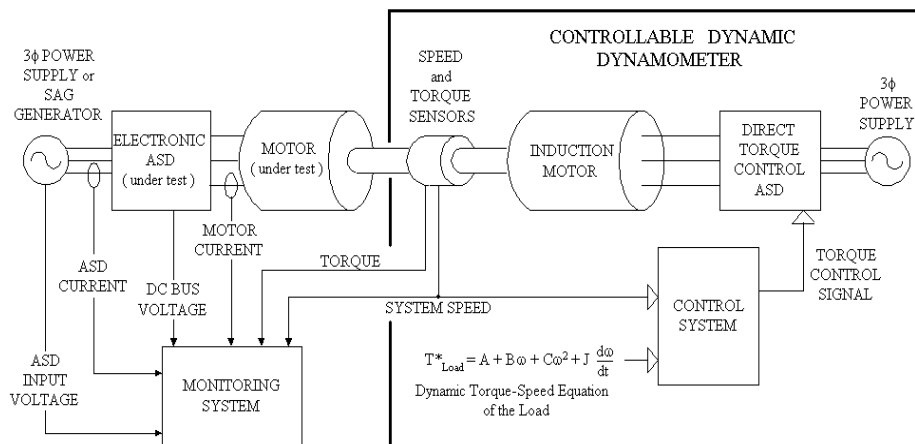
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<sup>8</sup> R. Langley, A. Mansoor, PEAC, *A Controllable Dynamic Dynamometer for Evaluating Voltage Sag Response of Electronic Adjustable-speed Drives*

Traditional dynamometers used for such testing have limitations that make them inappropriate for analyzing the true impact of power system disturbances. Most are incapable of more than one load characteristic and have no means for altering the load inertia imposed on the motor and ASD under test. The following paragraphs describe the controllable dynamic dynamometer test system used at PEAC for testing ASD/motor responses to voltages sags with a dynamometer that accurately simulates various load types.

## The Controllable Dynamic Dynamometer Test System

The controllable dynamic dynamometer (CDD) is similar to other dynamometers because it is used for performance and analysis testing of electric motors and ASDs. However, the controllable dynamic dynamometer differs from other dynamometers traditionally used for testing in that the dynamic and steady-state characteristics are known and controllable. The controllable dynamic dynamometer Test System can be seen in Figure A-1.



**Figure A-1**  
**Controllable Dynamic Dynamometer Test System**

The Controllable Dynamic Dynamometer Test System is composed of three major components: the motor and drive under test, the monitoring system, and the dynamometer. The monitoring system is composed of a personal computer, some measurement devices, and a data acquisition card. The monitoring system is used for calibrating the dynamometer and acquiring measurement data during evaluation testing of electric motors and drives. The load torque, the system speed, the ASD current, the motor current, the DC bus voltage, and the ASD voltage data is acquired during testing and stored for future performance analysis.

The Controllable Dynamic Dynamometer is composed of an induction motor, a system speed sensor, a control system, and an ASD. The induction motor is a standard three-phase NEMA Class B inverter-type continuous duty motor. The ASD is a state-of-the-art direct torque control (DTC or sensorless vector control) ASD. The DTC ASD is a four-quadrant type that is capable of producing rated torque at zero speed. The dynamometer is controlled by a main program running on a personal computer. The main program serves as the interface between the user and the dynamometer. The user inputs the desired load characteristics, such as the desired load coefficients and the desired load inertia, into the main program. The program uses these characteristics to calculate the load torque required by the dynamometer. The computer reads the system speed data from the speed sensor and computes the required load torque based on the current values of the system speed and acceleration. The process of reading the system speed and calculating the required load torque is a continuous real-time process.

