AC Drive Technology

An overview for the converting industry

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Abstract

Advances in drive system technologies continue to provide increased performance, functionality, higher levels of efficiency, safety technology and ease of use. This paper offers a basic review of current AC drive system technology and details the features important to converting machinery drive system design.

The topics covered in this paper will include; A review of the drive control modes, i.e., V/hz, Vector and Servo control modes. A comparison of drive performance types, i.e., general purpose vs. high performance system drives.

An overview of synchronous and asynchronous motor technologies and best application practices for each type. Current motor feedback options with respect to application practice.

Drive system architecture options and considerations for utilizing AC/AC drives and common DC bus technology.

Drive power section technologies and the economic attractiveness when applied to common DC bus systems. Drive safety options and real world applications.

AC Motor Technology

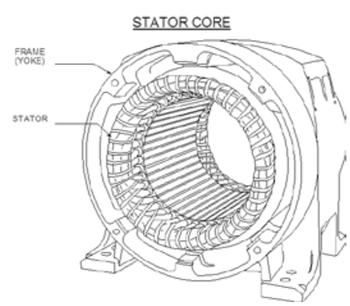
There are two types of motors commonly used with AC drives: induction and synchronous. Induction motors are also referred to as asynchronous motors. An asynchronous motor is a type of motor where the speed of the rotor is other than the speed of the rotating magnetic field. A synchronous motor is a type of motor where the speed of the rotor is exactly the same speed of the rotating magnetic field.

Motor Construction

The two basic elements of all AC motors are the stator and rotor. The principle of operation of a stator is the same in asynchronous and synchronous motors. There are, however, differences in rotor construction. The stator and the rotor are electrical circuits that perform as electromagnets.

The stator is the stationary electrical part of the motor. The stator core of the AC motor is made up of several hundred thin laminations. Stator laminations are stacked together forming a hollow cylinder. Coils of insulated wire are inserted into slots of the stator core. Each grouping of coils, together with the steel core it surrounds, form an electromagnet. Electromagnetism is the principle behind motor operation. The stator windings are connected directly to the power source. (Figure 1)

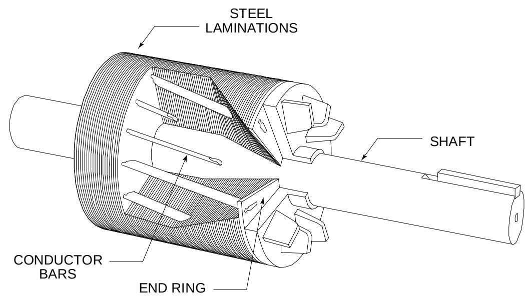
Figure 1: Stator Construction



The rotor is the rotating part of the electromagnetic circuit. The asynchronous rotor consists of a stack of steel laminations with evenly spaced conductor bars around the circumference. The laminations are stacked together to form a rotor core. Aluminum is die cast in the slots of the rotor core to form a series of conductors around the perimeter of the rotor. The conductor bars are mechanically and electrically connected with end rings. The synchronous motor has a permanent magnet rotor. Permanent rare-earth magnets are glued onto the rotor. Both rotor cores mount on a steel shaft to form a rotor assembly.

Figure 2: Asynchronous Rotor

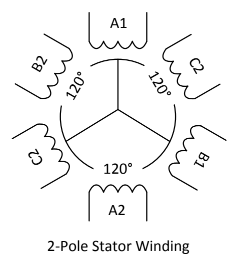
ROTOR CORE



The Stator and a Rotating Magnetic Field

A rotating magnetic field must be developed in the stator of an AC motor in order to produce mechanical rotation of the rotor. Wire is coiled into loops and placed in slots in the motor housing. These loops of wire are referred to as the stator windings. Figure 3 illustrates a three-phase stator. Phase windings (A, B, and C) are placed 120° apart. In this example, a second set of three-phase windings is installed. The number of poles is determined by how many times a phase winding appears. In this example, each phase winding appears two times. This is a two-pole stator. If each phase winding appeared four times it would be a four-pole stator.

Figure 3: 2 Pole Stator Winding

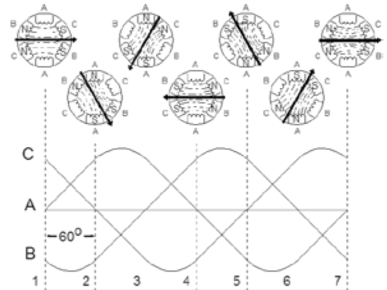


The Magnetic Field

When AC voltage is applied to the stator, current flows through the windings. The magnetic field developed in a phase winding depends on the direction of current flow through that winding. The following chart is used here for explanation only. It assumes that a positive current flow in the A1, B1 and C1 windings result in a north pole. The amount of flux lines (F) the magnetic field produces is approximately equal to the voltage (E) divided by the frequency (F). Increasing the supply voltage increases the flux of the magnetic field. Decreasing the frequency increases the flux.

