# Optimizing Motor and Drives Packages for Best Cost of Ownership, Performance & Reliability


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***Abstract*** – In modern industrial systems, it can be shown that there is a large advantage in total cost of ownership to match driven equipment, variable speed drives, and motors at ratings which fully utilize said components. Many industries see a demand for larger and larger power ratings where the sizing of the components and selection of operating points becomes much more critical than their smaller predecessors. These operating points include the speed at which the equipment is capable of operating, at what voltage, and at what temperature. These factors will impact the initial capital cost of the system, the operating cost in terms of power consumption, as well as the flexibility or robustness of the system. The goal of this paper is to demonstrate the importance of selecting the appropriate operating voltage, as well as the benefits of matching fully utilized components. These benefits can be shown to provide enough return on investment to justify collaborative development efforts between various equipment manufacturers, thereby providing the most cost effective, reliable solutions.

## ACRONYMS

AFD - Adjustable Frequency Drive
PWM - Pulse Width Modulation
NPC - Neutral Point Clamped
IGBT - Insulated Gate Bipolar Transistor
LRT - Locked Rotor Torque
ASD - Adjustable Speed Drive
THD - Total Harmonic Distortion
CSI - Current Source Inverter
IGCT - Integrated Gate-Commutated Thyristor
GTO - Gate Turn-Off Thyristor

## I. INTRODUCTION

There is an advantage to total cost of ownership when a motor and an AFD drive are sized to work together. There is also an opportunity for considerable cost and reliability optimization of the package with a Mechanical Drive (Gear Box).

In this paper we will provide examples of the improvements in component size and cost when they are sized together as one package, verses having each component sized separately without consideration of the other components.

We will also give examples of how total cost of ownership due to efficiency improvements can be improved when taking the entire motor package into account.

We will address application considerations that must be evaluated to ensure drive train reliability over the life of the installation.

## II. What makes up a total Drive train

To understand and establish long term operational reliability, one has to first understand what makes up a complete drive train. A Drive Train is made up of an AFD, a Motor, a coupling, the driven load, and often times a Gear Box; some of which or all of which may be mounted on a common base. Each of these components has potential failure modes, and it is important to understand what can be done to avoid premature failures. In addition, it is important to understand what features and capabilities drive initial cost, operating cost, and longevity. We will first describe the various components and discuss issues that need to be considered.

### A. AFD

An AFD is a device used to convert a fixed incoming voltage and frequency (typically 50 or 60 Hz) to an outgoing voltage and frequency to the motor to achieve the voltage and speed required to produce the desired torque. Normally the voltage to the motor is directly proportional to the frequency for either a constant or variable torque output in order to achieve a constant flux (or volts per hertz) in the motor up to the maximum possible Horse Power. A voltage boost may be required at low speed to offset the voltage drop across the stator which results in lower flux and therefore lower torque. In the formula below (Equation 1), for flux ($\Phi$), the Voltage $E_{LL}$ and Frequency are proportional to each other and the flux (at the base frequency) will remain approximately constant. After the speed increases to the maximum power the motor is capable of delivering at the shaft (while remaining within the motors heat dissipation capability), the motor can be driven at constant HP and voltage with increasing frequency. However, there is a limit as to how fast the motor can run and how high a frequency an AFD can produce. Typically, motors are considered to be torque limited, the association between speed, torque, and power is given below is Equation 2.

$$\Phi = \frac{1.73 * E_{LL} * \text{Connection} * \#\text{Circuits}}{4.44 * N_s * f_e * T * K_P * K_D * 10^{-8}} \qquad \text{(Eq. 1)}$$

Where:

- $\Phi$ = Flux Per Pole (Lines)
- $E_{LL}$ = Voltage Phase to Phase
- #Circuits = # Parallel Circuits
- Connection = (1.732 for Δ) or (1 for Y)
- $N_s$ = # of Stator Slots
- $f_e$ = Rated frequency, cycles per second
- $K_P$ = Pitch Factor=Sine ((90)(Coil Span)/Slots/Pole)
- $K_D$ = Distribution factor
- T = Turns per coil

$$\tau = \frac{5252 * HP}{RPM} \quad \text{(Eq. 2)}$$

Where:

- $\tau$ = Torque (ft-lbs)
- HP = Shaft Power
- RPM = Rotational Speed

## Drive Topologies

There are several topologies that are consistently used in the current AFD offerings. An overview of the basic topologies is shown in Figure 1. These topologies perform the same basic function. Each has its own unique advantages and disadvantages and offers the user varying levels of performance.

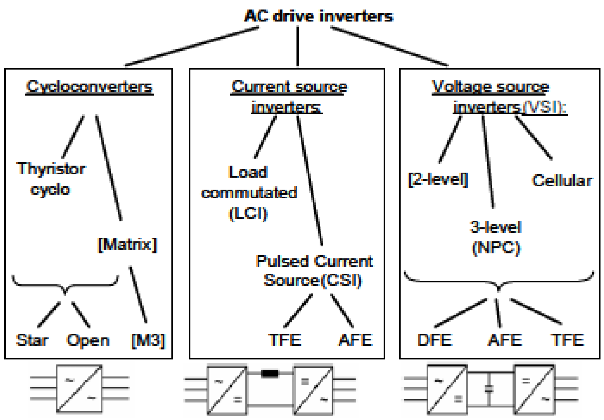



Figure 1 ASD Topologies

Although the current source, CSI topology, with its long history, is still available, it is used in less and less applications due to its inherent difficulties with the motor. These are solved by applying additional filtering, isolation and harmonic traps. CSI topology highlights the need for a systems approach to the plant-drive-motor design and selection. An apparent cost-effective solution for one component can result in a more expensive system once all the additional components required to protect the power line from distortion or shortened motor life are identified.

In general, the ASD or drive is one part of a system which includes the interface to the power grid or plant power and the interface to the motor. In the simplest cases, the drive is a turn-key system that has three wires in and three wires out and is a single integrated unit. Care must be taken when comparing the topologies because all components necessary for a successful implementation must be considered. Typically, performance numbers such as efficiency (98%) will be presented for the converter or power electronics section but this may be only one section contributing system losses and additional losses due to isolation transformers or reactors, line filters, sine-wave filters and frequency traps may be overlooked. This may result in efficiency numbers significantly worse that originally planned.

All drives convert the incoming AC line to DC through rectification. The rectification may be diodes, thyristors or transistors in Active Front Ends but they all convert the incoming AC power to a DC level. The DC voltage is filtered through a DC filter or DC Link. The DC link provides an immediate indication of the type of drive. If the DC link is a reactor, the drive is a current-source drive. When capacitors are used in the DC link, the drive is a voltage source drive.