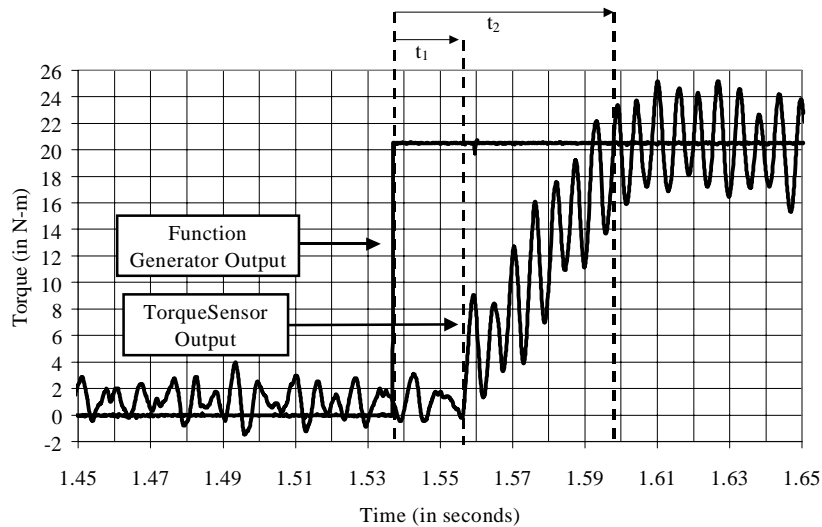
### **Dynamometer Torque Step Response**

A test was designed to evaluate the response time of the dynamometer's DTC ASD to a torque step input. The torque control input of the DTC ASD was fed from a programmable function generator that was programmed to output a step voltage upon command. The torque step was a dc voltage that forced the dynamometer to create rated load torque on the motor under test. The motor under test was a 5-hp 4-pole three-phase NEMA Class B line connected induction motor. The step voltage value changes from zero to the value corresponding to a 5-hp load.

The monitoring system was set up to monitor the outputs of the torque sensor and the function generator. The motor was allowed to start and run at no-load, i.e., no load torque from the controllable dynamic dynamometer. With the 5-hp induction motor running at no-load and the monitoring system operating, the torque step voltage was applied to the DTC ASD with the function generator. The torque sensor and step voltage data were recorded during execution of the test and was plotted as a function of time. The results of the torque step response test can be seen in Figure A-2.

Figure A-2 shows the output of the torque sensor and the function generator as sampled by the monitoring system during the test. The output of the function generator has been scaled to represent the ideal torque step response of the DTC ASD. From analysis of Figure A-2, the torque step reaction time,  $t_1$ , of the DTC ASD is 19.5ms and the torque step response time,  $t_2$ , is 61.5ms. The torque step reaction time of the DTC ASD is the length of time for the DTC ASD to recognize the torque step input, to calculate all necessary parameters, and to begin to change the load torque of the dynamometer. The torque step response time is the sum of the torque step reaction time and the length of time for the DTC ASD to successfully change the load torque of the dynamometer to the new value. The control system updates the torque signal of the

DTC ASD at 35ms intervals. It is reasonable to say that the torque step response time of the controllable dynamic dynamometer is 96.5ms (sum of the control system update and the torque step response times). This means that the controllable dynamic dynamometer is capable of changing the load torque on the motor and drive under test 10.4 times a second.



**Figure A-2**  
**Torque Step Response of the DTC ASD**

## Sample Experimental Results

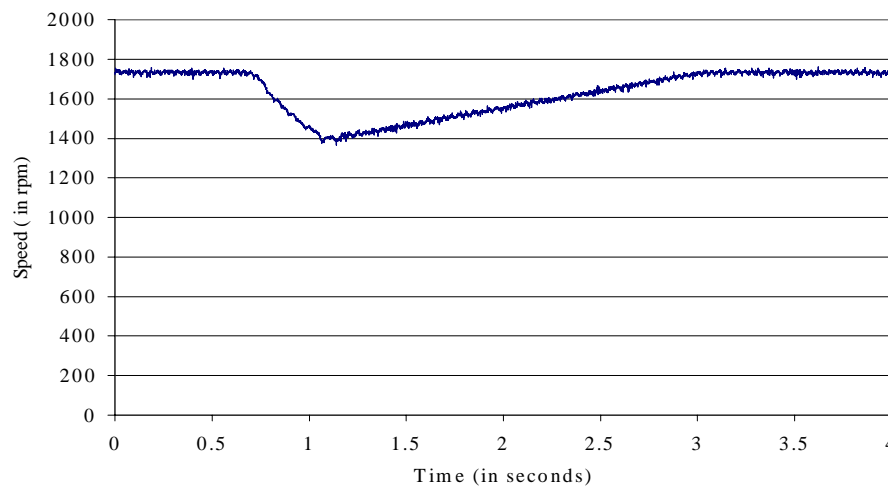
The controllable dynamic dynamometer allows the user to evaluate a motor and ASD combination with different load types and different load inertias. The sample experimental results will show that the load type and the load inertia significantly affect the voltage sag response of an electronic ASD.

