Fundamentals of Inverter–Fed Motors

Technical Manual

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The Growing Use Of Inverters

The long standing desire to be able to adjust the speed of AC induction motors electronically became a reality in the early 1980's. Called Adjustable Speed Drives, Variable Frequency Drives or just Inverters, they caught on quickly due to the many advantages they offer.

Equipment builders and plant engineers quickly saw the advantages of matching the machine's speed to process needs and variables. Modern drives can control starting currents, maintain precise set speeds, quickly change speeds, control reversing and quickly stop. This makes machinery of all types more productive, improves quality and more flexible with quick change over to run different materials with a minimum of downtime. Multiple machines can be coordinated to have the right number of parts come together in the right place, and at the right time.

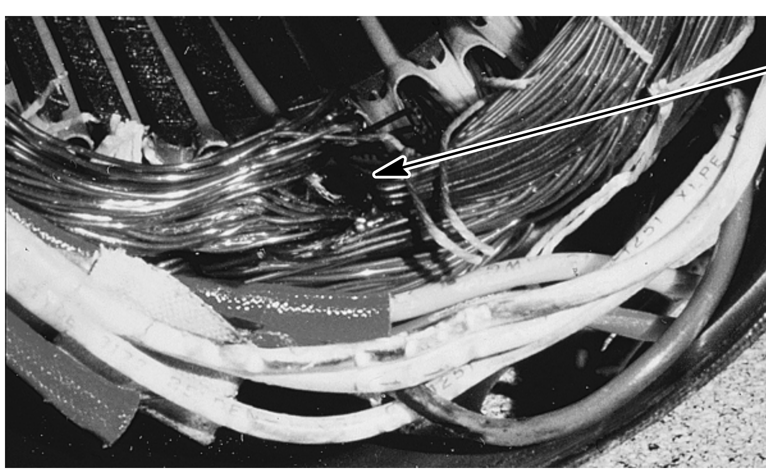
Another great advantage is the potential for energy savings. Variable torque loads like fans and pumps that vary their output by mechanical means can now adjust the motor's speed and reduce energy input by 25% to 50% with the simple addition of an inverter. They can also continuously adjust the speed to maintain a desired situation under varying system conditions.

Inverters have taken their place in machinery of all kinds: metalworking, woodworking, chemical processing, water treatment, conveyors, heating, cooling, refrigeration, hoists, and just about every industrial or commercial process. The advantages are so obvious and numerous that today there are millions of them in use and will continue to grow well into the next century.

How Inverters Affect Motors

Early inverters caused significantly higher temperature rise in the motor, and mismatched could easily burn out the motor. As new transistor devices and software attempted to minimize this effect, they introduced other stresses on the motor's insulation system. It is time to design motors specifically to operate on these new power sources. New IGBT, PWM inverters can output very high switching frequencies, very rapid changes in voltage, and transient voltage spikes that can burn pin holes in the motors insulation causing short circuits and premature motor failure.

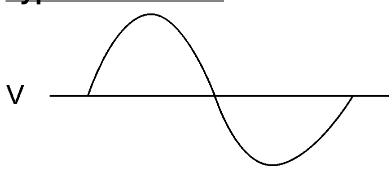
Insulation systems must be improved to prevent this cause of unscheduled and costly downtime. Other issues are increased motor noise and bearing failure. These pages address these issues and how to minimize these problems by proper equipment selection and application engineering.



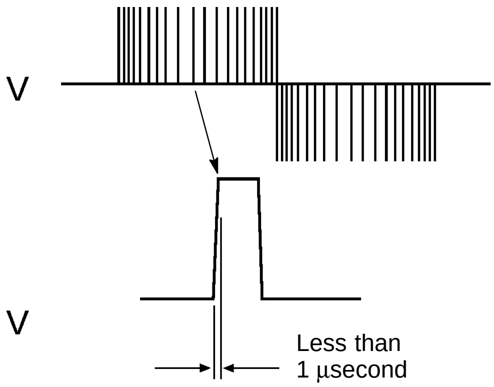
Burned Endturns

"Typical inverter spike damage to motor windings. Usually in the first turn near the lamination stack."