The DC voltage is then fed to an inverter that uses semiconductor switches (IGBT, IGCT, GTO, etc.) to assemble an AC waveform which will be applied to the motor. There are various techniques used to turn on and off the inverter switching devices to develop the AC output. The output waveform frequency can also be varied along with the amplitude. We can quickly review the various topologies beginning with the current source or CSI topology shown in the simplified form in Figure 2. Note the DC link reactor which identifies it as a current source drive topology. The output inverter produces an output voltage and current that will generally require additional filtering to protect the motor and maintain a reasonable motor life.

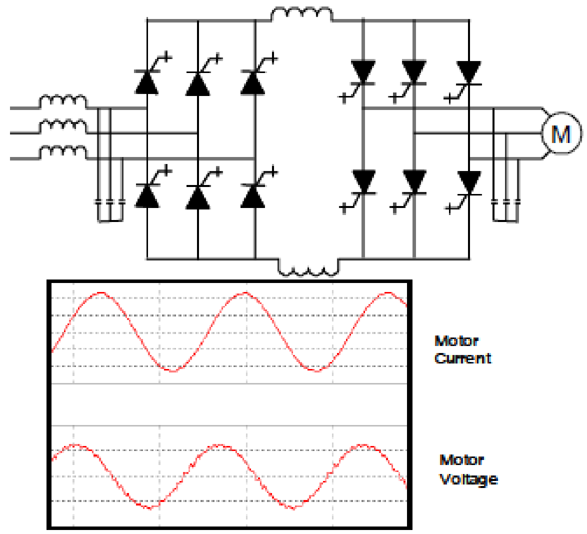



Figure 2 CSI Topology

The major voltage source topologies are (Neutral Point Clamped) NPC, flying capacitor NPC and cascaded H-bridge. The flying capacitor NPC is a version of the classic NPC topology but allows for another level of voltage step and therefore improves the quality of the output waveform presented to the motor. However, it has not been a sustained design approach.

The typical NPC shown in Figure 3 will generate a multi-level output waveform of either two to five levels. The number of levels will directly affect the motor. With a two or three level drive, output filters must be used to preserve motor life. Additionally steps must be taken to eliminate common mode voltages that could damage the motor bearing.

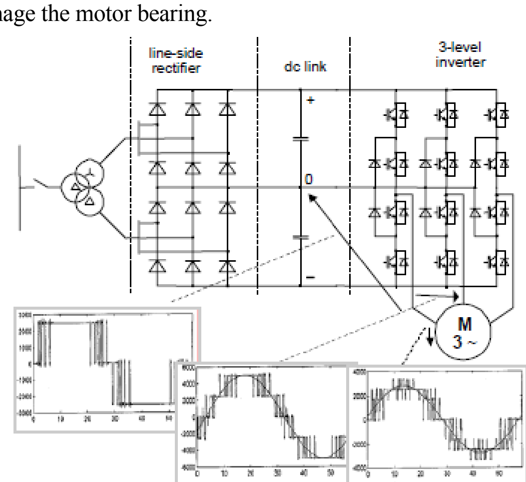



Figure 3 NPC Topology

The last and most complex, but highest performing, drive topology is the cascaded H-bridge which can use individual power modules. These can be a single module per phase or multiple power modules located in each phase. The advantage of the latter arrangement is the availability of a redundancy and bypass feature that can allow the drive to continue to run if a power module failure occurs. One form of the cascaded H-bridge topology is shown in Figure 4. The individual power modules are shown connected in series with the power module schematic.

The cascaded H-bridge topology allows for additional levels to improve the quality of the output waveform presented to the motor. Typically, these topologies will not require any additional output filtering to ensure rated motor life. The output waveform presented to the motor is in many cases no different than that of the line and the drive is transparent to the motor.

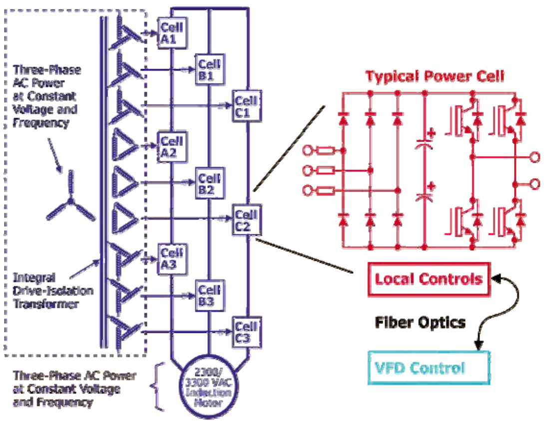



Figure 4 Typical Cascaded H-bridge topology

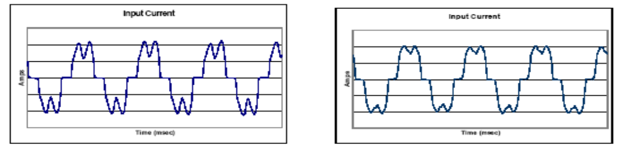
There are many performance characteristics that might interest an end user of drives. However, there are two primary concerns that will dominate the application of the drive:

1. The effect of the drive on the plant power
2. The effect of the drive on the motor

Both drive input and output characteristics are discussed in the following paragraphs.

### Drive Input Characteristics

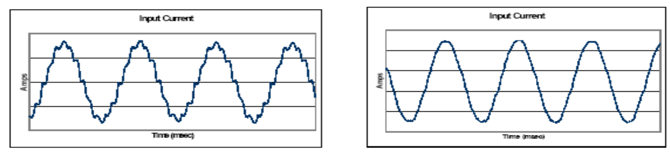
Typically, power electronics tend to distort the incoming line due to line notching and distortion of the fundamental sine wave. This distortion and the associated harmonics may cause unwanted heating in transformers and motors attached to the power line. Industry has adopted IEEE-519 as a standard for the allowable distortion of the power grid at a plant's common point of coupling. However, most drive manufacturer's today attempt to meet IEEE-519 at the input terminals of the drive. The predominant performance specification for input power line distortion can be approximated by understanding the pulse count of a particular drive. Higher pulse counts reduce line distortion and if high enough can meet the IEEE-519 standard at the drive terminals thus eliminating any concerns within the plant. The pulse count is derived from the rectification process first observed in low voltage drives. A typical input line waveform is shown in Figure 5(a) while operating on a 6-pulse drive. The 6-pulse terminology is derived from the 6 diodes in a three-phase full bridge rectifier and the 6-pulses that are generated in that circuit.