A standard 5 hp electronic ASD (Volts/Hz control technology) was setup to control a 5 hp inverter-duty NEMA Class B three-phase induction motor. The ASD was programmed to operate the motor at rated frequency (60 Hz). The particular ASD chosen for this experiment was equipped with voltage sag ride-through features. When the ASD senses a voltage sag, it temporarily stops applying voltage to the motor. This allows the motor and load to coast. When the ASD senses the voltage sag condition is over, the drive accelerates the motor back to the 60 Hz setpoint based on the drive's programmed acceleration rate. The acceleration rate was set to 180 rpm/sec.

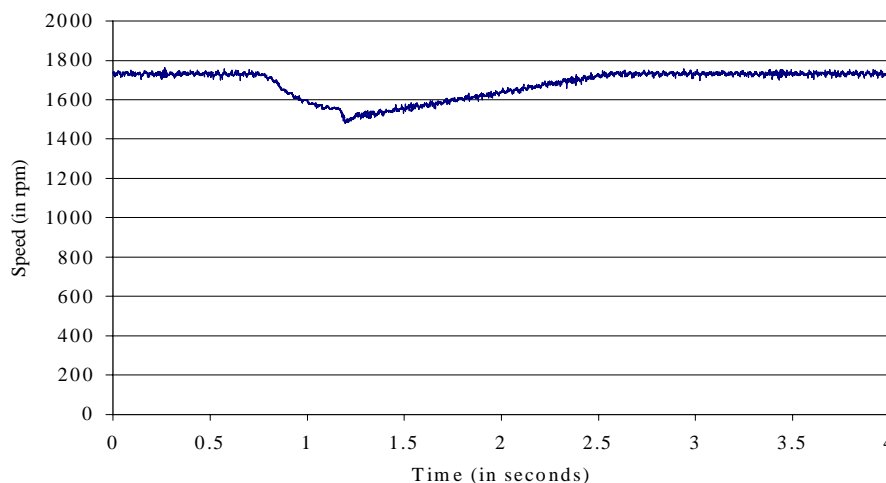
**ASD Response With Different Load Types, Same Inertia:** For this evaluation test, the controllable dynamic dynamometer was programmed to apply a constant horsepower

load type for the first test and a quadratic (variable) torque load type for the second test. The coefficients for the dynamic load torque equations of both load types tested were adjusted such that the dynamometer would require 4 hp from the motor under test at the ASD output frequency of 60 Hz. Thus, both load types would cause the motor to operate in steady-state at 1760 rpm. Both load types were applied with the same load inertia ( $0.0485 \text{ kg}\cdot\text{m}^2$  or 3.6 times the motor inertia).

With the ASD, motor, and dynamometer operating in steady-state (1760 rpm), a voltage sag was applied to the input of the ASD. The sag was a three-phase symmetrical voltage sag down to 70% of nominal voltage on all phases for a duration of 167 ms (or 10 cycles). The response of the ASD can be seen in Figures A-3 and A-4.



**Figure A-3**  
**ASD Response to Three-Phase Symmetrical Voltage Sag Down to 70% for a Duration of 167ms with a Constant Horsepower Load**