Typical Problems

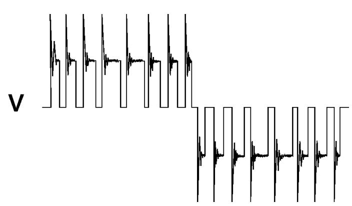


Sine Wave
The ideal power source and what induction motors were designed to run on.

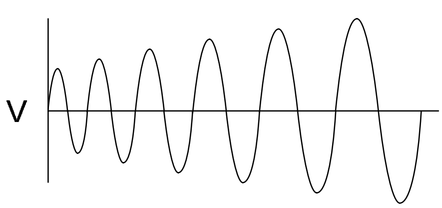


High Frequency Switching
Pulse Width Modulation attempts to simulate a sine wave by firing many full voltage pulses in rapid succession. To minimize noise, the frequency can sometimes be raised to 20,000 pulses per second.

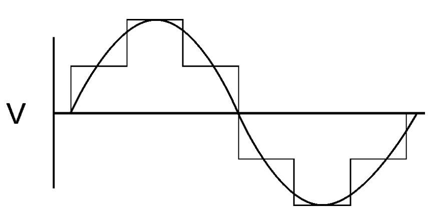
Short Rise Time
To get higher modulation frequency, each pulse must be very short and the inverter output goes from 0 volts to 650 volts DC in one–millionth of a second. This can seriously stress the motor's insulation system.



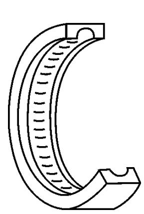
Transient Voltage Spikes
This is what the motor sees as the voltage pulse from a PWM output enters the motor windings. Each rectangular pulse begins with a spike of overvoltage nearly twice the DC bus voltage and then settles down to the bus volts. This "High Potting" can cause pin holes in the motor's insulation turn to turn or phase to phase.



Reflected Wave Voltage
Also known as standing wave and voltage ring–up. Some of the inverter output is reflected from the motor, back up the line toward the inverter. If the distance and switching frequency are right, a standing wave forms. Voltage from the inverter pulse and the reflected wave add together increasing voltage to the motor. At long distances a 460V RMS output can exceed 2000 volts at the motor terminals.



Additional Heat
Basically, any portion of the waveform that is not a sine wave is converted to heat in the windings. This is more prevalent on the older 6 step inverters but still can overheat or burn out some motors even on PWM inverters.

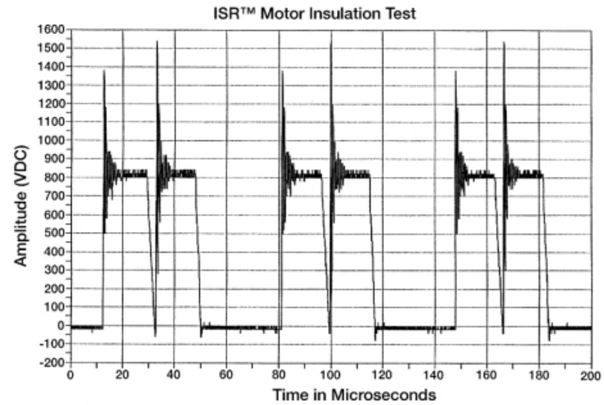


Bearing Currents
The high frequencies in the switching and transient spikes are also induced into the rotor and build up a voltage potential between the rotor and stator. This voltage is dissipated by arcing through the ball bearings. This continuous lightning storm will ruin the finish in the bearing races and cause premature failure.

Suggested Solutions

ISR – Inverter Spike Resistant™

Baldor's Inverter Spike Resistant™ wire has up to 100 times more resistance to fast rising voltage spikes, and fast rise high frequency inverter pulses as compared to standard wire. This advanced feature is standard on all Baldor Inverter Drive® and Vector Drive® motors and all standard motors 1hp and up. It is also available as an option on custom motors in most frame sizes.