Current THD = 31.4% 6-Pulse Front-end | Current THD = 24.2% 6-Pulse Front-end plus 3% Line Reactor

Fig 5(a) 6-pulse line side waveforms

Early drives used two diode bridges to generate a 12-pulse arrangement which was then filtered to meet industry standards. Multi-pulse transformers extended the 12-pulse arrangement so that a minimum pulse count of 18 is now the industry standard as shown in Figure 5(b).



Current THD = 9.1% 12-Pulse Front-end | Current THD = 4.8% 18-Pulse Front-end

Figure 5(b) 12 and 18 pulse waveforms

In multi-cell, cascaded H-bridge arrangements the pulse count can be as high as 36 or 48 pulse. As a general rule, the higher the pulse count, the more sinusoidal and less distortion will be present on the incoming line with 18 being the minimum required to meet IEEE-519 distortion limits. Pulse count will always refer to the line side of the drive and apply to incoming power distortion.

### Drive Output Characteristics

The second and perhaps most important concern is the effect of the drive on the motor. The drive must be designed so that the peak voltages do not exceed the motor insulation system and the dv/dt does not cause failures or insulation shoot through. Since modern semiconductor devices can turn on very quickly (microseconds) the voltage that is switched on can present a very fast rising voltage wave front to the motor. Due to the high voltage spikes associated with dv/dt, adjacent windings in the motor may develop high voltage potentials between the windings which exceed the insulation system ratings. In the past and with some existing designs, an inverter grade motor was specified with a more robust insulation system. Today, most drives that switch high voltages will require and specify a motor with twice rated insulation or will add a dv/dt filter to the output of the drive.

The different drive topologies vary in their approach to output voltage quality. The simplest topologies such as the 3 to 5-level Neutral Point Clamp (NPC) drives are switching very high voltages and in some cases the full motor voltage which causes extremely high dv/dt values and almost all of these topologies will require some sort of filter to protect the motor from their inherent high voltages. The cascaded H-bridge is a more complex drive but switches low voltages with an associated elimination of dv/dt concerns and can be used with standard motors. In general, the NPC topologies will produce voltage spikes two to three times higher than the multi-bridge, cascaded designs. The additional advantage of at least one of the cascaded bridge topologies is the possibility of power electronics redundancy which allows the drive to continue operation with one or more failed power electronics modules.

A multi-level drive using more levels to build up an output waveform will generally not require any additional output devices to improve the output waveform to minimize the reduction of motor life due to voltage spikes and harmonic heating. A waveform taken from a cascaded H-bridge is shown in Figure 6. From the waveform, the voltage steps can be seen. Note that the current waveform is very clean and sinusoidal and causes no additional heating in the motor.

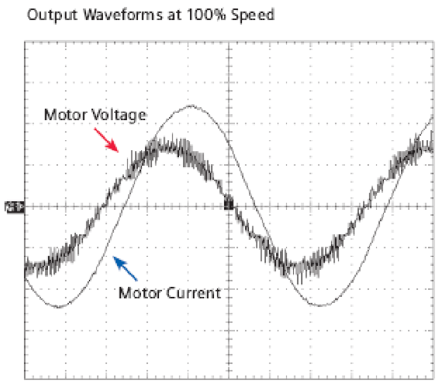



Figure 6 Cascaded H-bridge Output Waveforms

The output waveform quality or total harmonic distortion (THD) will also cause motor heating and reduce the motor life. This poor output waveform is usually improved with the addition of filtering and/or harmonic filter traps located on the output of the drive. Some of these can be quite large and are usually located in a separate enclosure. Consequently, the additional losses are not always represented in the overall efficiency numbers. An additional concern when using output harmonic filter traps, usually designed for specific frequencies of 5$^{th}$ and 7$^{th}$ harmonics is the possibility of resonance and additional power line disturbances caused by the filter itself.

Another effect that drives may have on the motor is the possibility of allowing the generation of motor bearing currents. Motor bearing currents are generally the result of common mode voltages present on the drive output voltage. These common mode voltages develop a voltage potential across the motor bearing which in turn cause bearing current to flow through the motor bearing. Eventually, bearing failure may occur due to pitting and degradation of the bearings due to the common mode voltage and associated current. The simplest method in the drive for mitigating the flow of bearing currents is the use of an input transformer located on the line side of the drive. Adding an input transformer to the drive increases the capacitance to ground and reduces the voltage available to generate motor bearing currents. As shown in Figure 7, the capacitance may be as much as ten times greater than the motor capacitance and acts as a voltage divider reducing the voltage present across the motor bearing.

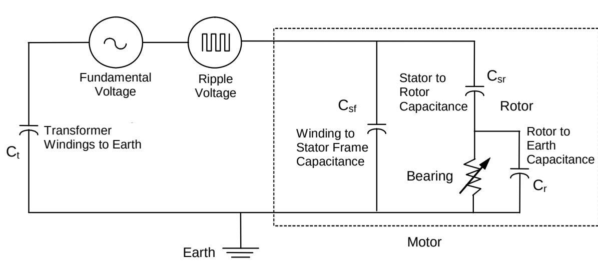



Figure 7 Drive-Motor Bearing Currents

In topologies that require no isolation transformer, typically where the line voltage and motor voltage are identical, the potential for motor bearing currents is great and must be addressed

An additional advantage of cascaded H-bridge topologies is their inherent reduction of common mode voltages. Because these topologies switch their semiconductors at much lower voltages, this voltage step can be much lower than the associated voltage switching steps of the NPC topologies. This voltage step is what contributes to the common mode voltage and the reduction of the switching voltage step is directly proportional to a reduction in the voltage that can be developed across the motor bearing.

### Drive Conclusions

The input pulse count of the drive system will determine the drives effect on the power grid within the plant. The effect of the drive on the motor is driven by three major performance characteristics:

1. Output Voltage levels
2. Output Waveform Harmonics THD and dv/dt
3. Common mode voltage

The more output voltage levels used to develop or "assemble" the output waveform, the more sinusoidal the output voltage present on the motor stator will be.

Smaller voltage steps associated with the voltage that is switched by the semiconductor devices reduces the dv/dt and common mode voltage that can contribute to the reduction of motor life. Insulation shoot-through failures, particularly in the end turns and bearing currents can be reduced or eliminated by the use of multi-level H-bridge designs or by the addition of filters, reactors, and harmonic traps on lower-level output topologies.

The addition of filters, reactors, and harmonic traps should also be included in over-all system efficiency calculations. In many cases these are overlooked and result in performance efficiency losses greater than originally specified.