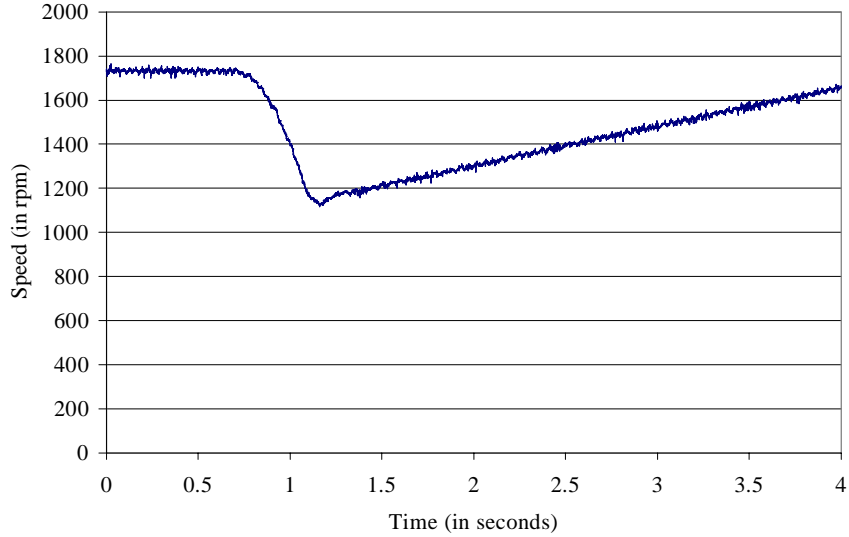
**Figure A-4**  
**ASD Response to Three-Phase Symmetrical Voltage Sag Down to 70% for a Duration of 167ms with a Quadratic (Variable) Torque Load**

When the voltage sag was applied to the ASD, the system speed fell to 1380 rpm for the constant horsepower load type. For the quadratic variable torque load type, the system speed only fell to 1500 rpm. From prior observations of mechanical process load characteristics, it was documented that the load torque increases as the speed decreases for the constant horsepower load type while the load torque decrease as the speed decreases for the quadratic variable torque load type. Therefore, the speed reduction under a constant horsepower load is expected to be higher. The lab tests confirm this expected behavior. The rate at which the system decelerates initially after the sag also differed between the type load types. This was a direct result of the differing load characteristics.

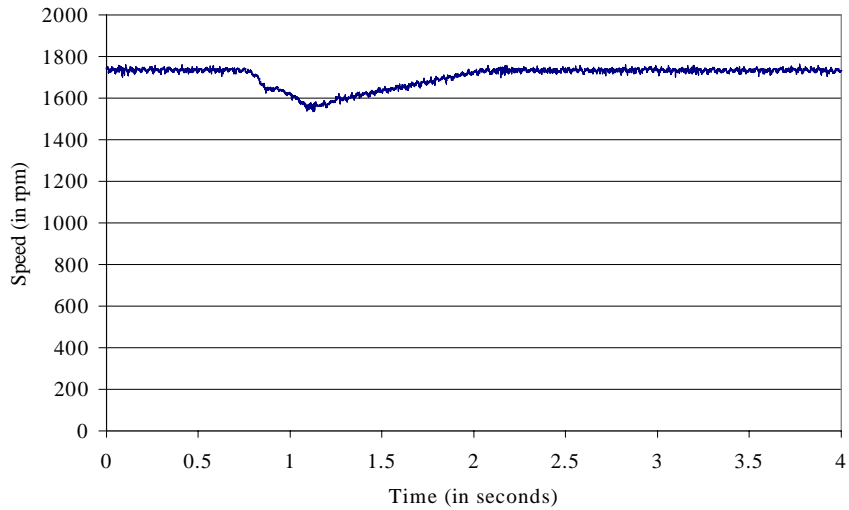
The user-programmed acceleration ramp for the ASD was 180 rpm/s. The drive's manufacturer has chosen to use this ramp for reacceleration upon recovery from a sag. Since the system speed dropped more with the constant horsepower load type, the recovery time of the constant horsepower load type takes longer. Also the total load disturbance lasted longer for the constant horsepower load than for the variable torque load, even though the initial starting power (load power) was the same. Thus, this test shows that the load type had a significant effect on the system speed and the response of the ASD after a sag even though the initial conditions for both loads was the same.