3 HP 182T Frame 70 Foot Leads 15,000 Hz Switching Frequency
No Failure After More Than 2,000 Hrs

Lead Lengths

The best installation will keep inverters and motors close together. The effect of reflected wave voltage is generally not a problem if the power run is less than 15 feet (5 meters). However, as the run gets longer, voltage at the motor terminals rises higher than the insulation system's design voltage. One installation had 30 motors driven from one inverter. Although the first motor saw 460 volts (RMS), the last motor, 1000 feet of wire away saw 2000 volts. The best way to solve this problem is to not create it in the first place. Keep the run between an inverter and motor as short as possible.

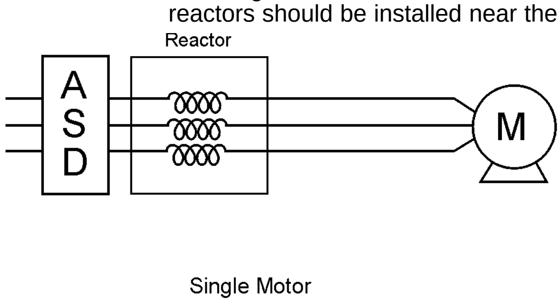
Some applications require the motor and control to be separated by distance. In some plants the motors can withstand harsh environments, but the control cannot; therefore, forcing long distances between the MCC (Motor Control Center) and the motor. Conveyors often use one inverter to control multiple motors placed along the length of the conveyor. In this case, the conveyor length dictates the distance between the motor and the control. These long distances can cause problems in motors due to fast power transistor switching frequencies and reflected waveforms that adversely affect motor winding insulation.

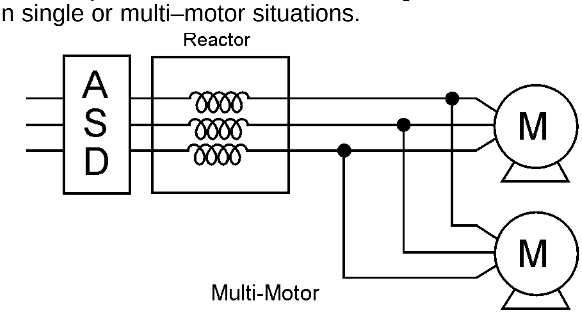
IGBT's (Insulated Gate Bipolar Transistors) are the choice of power device by most ASD makers due to their fast switching times which provide low power losses along with their ability to switch at frequencies beyond the audible range. Switching times of 100–200 nanoseconds are possible with the present generation of IGBT's. When used in a 480 volt control having a DC bus voltage of about 650 volts, the rate of change of voltage with respect to time (dv/dt) can exceed 7500 volts per microsecond. These high dv/dt voltage spikes can cause the voltage of adjacent motor windings to exceed the insulation's limits and it fails.

Reflected voltage waveforms are a function of the switching time and the length of the cable to the motor from the control. The cable acts as a transmission line with an impedance mismatch at each end. The mismatch causes the leading edge of the high frequency PWM waveforms to be reflected back in the direction from which they came. When these collide the leading edge waveforms add together causing voltage ringup which has also been termed: voltage overshoot. On a 480 VAC system it is common to find voltage spikes of 1200–1500 volts or more at the motor terminals. Higher voltage drives (575/600) can exhibit these voltage levels and higher.

Load Reactors / Low Pass Filters

Load Reactors: These add inductance to the line between the inverter and motor. This can slow down the rate of voltage increase and reduce stress on the motor's insulation. Reactors are normally specified by their impedance rating, however, Baldor stocks them in convenient hp ratings so they can be specified along with the motors and inverters. Reactors offer the additional advantage of limiting the rise in current as well as voltage. This gives added protection to the inverter in case of a short circuit on the output of the inverter. Limiting surge current gives the inverter time to shut down before amps exceed the transistor ratings. When used, reactors should be installed near the inverter in single or multi–motor situations.





Low Pass Filters: These add a combination of inductance, capacitance and resistance between the inverter and motor. These are recommended on very long runs (50ft. to several thousand ft.) to control reflected wave voltages. In most cases, these would be tuned to the natural frequency of the wire run.