## B. Motors

The motor is used to convert electrical power into mechanical power. Base speed and voltage can vary within a range to achieve the desired output. Voltage input to motor, if intended for across the line operation, will be defined by the fixed voltage of the power system, for example 460, 4000, 6600 volts etc. If motor will always be driven from an AFD and never be connected to a main power system then there may be considerable flexibility in input voltage. You can see from the flux formula in equation 1, there are almost infinite possible input voltages. The biggest limitation is a result of too few turns on a coil due to high power output and low voltage or too many turns on the coil as a result of too high a voltage and too low a power output. Beyond that, virtually every other voltage in between is possible. This becomes of interest later when we talk about using this flexibility to better optimize the motor drive package.

Power output capability is strictly the result of the ability to adequately cool the machine and produce enough flux to generate the needed torque.

The motor is subject to many environmental conditions and concerns that must be addressed. This includes all the following surrounding and ambient conditions:

1) Environmental (contamination in cooling)
2) Environmental (contamination in contact with frame)
    a) Enclosure Required
3) Maximum Ambient Temperature
4) Minimum Ambient Temperature
5) Ambient Temperature swings
6) Altitude
7) Ambient Motion/Vibration
8) Hazardous Area
9) System Vibration

1) Enclosure

This paper will not go into great detail regarding the different enclosure types. Please see Ref. [4] for enclosure descriptions. The environmental conditions along with mechanical stress will dictate the motor enclosure required. The motor must be clearly defined by the user, the system installer, or possibly with help of the motor manufacturer if asked to assist. It is therefore important that the user has a basic understanding of what enclosure is needed to ensure product reliability and possibly the safe use of the motor. In the section under specification requirements we will define the necessary information required to ensure one chooses the proper motor with necessary environmental protection.

2) Stator

Motors life expectancy is directly affected by the magnitude of the voltage, and how often the voltage oscillates from a voltage level below its corona inception and extinction voltages to its peak level above its corona inception voltage. On a sinusoidal supply, this would occur as the voltage swings from zero to peak.

It is also affected by the temperature of the winding throughout its life. These are both typically referred to as the voltage endurance life and the thermal endurance life (see Figure 8). Life can be greatly extended if not continuously running at maximum voltage or temperature. Life is a function of voltage stress and temperature over time but it is common not to see any degradation in expected motor life until exceeding the nominal temperature class of the machine (ex. 135 degrees for a "B" rated thermal class). Also, under normal conditions, the voltage endurance can far exceed the thermal endurance when operating even at normal temperatures; not until much higher voltage stresses are seen would voltage endurance be considered a primary aging mechanism. The electrical stresses coming from the drive to the motor must be clearly defined so that the motor manufacturer can design the motor with adequate stator insulation to protect the machines from excessive voltage thereby ensuring product reliability.

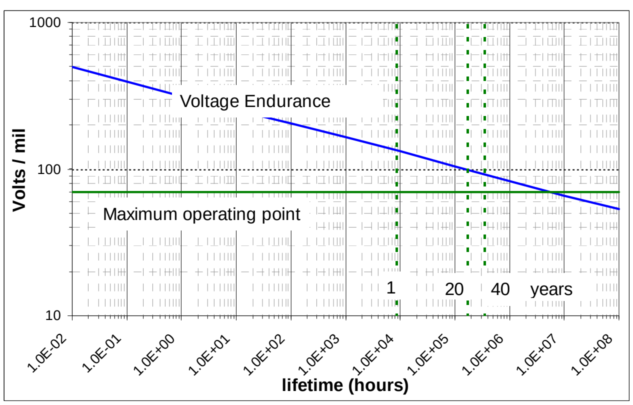



Figure 8. Voltage endurance

3) Rotor

Rotors in AFD applications are subject to different service conditions than when used on a fixed power supply. While some of the conditions improve reliability, others can drastically reduce reliability if not properly considered in the design. Since starting on an AFD does not introduce the same high transient torques as exists when the voltage to the motor is thrown across the line, the shaft stresses will be considerably less. However, there is a much greater risk of running on a lateral or Torsional resonance when the system can potentially run at any speed vs. one fixed speed. One can see the relative order, of the vibratory forcing frequency on the right hand side of Fig. 9, as a function of 1-12 times the rotational speed. This is dependent on the number of Torsional pulsations per revolution. For example, a 4-piston or 4-lobe compressor will produce a pulsating force at 4 times the rotational speed. There are also fixed Torsional resonate frequencies of the drive train system. In the graph we show 2 possible resonances, both of which have an upper and lower frequency range between which vibratory forces must be avoided to minimize excessive vibration. One must also keep in mind these ranges could vary from the calculations due to manufacturing variation.

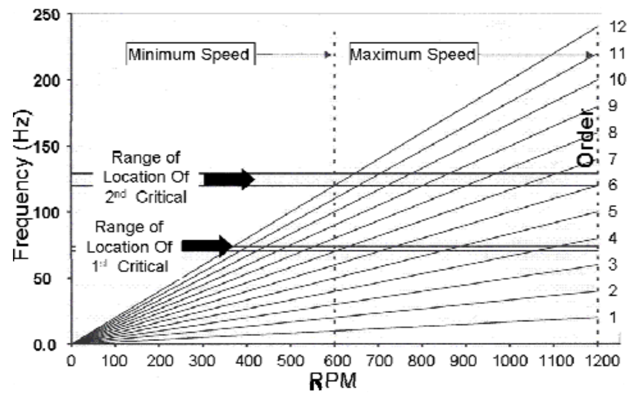



Figure 9. Campbell Diagram

For example, components such as the motor shaft stiffness are greatly influenced by the shrink onto the shaft. On spider shafts, one or all welded spider arms can contribute to the stiffness. In the example shown, in the Campbell Diagram, a 7 order vibratory force would need to avoid system speeds in ranges between 610-650 RPM and 1020-1100 RPM. Additional margins from these speed ranges will need to be considered depending on the amplification. If a second resonance such as a air compression chamber resonance (acoustical resonance) exists at the same frequency the force magnitude can be greatly increased. To avoid problems, field testing to verify resonant frequencies is highly recommended.

*Some Benefits of a Motor on an AFD*

When starting on an AFD, the stator winding, rotor bars and end connectors are not subject to high temperatures and thermal stresses due to the typical 6.5 times rated amps, seen on across the line start up. This is sometimes referred to as a soft start (not to be confused with SCR soft starters). Since the motor is brought up to speed with a very low slip frequency, the inrush and locked rotor torque concerns do not exist. In many cases this allows for higher motor efficiency. The rotor bar can often be designed slightly larger, yielding lower rotor I2R loss. Additionally, certain features of die-cast rotors can be removed which are no longer necessary. The narrow tips of die-cast rotors may be prone to porosity and uneven heating, as well as increased susceptibility to electrically induced vibration.