If the field is evaluated at 60° intervals from the starting point, at point 1 it can be seen that the field will rotate 60°. At point 1 phase C has no current flow, phase A has current flow in a positive direction and phase B has current flow in a negative direction. Following the same logic as used for the starting point, windings A1 and B2 are north poles and windings A2 and B1 are south poles. At the end of six such intervals the magnetic field will have rotated one full revolution or 360°.

Figure 4: Rotor rotation with magnetic field



Synchronous Speed

The speed of the rotating magnetic field is referred to as synchronous speed (NS). Synchronous speed is equal to 120 times the frequency (F), Divided by the number of poles (P). If the applied frequency of the two-pole stator used in the previous example is 60 hertz, synchronous speed is 3600 RPM.

$$Ns = \frac{120F}{P} \qquad Ns = \frac{120*60}{2} \qquad Ns = 3600RPM$$

Slip

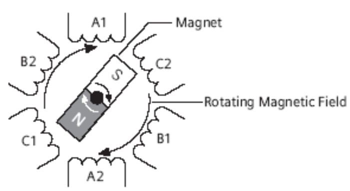
There must be a relative difference in speed between the rotor and the rotating magnetic field. The difference in speed of the rotating magnetic field, expressed in RPM, and the rotor, expressed in RPM, is known as slip. Slip is necessary to produce torque. If the rotor and the rotating magnetic field were turning at the same speed no relative motion would exist between the two, therefore no lines of flux would be cut, and no voltage would be induced in the rotor. Slip is dependent on load. An increase in load will cause the rotor to slow down or increase slip. A decrease in load will cause the rotor to speed up or decrease slip.

The Synchronous Motor

Synchronous motors are called "synchronous" because the rotor operates at the same speed as the rotating magnetic field. There are different methods to achieve synchronization between the rotor and the rotating magnetic field. The most common method in servomotor applications is the use of a permanent magnet rotor. Permanent rare-earth magnets are glued onto the rotor. A synchronous motor of this design is relatively small with low rotor inertia. The smaller, low inertia rotor provides fast acceleration and high overload torque ratings.

When the stator windings are energized, a rotating magnetic field is established. The permanent magnet rotor has its own magnetic field that interacts with the rotating magnetic field of the stator. The north pole of the rotating magnetic field attracts the south pole of the permanent magnet rotor. As the rotating magnetic field rotates, it pulls the permanent magnet rotor, causing it to rotate.

Figure 5: 2 Pole Stator Winding



Permanent magnet synchronous servomotors offer many advantages over AC Induction motors. The permanent magnetic field is generated by the rotor instead of the stator. There is no current flow to generate heat in the rotor. Instead, heat is generated in the stator windings which are close to the surface of the motor. Synchronous motors have a higher efficiency since there are no losses in a rotor/armature winding.

Closed Loop Control

In many applications, precise control must be maintained over acceleration, deceleration, velocity, and position. This requires that the drive be provided with feedback associated with these items. The drive determines the correct output to the motor by comparing the actual values with the command values. The actual values are calculated based upon feedback received from the encoder feedback. This is an example of closed-loop control.

Feedback (Encoder) Technology

Rotary Pulse Encoder

This encoder has two output channels (Ua1 and Ua2) which are phase shifted by 90°. The encoder traditionally has 1024 or 2048 increments per revolution. When power is initially applied to the motor the drive will not know the exact position of the rotor. Rotor position can only be calculated within one revolution once the zero reference mark has been crossed the first time. Because synchronous servomotors must know rotor position within one revolution this encoder is only used with asynchronous motors.

Figure 6: Pulse Encoder Construction

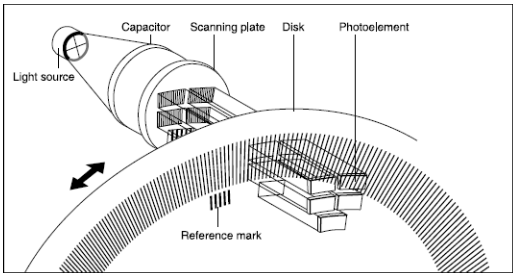
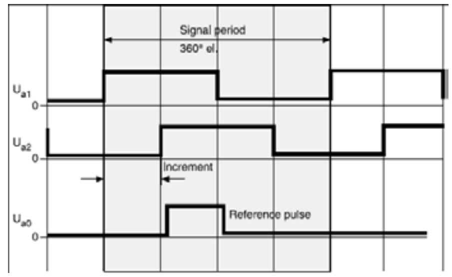


Figure 7: Pulse Encoder Signal



By comparing channel Ua1 and Ua2 the drive can determine which direction the motor is running.