Derating / Oversizing: All inverters generate more heat in the motor than a pure sine wave does. This was particularly true with the older 6–step inverters where derating the motor one hp step was standard practice. With PWM inverters, the heating is less, allowing closer hp to hp matching, most of the time. However, some motors should not be run at full load powered by an inverter even at 60 hertz. Extreme caution should be used if the motor has a class F temperature rise or 1.0 service factor. Derate these motors or go up to the next higher rating. Motors to be used on inverters should be wound in F or H insulation but operate with only a class B rise at full load. They should also have a 1.15 service factor. If the ambient temperature is high or high altitude (3300 + ft.), still derate.

Load Reactors / Low Pass Filters Continued

Shaft Grounding Inverter induced voltages in the rotor can reduce bearing life by 80% or more by continuously arcing through the bearing rotating elements. Isolating the bearing may force the rotor voltage to conduct out through the load and potentially harm it. This effect is still being studied. Baldor now has an optional grounding system that shorts the rotor voltage to ground by a brush riding on the shaft. The grounding brush is standard on 250 hp and larger stock Inverter Drive® or Vector Drive® motors and is optional on other motors.

Noise Versus Switching Frequency Inverter–fed motors always make more audible noise than line–fed motors. To reduce this effect, fast switching IGBT inverters raised the frequency of the noise into the range above human hearing. This unfortunately contributes to early insulation failure. These two are a balance of one versus the other. The optimum switching frequency is the lowest possible setting that minimizes the noise. This should be in the 2 kHZ to 5 kHZ range. Frequencies above 8 or 10 kHZ should be avoided. If not possible, apply reactors and low pass filters and consider shaft grounding.

Design In Reliability

Application Engineering

The key to a successful installation is to know, as much as possible, about the application in order to specify the right motor and control.

- Know what type of load the motor is driving.

Variable Torque	Constant Torque	Constant hp
Fans	Conveyors	Machine Tools
Centrifugal Pumps	Mixers	Centrifuge
Blowers	Compressors	Grinders

- Know the total speed range required.
  2 to 1, 3 to 1, 10 to 1, 100 to 1.......
- Know the total lead length. The total wire between motor and control. Short (less than 15 ft), medium, and long (over 200 ft.) Change the floor plan to keep lead length short, if possible.
- Know the environment.
  Is it clean, cool, dry, and dust free? Probably not. Important factors are: Altitude, ambient temperature, humidity, washdown, chemical, explosive liquids or dust, etc.

These elements will be critical to the selection of the correct inverter, motor, wiring, accessories, and protective devices and will contribute to an installation that works on its first day and reliably for years to come.

AC Motor Adjustable Speed Range Capabilities ¤

Baldor Super–E Motors 230, 460 and 575 volts

Family	Frame Size	Constant Torque	Variable Torque	Comments
EM (TEFC)	143 – 449	20:1	20:1	
EM (ODP)	143 – 445	20:1	20:1	
ECP	143 – 449	20:1	20:1	
ECP8 (IEEE 841)	143 – 449	20:1	20:1	May not meet temp rise as specified in IEEE 841 when used with ASD.
EWDM	143 - 215	20:1	20:1	Washdown Duty

Baldor Standard–E Motors 230, 460 and 575 volts

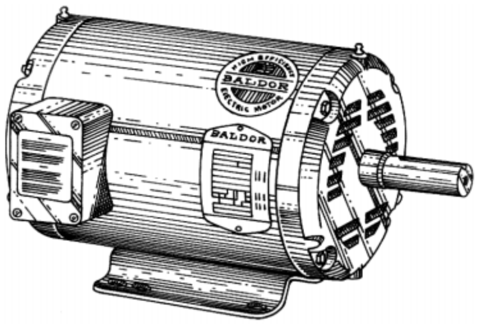
Family	Frame Size	Constant Torque	Variable Torque	Comments
M (TEFC)	143 – 5009	4:1	10:1	
M (ODP)	143 – 5009	4:1	10:1	
CP	143 – 405	4:1	10:1	
WDM	56 - 215	4:1	10:1	Washdown Duty