As previously mentioned, the motor is brought up to speed with a very low slip frequency. This means that starting on an AFD the frequency of the magnetic field seen by the rotor bars when starting will remain low at slip frequency since the rotor's rotational speed closely equals the rotation of the stator's field with only a small slip. This is quite different to an across the line starting process, where the stator magnetic field is rotating much faster than the rotor and can be quite detrimental to the rotor. At stand still the stator produces a 60 HZ magnetic field and 120Hz magnetic force (magnetostriction) when operated on a 60 HZ power supply. The rotor bars will therefore see a high frequency oscillating field which will force the current, due to the skin effect, into the upper .375 to .5 inches of the bar as shown in Fig 14, and then only distribute downward into the lower part of the bar as the motor comes up to speed. The interaction of the high current in the bars and the magnetic field will produce a high radial vibratory force on the rotor bars which could eventually cause the bars to break near the end connector joints. In addition, particularly on high inertia applications, the high rotor bar current in the top part of the rotor bar will produce uneven heating and bending of the rotor bars Fig. 10 which will produces excessive stresses at the end connector joints. See paper on Copper vs. Aluminum rotor bars for more details on this [5].

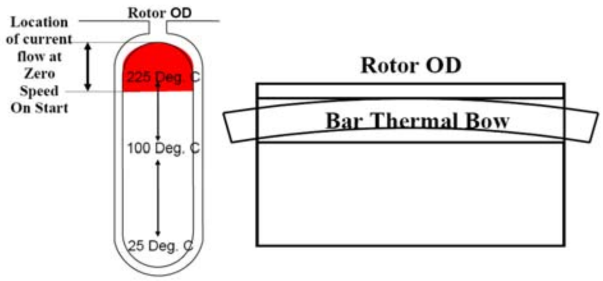



Figure 10. Current and Heat distribution resulting from skin effect during locked or starting conditions

Acceleration of high inertia loads: High inertia loads can be accelerated on an AFD with a current and torque not exceeding rated. Acceleration can be extended to accelerate at whatever rate is necessary to achieve the proper speed, without damage to the motor or as to meet process requirements. If a faster acceleration is necessary, most times the motor and drive can deliver up to 150% rated torque with approximately 150% rated current. This is a much greater torque per current ratio than an across the line start where one would normally get less than 100% rated torque with 650% rated current

Transient torque Reduction: When starting the motor across the line, the motor shaft and entire system can see a transient torque up to 6.5 times the LRT, for a short duration. This can do damage to the motor shaft, coupling or driven load if not properly sized. Keep in mind that if the motor operates on a ASD and never sees this transient torque it would not be necessary to build the extra cost into the shaft or coupling.

*Negative Impacts to Motor running on AFD*

1) Noise and vibration

There exist many various potential issues when operating at variable speed. There exists the potential to pass through structural resonances, rotor shaft lateral critical or reed critical frequencies in the case of vertical machines.

Acoustic resonances that exist at specific rotational speeds may cause minor or, in rare cases, major issues. Those resonances can be magnetic noise, whistling of vents, or other housing resonances based on volume and dimension.

In these cases, it may be necessary to block out a speed range, such that continuous operation at or near those speeds would not be allowed.

2) Stator

The motor stator may in some cases be exposed to much higher peak voltage stresses than normal. Certain standards exist to calculate what peak voltage output certain drive topologies would yield for example 61800-8. The peak voltage, base frequency, and total peak count will impact where on the voltage endurance curve the motor will operate and thusly it's resulting lifetime. The dv/dt resulting from certain drive topologies (in particular but not limited to lower voltages) will require attention to the motor winding's turn insulation. Higher voltage machines must have an adequate corona protection and stress grading to mitigate this problem.

Higher harmonics also contribute to motor heating. Drives with significant current THD% will be most notorious for increasing stator $I^2R$ losses. High harmonic content may cause additional iron losses as well, which also contributes to motor heating. The additional losses may contribute 8-12% or more additional heating. This will result in a direct impact to the total thermal lifetime. One must also be concerned if motor is intended to operate in a hazardous area where all internal and external surface temperatures must be maintained below a certain level at any operating condition.

3) Rotor

As previously mentioned, the system may pass through rotor lateral critical speeds, inducing high vibration, and wear on components. Additionally, harmonic content can occasionally result in torsional stresses. It is possible to excite torsional resonance in some cases, as well as experience torsional resonances which are cross-coupled with lateral critical speeds. Torsional stresses may also be induced by cyclic loading and/or cyclic speed changes. Reciprocating compressors are known for this even during normal operation, that example is provided to express a certain similarity. The stress induced by cyclic operation may in some cases exceed the endurance limit of the shaft, materials, or rotor assembly and therefore have a finite life less that $10^6$ cycles. The loading scenario should be communicated such that the rotor may be adequately designed to prevent fatigue failures.

C. Gearbox and couplings

In selection of the gearbox and couplings for a system, it is critical to consider various aspects of the system and application. It is important to select the correct gear ratio corresponding to the correct pole count motor and operating frequency to result in the desired output speed. For example, certain benefits can be seen when picking a higher speed motor which would then result in a higher gear ratio or lower operating frequency if the driven equipment operates at very slow speeds, due to the power density for a given motor type with certain pole counts. It would typically be the case that slower speed motors have a substantially lower power output capability for a given size and that higher gear ratios can lead into larger gearboxes (in particular when additional gear stages are required). Optimizing this combination can reduce initial capital investment.

The gearbox must be sized adequately to handle certain shock loading scenarios, overload capability, and starting duty. Also, consideration must be paid to the rotordynamics of the complete system. The design of the gearbox may also change for variable speed operation, variable torque loading, bidirectional operation (in the case of some fan cooled arrangements), and other aspects. However, operation on a drive can substantially alleviate the shock load seen during startup. Other shock load seen directly from the driven equipment and the process is common in certain applications (i.e. crushers, heavy duty conveyors, reciprocating compressors).

Coupling selection criteria must also suit the application. Factors affecting coupling selection include mis-alignment capability, coupling mass, torsional or lateral stiffness, torque transmission, maximum speed, and any effect on drive train rotordynamics. Mechanical couplings are by far the most common, but other options include for example fluid couplings. In applications where a variable speed drive would only be needed for starting, these may be an especially attractive option. Additionally, under certain circumstances, they may be used to alleviate shock loading.