Sine/Cosine (Sin/Cos) Pulse Encoder

The Sine/Cosine pulse encoder has four tracks and a reference pulse. Encoders A1 channel produces one sine signal per revolution and B1 channel produces one cosine signal. These signals are used to determine exact rotor position from initial power up within one revolution. After each revolution the calculated position is adjusted to the position indicated by the reference pulse position, if necessary. This encoder is suitable for use with all synchronous and asynchronous motors. 22 bit (typical) Sin/Cos encoders produce a sinewave output of 2048 micro-periods per revolution. Evaluation electronics within the drive can interpolate a usable the resolution of 4 million pulses per encoder revolution (ppr).

Figure 8: Sin/Cos Encoder Construction

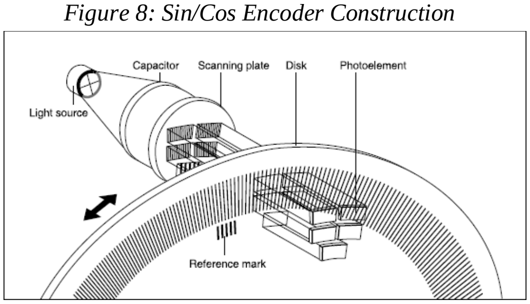
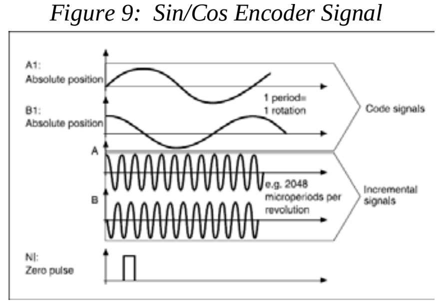


Figure 9: Sin/Cos Encoder Signal



Absolute Value Sin/Cos Encoder

The absolute value encoder is made up of two sections. The outer ring is identical to the Sin/Cos and is used to provide speed and direction information. Two output channels, A and B, produce 2048 periods per revolution. Channel B is offset from channel A by 180 degrees. The drive can determine which direction the motor is running by comparing channel A with channel B. A second feature of the Absolute value encoder is the coded inner rings. These provide a unique code for 8192 positions. This unique code is sent to the drive. The drive uses this unique code number to determine rotor positon. In addition, the encoder uses a mechanical gear sequence to count up to 4096 revolutions and store them. As long as the distance the application moves is less than 4096 revolutions there is no need to "home" the application as the absolute position is always known by the encoder count. As soon as it counts 4096 revolutions the encoder starts counting again from zero. These encoders are designed for use with synchronous and asynchronous servomotors.

Figure 10: Absolute Value Encoder Construction

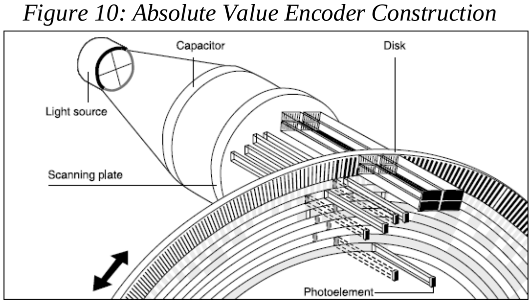
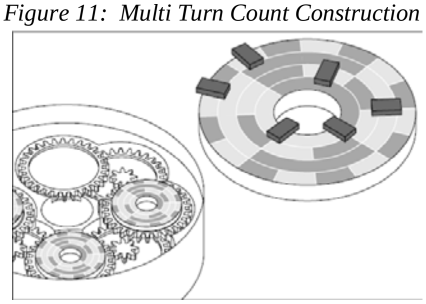