Baldor Inverter Duty and Vector Duty Motors 230, 460 and 575 volts

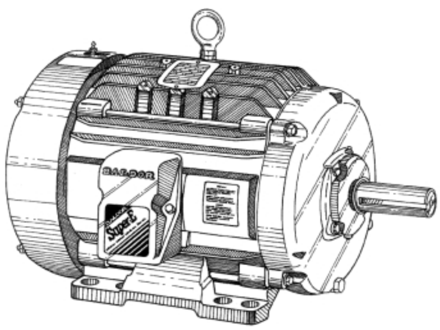
Family	Frame Size	Constant Torque	Variable Torque	Comments
IDM (TEBC) IDNV (TENV)	143 – 5009 143 - 256	1000:1 1000:1	1000:1 1000:1	
ZDM (TEBC) IDNV (TENV)	143 – 5009 143 - 256	1000:1 1000:1	1000:1 1000:1	
IDXM (2 families)	56 – 405 182 - 405	2:1 10:1	10:1 10:1	Explosion Proof
IDWNM	143 - 254	1000:1	1000:1	Washdown Duty
ZDWNM	143 - 254	1000:1	1000:1	Washdown Duty

¤ See “Select The Right Motor” for application details

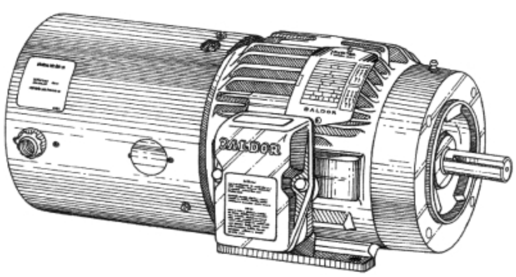
Select The Right Motor The Baldor catalog has over 200 5hp motors listed in it. Selecting the right one is a matter of matching motor features to application needs.



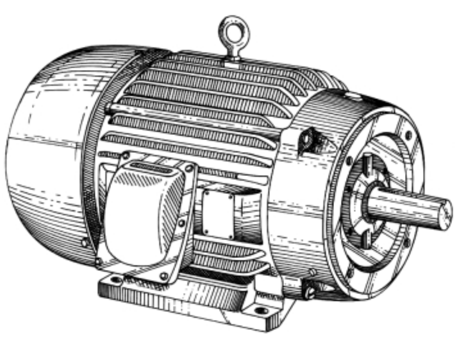
Standard–E® Motors
EPAct efficient motors are suitable for use in variable frequency applications per NEMA MG–1 part 30. With proper motor/inverter set up, Standard–E motors are suitable for use at 20:1 variable torque and 4:1 constant torque applications. It is necessary that motor–control applications are commissioned by technicians familiar with the operation and setup of adjustable speed drives, applicable electrical codes and regulations. Each control must be tuned to the motor for the specific application. System operating parameters must be checked, including voltage at the motor power leads, to ensure that motor/control set up has been successfully completed. Applications that are not properly set up can lead to substandard performance and failure of system components.



Super–E® Premium Efficient Motors
All Baldor Super–E Inverter–Ready motors meet NEMA MG–1 Part 31.4.4.2. Super–E motors are suitable for use with inverter drives in applications for variable torque and with a constant torque 20:1 speed range. Motor–inverter set up is unique to each specific application. Set up and correct wiring procedures must be closely followed.



Inverter Drive® & Vector Drive® Motors
Motors exceed all requirements of NEMA MG–1 Parts 30 and 31 for AC induction motors powered from adjustable speed controls. Definite–Purpose Inverter–Fed Polyphase Motors. Inverter Drive Motors are suitable for variable torque applications and rated 1000:1 for constant torque (except for those Inverter Duty motors rated for use in hazardous locations). Vector Drive motors are capable of full, rated torque at 0 RPM, continuous duty. Satisfactory motor performance depends on proper drive setup.



Definite Purpose Motors
Inverter Drive® washdown motors are designed for food processing sanitation requirements and still have the benefits of an inverter. These motors combine the features of an Inverter Drive® motor with a totally enclosed, non–ventilated washdown duty motor and all of its corrosion protection and sanitary finish.

Inverter Drive® explosion–proof motors are designed for flammable environments. They have been approved for adjustable speed by UL and CSA in environments of Class 1, Group D, liquid and gaseous flammables. These are rated for PWM (only) inverters in 2 to 1 speed range at constant torque and 10 to 1 speed range at variable torque.