## III. System Considerations

To ensure drive train reliability there are variety of issues that must be addressed. The first thing would be to answer a few questions. Table 1 is provided on the following page to help identify or remind the reader of the issues. Table 1 refers to the section & part in the paper that describes the issue in detail which needs to address.

### A. Application

1) Driven Equipment e.g. Fan, Pump, Compressor

It is important that the manufacturer knows the application in which the driving equipment is to operate. This will provide valuable information regarding loading at different speeds. Induction motors tend to run hotter at lower speeds in constant torque applications (See Fig. 11) which have approximately constant amps, but normally if it is a variable torque application the amps will drop with speed, as would the motor operating temperature.

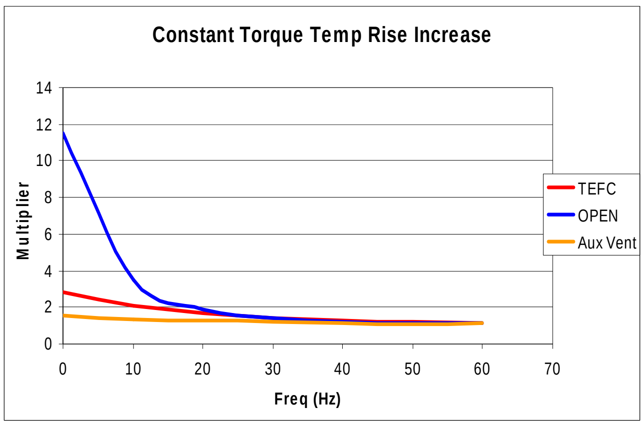



Figure 11. P.U. Temperature rise increase at lower speed

2) Inertia ($WK^2$)

Inertia is critical for across the line starting since it is needed to determine the acceleration time and how much heat is generated during starting, It is also important in AFD applications to understand how fast the speed can be adjusted with the available torque.

3) Duty cycle

The thermal life is a function of Temperature and time. If the machine is only to operate for short period of time at higher loads it may be oversized if designed around the maximum load point which gives the maximum continuous temperature rise. The benefits of using an AFD are very dependent on the loading and speed conditions. If the speed and loading are nearly constant, the drive will off less advantage and may in some cases decrease the system efficiency.

4) Starts per day

Number of accelerations is normally critical for across the line start but may also be important on an AFD if the machine is to accelerate to a speed in which the stress cycles beyond the endurance limit. In either case a machine may have a finite number of starts.

5) Horsepower (HP) or kilowatt rating

The nameplate HP or kW rating is the basis for the design but does not tell the full story if operated on an AFD. Then the duty cycle and other loading conditions become critical.

6.) Speed Range

The speed range is critical not only to understand the thermal effects due to speed and load changes as mentioned in duty cycle. If a gear box is provided it is important to know design around the speed and torque at each end.

7.) Torque or HP requirement throughout speed ranges

Similar to above under duty cycle the HP & KW rating through out speed range is critical

8.) Is AFD Bypass required

If AFD bypass is required then motor must be capable of starting across the line. Motor must have torque and starting current suitable for the application. Motor Design Engineering will not be able to optimize design for lower cost of ownership as well as if bypass was not required.

9.) Is Overload Required, Duty Cycle, & Frequency

It is common that a motor and drive can handle a 50% overload for up to 2 minutes, but needs to be communicated to ensure the best design. Also important to note is the amount of time needed to cool before overloading can occur again. In one example, a motor application required 1.37% overload for 2 minutes once per hour, however did not require extra cooling until after 6.5 minutes of overloading an hour. The requirement was changed to add various overloading points and cooling times.

8) Service Factor

Service Factor represents a potential overload condition. This will affect the insulation life of the motor insulation as well as the Torsional shaft stresses on all the equipment.

9) Temperature rise limit on each component

All temperature requirements for Motor drive or gear box need to be clearly communicated

10) Mounting

Special mounting requirements must be communicated

11) Dynamic Braking

If dynamic breaking is required drive will need to be designed with an active front end and motor must be able to take the additional heating related to that part of the duty cycle.

12) Additional specification requirements

Any additional specification requirements, such as requirement to comply with IEEE 519 (in the case of the drive) must be communicated. These requirements may, in some occasions, require specialized solutions.

### B. Applicable Standards

All applicable standards should be identified. Listed below are some of the common ones. If the standard is not identified as a requirement there are no guarantees the product will be design to meet them. For example unless the voltage withstand levels of MG 1 part 31 or IEC 60034-25 and invoked as a requirement the design will be per agreement of the purchaser and vendor.