Figure 11: Multi Turn Count Construction

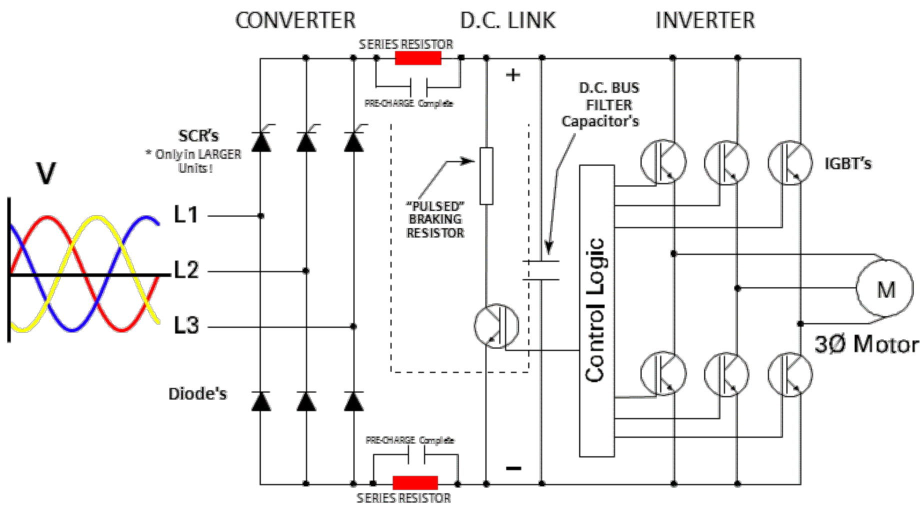


AC Drive Technology

Pulse Width Modulation (PWM) Technology

Before discussing the AC Drive it is necessary to review Pulse Width Modulation (PWM). PWM drives convert a fixed voltage, fixed frequency into a variable voltage, variable frequency output to control the speed of an AC motor. Pulse width modulation provides a more nearly sinusoidal current output to control frequency and voltage supplied to an AC motor than other technologies. PWM drives are more efficient and typically provide higher levels of performance than other drives. A basic PWM drive consists of a converter, control logic, and an inverter.

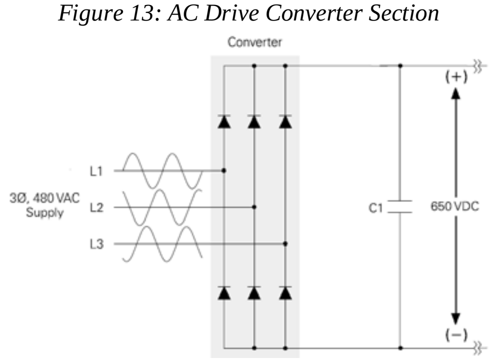
Figure 12: Basic "AC Power Section" Layout



The Converter Section

The converter section consists of a either a fixed diode bridge rectifier which converts the three-phase power supply to a DC voltage. The C1 capacitor(s) smooths the converted DC voltage by limiting current peaks and reducing harmonics. The rectified DC value is approximately 1.35 times the line-to-line value of the supply voltage. For example, the rectified DC value is approximately 650 VDC for a 480 VAC supply.

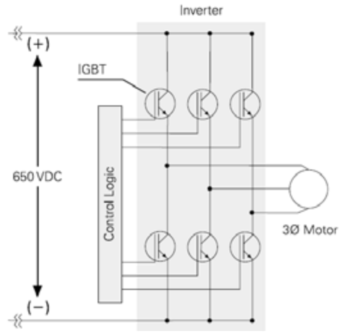
Figure 13: AC Drive Converter Section



Control Logic and the Inverter

Output voltage and frequency to the motor are controlled by the control logic and inverter section. The inverter section consists of six switching devices, commonly IGBTs. The following schematic shows an inverter that utilizes IGBTs. The control logic switches the IGBTs on and off providing a variable voltage and frequency to the motor.

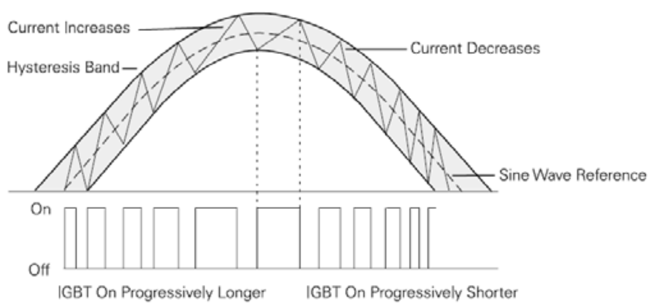
Figure 14: AC Drive Control & Inverter Section



Developing PWM Waveforms

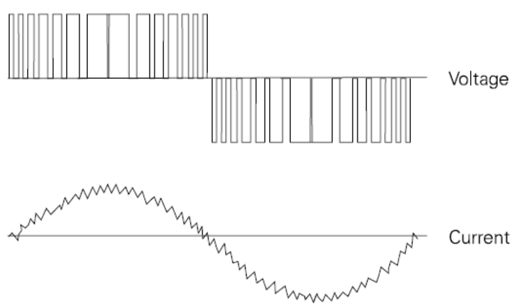
There are several PWM techniques. It is beyond the scope of this paper to describe them all in detail. The following text and illustrations describe one method. An IGBT can be switched on, connecting the motor to the positive value of DC voltage (650VDC from the converter). Current flows in the motor. The IGBT is switched on for a short period of time, allowing only a small amount of current to build up in the motor, and then switched off. The IGBT is switched on and left on for progressively longer periods of time, allowing current to build up to higher levels until current in the motor reaches a peak. The IGBT is then switched on for progressively shorter periods of time, decreasing current build up in the motor.