Explosion–Proof motors
Baldor manufactures a line of Inverter–Duty explosion proof motors suitable for use with adjustable speed drives. These motors are available in 10:1 constant or variable torque or 2:1 constant and 10:1 variable torque designs. **Note: Only explosion proof motors listed for adjustable speed drives use should be used with inverter or vector drives.**

ISR – Inverter Spike Resistant™ Magnet Wire
All Baldor Inverter Drive® motors and Vector Drive® motors are protected from inverter transient voltage spikes by our unique insulation system. In addition, all of Baldor's other motors, 1 hp and larger, also contain this feature since so many of these motors are used on inverters now or in the future. These motors are built in accordance with the standards set forth in NEMA MG–1 part 31 on Performance Standards of Definite Purpose Inverter–Fed Motors.

Adjusting The Inverter

The inverter operating limits should be programmed only to the actual characteristics needed to do the job, and prevent operation outside that envelope which could harm the motor or the inverter, and produce unnecessary downtime.

Minimum And Maximum Speed Limits
Do not allow the drive to go any slower than is necessary. The motor could overheat at full load and very low speed. Inverters have programmable set points that prevent it from going below that limit. Caution should always be exercised on high speeds above 60 hertz, particularly on variable torque loads. Overspeeding only 25% will double the load on the drive system and something will fail soon. Program only the speed you need and lock out everything above and below that range.

Switching Frequency
IGBT inverters were invented to increase the number of pulses per second on PWM drives. The reason was to more closely simulate a sine wave and to reduce heat and noise in the motor. Unfortunately, the switching frequency could, on some units, be set as high as 20,000 hertz. This moves noise above human hearing but also hits the windings with voltage pulses 10 times as often as 2,000 hertz operation. The insulation could fail in only one tenth of the time. Always try to start set–up with the lowest frequency and step it up just until the noise is no longer a problem.

Acceleration / Deceleration Rates
Jack rabbit starts and emergency stops should be avoided. Maximum current at maximum voltage will not contribute to the life expectancy of the motor or the inverter. Soft starts and soft stops help all the equipment last longer and does not interrupt production with surprise downtime.

Program Motor Amps
Most modern inverters have built–in electronic overload protection. It is very important to program the motor’s full load amps (FLA) and no load amps (NLA) into the inverter. This will calibrate the trigger point for an overload relay which will shut down the system before the motor is damaged.

Reverse Lock–out
Some driven loads or machines cannot and should not be run backwards. Program the basic direction of rotation and lock out the opposite direction to prevent damage to the whole system.

Skip Frequencies
Sometimes excessive noise or vibration can happen within the system when the motor’s speed reaches a point of resonance with the driven load. Inverters include the ability to program this point out so that the output will skip over this frequency and the motor will not dwell at that point.

Installation

- Distance between the motor and inverter should be minimized. If they must be very far apart, specify a load reactor and a low pass filter in between.
- Monitor the temperature of the motor. A simple thermostat in the motor can prevent catastrophic failure from overload or too low a speed.
- Grounding is very important. The motor and inverter should be at the same ground potential and this common ground should be tied to true earth ground. Failure can occur from the motor and inverter at different voltage references.
- Load reactors can also be used as line reactors. Sometimes other equipment in the building (like compressors) or power company capacitor bank switching, can introduce line voltage spikes which may cause an inverter to shut down on overvoltage. Line/load reactors can help reduce the magnitude of the spike and let the drive continue operation.

Conclusion

Capturing the advantages of modern drive systems and their productivity enhancement need no longer be a trial and error process. With many years of experience in actual field use, we can predict the potential problems that can reduce motor life and have the materials available to make installation a success rather than a headache.

Understand the application and the environment. Select the right inverter and the right motor for that application. When appropriate, include the right optional equipment to protect the motor. Set the adjustments and tailor the drive to the needs of the application but not overstress on the equipment.

Baldor is working continuously to develop better inverters, better motors and offer the accessories that will provide the productivity and reliability that industry needs today and in the future. Baldor’s extensive and unique line of Inverter Drive® motors and ISR™ insulation system can match the right motor for your system. We can offer the right accessories to keep that system running reliably. The most expensive part of any factory or process is downtime. Keep it running and producing with Baldor. A better motor, a better quality and a better value.

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