1) NEMA MG 1 Part 31
2) IEC 60034-25
3) IEEE 112
4) IEEE 519
5) API 541 or API 547
6) IEEE 841
7) IEEE 1566

| | Motor | AFD | Gearbox | g | Base |
|---|---|---|---|---|---|
| Application *(I,e, Pump,Fan Compressor)* | See III-A-1 | | | | |
| Hazardous Area | See III-C-7 | | | | |
| Enviorment | See III-C | | | | |
| Enclosure Required | III-C-1 | III-C-1 | III-C-1 | III-C-1 | III-C-1 |
| Load Wk2 | III-A-2 | | | | |
| Ambient Motion/Vibration | See III-C-5 | | | | |
| Altitude | See III-C-6 | | | | |
| Gearbox rating as per AGMA or DIN? | | | See III-F | | |
| Pulley Diameter if Applicable Output | See III-F | | See III-F | | |
| Pulley Diameter if Applicable Input | | | See III-F | | |
| Backstop required? | See III-G | See III-G | | | |
| Drive Output Filter | See III-E | | | | |
| HP/KW | III-A-5 | III-A-5 | III-A-5 | III-A-5 | III-A-5 |
| Service Factor | III-A-10 | III-A-10 | III-A-10 | III-A-10 | |
| Motor FLA | III-E | III-E | III-E | III-E | |
| Voltage Into Motor | III-E,D | III-E,D | | | |
| Voltage in to Drive | III-E,D | III-E,D | | | |
| Cable In | III-D | III-D | | | |
| Cable Out | | III-D | | | |
| Gear Ratio N2/N1 | | | III-F | | |
| RPM (Base) *(Input to Gearbox)* | III-A-6 | | III-A-6 | | |
| Duty Cycle | III-A-3 | III-A-3 | III-A-3 | III-A-3 | III-A-3 |
| Starts per Day | III-A-4 | III-A-4 | III-A-4 | III-A-4 | III-A-4 |
| Speed Range | III-A | III-A | III-A | III-A | III-A |
| Variable Torque Speed Range | III-A | III-A | III-A | III-A | III-A |
| Constant Torque Speed Range | III-A | III-A | III-A | III-A | III-A |
| CHP Speed Range | III-A | III-A | III-A | III-A | III-A |
| Motor (Base) Voltage | III-E,D | III-D | | | |
| Motor Required to start on Bypass | III-A-8 | III-A-8 | III-A-8 | III-A-8 | |
| AFD Overload *(i.e.150% Torque for 60 Sec, 1/Hr up to Base Speed)* | | III-A-9 | | | |
| Max Ambient Temp | III-C-2,4 | III-C-2,4 | III-C-2,4 | III-C-2,4 | III-C-2,4 |
| Min Ambient Temp | III-C-3,4 | III-C-3,4 | III-C-3,4 | III-C-3,4 | III-C-3,4 |
| Temp Rise Limit of Product | III-A-11 | III-A-11 | III-A-11 | III-A-11 | III-A-11 |
| Mounting *(Horiz., Vert.)* | H or V | | | | |
| Connection | III-D,E | III-D | | | |
| Bearing Type | III-G | | III-G | | |
| Lubrication | III-G | | III-G | III-G | |
| Bearing Life in Hours | III-G | | III-G | | |
| Insulated Bearings/Couplings | III-E | | III-E | III-E | |
| Special Inverter duty Insulation | III-E | | | | |
| Drive Bypass Starting *(90% voltage min at Motor)* | | III-A-8 | | | |
| Accessories *(Space Heaters, 100 Ohm RTD's Vibration Detectors, etc.* | III-G | III-G | III-G | | |
| List all Applicable Standards | III-3-B | III-3-B | III-3-B | | |
| Tachometer *(Yes, Single Output, 1024 PPR, 5-18vDC)* | III-G | | | | |
| Dynamic Braking | | III-A-13 | | | |
| Who is Responsibility for Interfacing Driven Equip. | Must be established who has system responsible and responsible for ensuring all the equipment works together. | | | | |

Table 1. Application Issues that Need Considerations

## C. Environmental

1) Environmental (contamination) Enclosure Required
The enclosure must be chosen to minimize the entrance of contaminants that could be harmful to the equipment. Different chemicals such as sulfur, Hydrocarbons, Chlorine, conductive dust and water can have detrimental effect on the equipment and must be communicated

2) Maximum Ambient Temperature
All equipment has limitations on maximum allowable ambient temperatures so as to limit the total temperature and maintain an adequate expected life as discussed in section II-B-2.

3) Minimum Ambient Temperature
Also most equipment has limitations on minimum allowed operating temperatures. Oil temperatures too low will not flow and lubricated the equipment and cast-iron and shafts can become extremely bridal at low temperatures.

4) Ambient Temperature swings
One reason to be concerned with ambient swings is the thermal growth of different equipment (e.g. motor, gearbox, and load) may not allow the equipment to be compatible. For example differences in shaft height growth could lead to misalignment at different ambient temperatures.

5) Ambient Motion/Vibration
Vibration or movement of a motor which is not moving can cause false embitterment of the bearings

6) Altitude
High altitudes reduce the density of the air decreasing its ability to cool the equipment and can lead to an increase in corona.

7) Hazardous Area
If product is to be located in a hazardous area, to ensure safety, the Class Group and division or zone should be identified. Different gasses and dusts have different ignition temperatures. The motor may run hotter due to harmonics coming out of the drive, or when running at speeds which produce less effective cooling. All this must be taken into account when designing the system.

## D. Voltage & Frequency to AFDS

It is important to know if the AFD has a filtered output or a need for a filtered output so the motor can be designed appropriately. The required location for all cable inputs and outputs needs to be documented. It may be required that the motor be connected in a Y or delta connection or with a special quantity of lead brought out. This needs to be clearly communicated.

1) Does AFD have a filter output
2) Cable In
3) Cable out

## E. Voltage Levels and Cleanliness, including Need for Insulated Bearings.

It is clear that it is important to understand what the base voltage and frequency are. It is also critical to know if a filter is provided or required. The full load current must also be known by the system integrator so as the size the drive, cabling and other auxiliary equipment. Voltage levels to the motor will also need to be communicated to ensure the proper level of insulation is provided.

As was discussed earlier in this paper, the drive and systems can be designed to minimize the need for insulated bearings, but it may be more economical at times, to address it in the motor and insulate the motor bearings. This may not protect the driven equipment so it may be necessary to provide an insulated coupling.

1) Motor Base Voltage
2) Is filter required to reduce voltage stress or prevent excess heating
3) Motor Full load current

4) Special Connection Required
5) Insulated bearings required 1 or 2.
6) Insulated coupling
7) Special Level of motor winding insulation

**F. Gear Box Rating (AGMA or DIN) & Couplings**

1) Pulley Diameter out of Motor
2) Pulley Diameter to Gear Box
3) Pulley Diameter Out of Gear Box
4) Gear ratio

**G. Accessories & Other**

There are many time special options or configurations required by the end user or system integrator. There are many performance, environmental or reliability reasons for these options. In any case they need to be clearly communicated to all the appropriate OEM's

1) Backstop Required
2) Space Heaters
3) RTD's
4) Vibration Detection
5) Tachometer
6) Bearing Type
7) Lubrication
8) Bearing Life

## IV. Total Cost of Ownership

The following figures show relative cost of motors and drives change with power. It would be advantageous to design products that fall in line with certain minimized costs. That is to say that cases where maximum power output of a particular drive, motor, gearbox, and load all nearly match, there would be very large cost advantages. Due to common application of certain size products over various power ranges, the cost per horsepower is minimized where the rating is at the maximum available from that certain size motor, drive, gearbox, and driven equipment

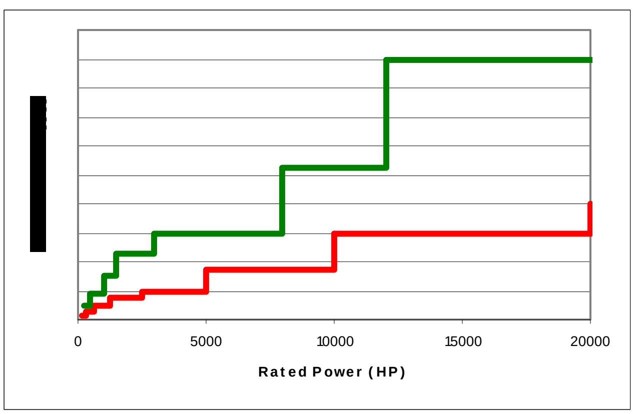



Figure 12. Example Initial investment cost for motor (red) and drive (green)

As can be seen in Figure 12, the relative costs of the motor and drive have certain frame break points where the cost jumps significantly at certain horsepower thresholds. This situation, while a known reality of producing somewhat standardized components, can also be harnessed to align these breakpoints. When breakpoints are aligned with particular care, significant benefits can be seen in the initial capital investment for a particular application. This may be further applied to the driven load and the power system used in the facility.