*ASD Response With Same Load Type, Different Inertia:* The next evaluation test was conducted to show how the load inertia affects the sag response on an electronic ASD. The dynamometer was programmed to apply the same constant horsepower load as in the previous test except different load inertia values were chosen for each trial. The

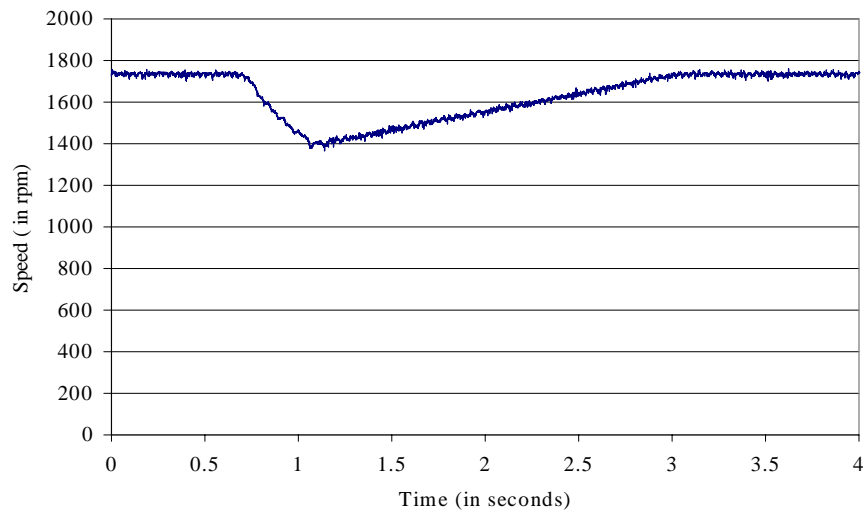
same voltage sag was applied to the electronic ASD for each trial. The load inertia values corresponded to 0.64 times, 3.6 times, and 7.7 times the motor inertia. The results are shown in Figures A-5, A-6, and A-7.



**Figure A-5**  
**ASD Response to Three-Phase Symmetrical Voltage Sag Down to 70% for a of Duration 167ms with a Constant Horsepower Load with Load Inertia of 0.00862 kg-m<sup>2</sup>**



**Figure A-6**  
**ASD Response to Three-Phase Symmetrical Voltage Sag Down to 70% for a Duration of 167ms with a Constant Horsepower Load with Load Inertia of 0.0485 kg-m<sup>2</sup>**



**Figure A-7**  
**ASD Response to Three-Phase Symmetrical Voltage Sag Down to 70% for a Duration of 167ms with a Constant Horsepower Load with Load Inertia of 0.104 kg-m<sup>2</sup>**

When the voltage sag was applied to the ASD, the system speed fell to 1100 rpm for the load with the least amount of inertia, 0.0086 kg-m<sup>2</sup>. For the load inertia values of 0.0485 kg-m<sup>2</sup> and 0.104 kg-m<sup>2</sup>, the system speed only fell to 1380 rpm and 1550 rpm, respectively. Higher load inertia values also produced slower rates of speed change before the ASD started to reaccelerate the load. This directly shows the impact of stored rotating energy on the speed fluctuation during the sag. A low inertia load supplies less energy for maintaining system speed. As a result, the system speed and the rate of deceleration were greater for the low inertia load.

## Conclusions

Traditional performance testing of electric motors and adjustable-speed drives has been conducted with dynamometers that do not behave as real industrial loads. They lack an ability to perform as a load type, and do not have adjustable inertia. Most industrial loads represent three steady-state load types: constant torque, constant horsepower, and variable torque. Furthermore, the load inertia of real industrial loads can vary widely between any two loads. When motors are tested with these dynamometers as loads under transient conditions (such as electric service system disturbances), the results are only valid for loads similar to the dynamometer itself.

The new controllable dynamic dynamometer presented is capable of reproducing all three major categories of steady-state load types: constant torque, constant power, and variable torque. It also provides the user an ability to change the load inertia seen by

the motor and ASD under test. The controllable dynamic dynamometer can reproduce the load torque of many industrial load types, such as extruders, cranes, and compressors, by emulating their steady-state and dynamic characteristics.

Two essential variables have been left out of previous voltage sag testing of electronic ASDs. The responses of the ASDs to voltage sag conditions are not dependent solely on the sag magnitude and duration, the steady-state load torque, and the ASD programming parameters. The information described above has shown that the load inertia and the load type can significantly affect process variables. Future evaluations involving ASDs and voltage disturbances should consider the impact of the load's characteristics on the response of the motor and drive.

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