It can also be shown that there are certain breakpoints or power ratings, where it becomes more advantageous to increase the operating voltage of the system. In worse cases, low voltage power cabling for high output power machines may cost more than the actual drive train. Of course, this cost varies with cable length, suggesting that low voltage and medium voltage ratings power ratings can be positively applied in cases where cable length is minimized.

Additional costs can be associated with high voltage, especially when applied to smaller machines or lower power ratings. In some cases, the additional winding clearances and cable spacing will displace what would have otherwise been active material, forcing the motor onto a large frame size or higher shaft height.
When sizing the motor and drive together, it would be advantageous to consider the maximum output voltage and current capability of the drive. By evaluating the total cost of the motor and drive together, their respective costs can be further minimized. In one case it was observed that selecting a motor to operate at a the drive maximum output voltage of 8010V (rather than a conventional 7200V) resulted in a significant reduction in motor current draw, I2R losses, required size, and ultimately cost. When sized for conventional voltage ratings, the shaft power was limited to 18000HP. Now at this higher voltage the motor is capable of delivering 20,000 HP without having to jump to a synchronous motor which could double the cost. In addition one drive was also limited to the same current which in turn would have forced the use of 2 Drives in parallel. Overall by optimizing the package the overall cost could have been cut nearly in half.

Commonly in processes where multiple motors are started one at a time in sequence with an autotransformer and then later switched over to line power via switch gear, the opportunity exist for cost savings. For Example application requiring high starting torque, the motor will have to be designed with high resistance rotor bars. As the rotor bar resistance increases, the motor's efficiency will decease and the temperature rise will increase. Starting the load with an adjustable speed drive will typical allow the motor to utilize 150% of its rated torque while still reducing starting current , and not requiring the high resistance and associated higher losses .

As an example an end user is looking for a drive train solution to move 5 screw compressors which require high starting torque. The horsepower requirement is 2000 at 3600 rpm. The switch gear and compressor capital and their operational cost will be omitted from this example for simplicity. The autotransformer will utilize the 65% voltage tap to reduce starting current. The starting characteristics of standard motor in Figure 13 shows that the motor with reduced voltage will stall at approximately 10% speed and not start the load. To achieve starting without stalling, the motor core length will need to be increased and the rotor bar resistance will be increased almost 3 times ultimately increasing the cost of motor. The nonstandard motor's efficiency will decrease more then a full percentage point but motor will now start the load. . These ASD starting solutions with the original higher efficient motor was able start the load and still reduce the starting current, recovering the capital cost of the ASD within two years due to the energy savings of the prime mover only.

There are additional energy savings to be had if the operation of the process is understood. The system integrator will need information about loading points and duration of loading to be able to choose parts of the drive train to achieve the highest efficiency and reliability. In general for pump applications, flow can be controlled mechanically from the pump or by speed control of the prime mover. As can be seen in Figure 14 any required flow quantity below ninety percent flow will result in substantial amount of energy conservation.

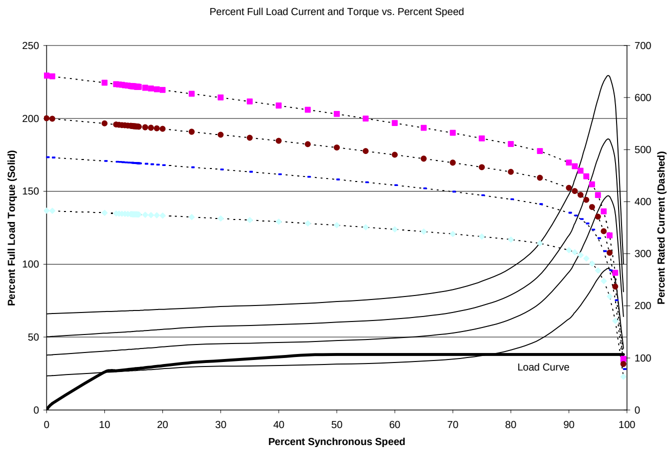



Figure 13. Speed Torque Curve of Standard Motor

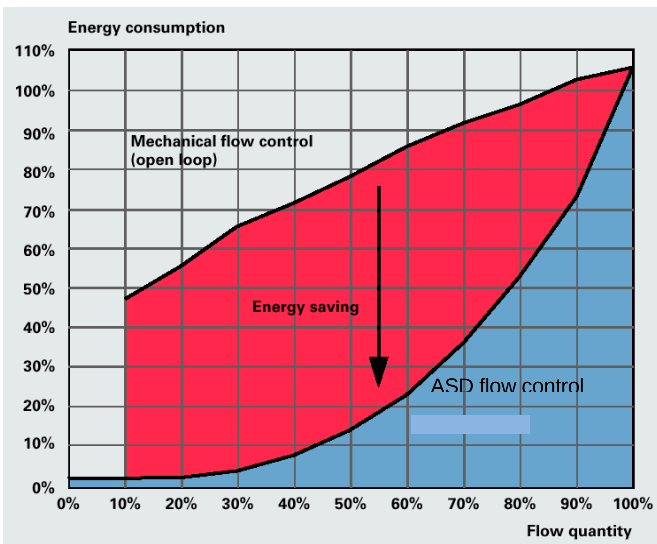



Figure 14. Flow Quantity and Energy Consumption

## V. CONCLUSION

When sizing the motor and drive in particular, it would be advantageous to make efforts to select products operating near their respective maximum power outputs. When selecting motors and drives, special attention should be paid to the operating voltage, in an effort to minimize the cost of those components as well as the total cost including cabling. Since a considerable portion of losses in motor and drive systems are fixed or do not increase proportionally to output power, operating at maximum power ratings will typically yield a better system efficiency thereby reducing energy consumption/operating cost.

One should consider total system efficiency for certain configurations. It is possible in some cases to recoup a higher initial investment relatively quickly just through better system efficiency.

Communication is key when designing motor drive systems, so that the many facets of their applications can be addressed and so that the many potential pitfalls can be avoided or mitigated.

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## VIII. VITA

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