Figure 15: PWM output



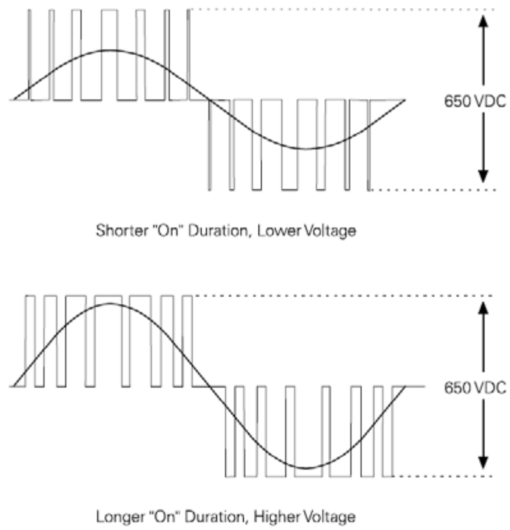
The negative half of the sine wave is generated by switching an IGBT connected to the negative value of the converted DC voltage.

Figure 16: PWM Full Wave Output



The voltage and frequency are controlled electronically by circuitry within the AC drive. The fixed DC voltage (650 VDC) is modulated, or clipped, with this method to provide a variable voltage and frequency. At low output frequencies a low output voltage is required. The switching devices are turned on for shorter periods of time. Voltage and current build up in the motor is low. At high output frequencies a high voltage is required. The switching devices are turned on for longer periods of time. Voltage and current build up in the motor increases.

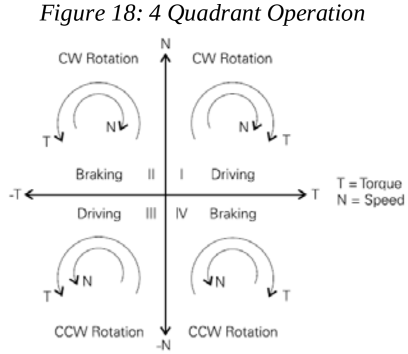
Figure 17: PWM Voltage and Frequency Control



Regeneration and Braking

In the speed-torque chart there are four quadrants according to direction of rotation and direction of torque. Quadrant I is forward motoring or driving (CW). Quadrant III is reverse motoring or driving (CCW). Reverse motoring is achieved by reversing the direction of the rotating magnetic field. The dynamics of certain loads, such as those associated with many applications, require four-quadrant operation. Torque will always act to cause the rotor to run towards synchronous speed. If the synchronous speed is suddenly reduced, negative torque is developed in the motor.
This could occur, for example when a stop command is initiated and the drive tries to slow down to bring the motor to a stop. The motor acts like a generator by converting mechanical power from the shaft into electrical power which is returned to the AC Drive. This is known as regeneration, and helps slow the motor. A similar process occurs when coasting downhill in a car. The car's engine will act as a brake. Braking occurs in quadrants II and IV.

Figure 18: 4 Quadrant Operation



One method of dealing with negative torque and the current it produces is controlled deceleration. Voltage and frequency is reduced gradually until the motor is at stop. This would be similar to slowly removing your foot from the accelerator of a car. Many applications, however, require the motor to stop quicker, and the drive must be capable of handling the excess energy produced by motor when this is done.

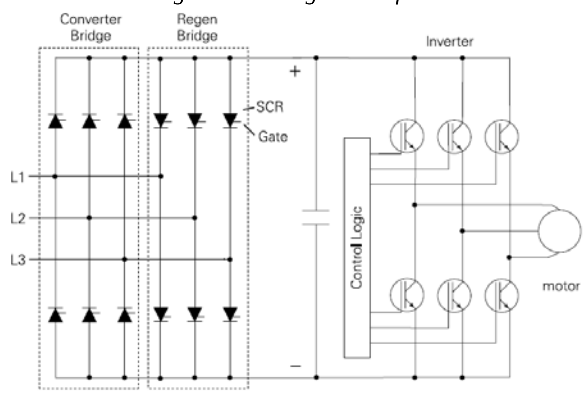
Braking Resistors

Electrical energy returned to the drive from the motor during regeneration can cause the DC link voltage to become excessively high. Braking resistors are one method used to control regeneration during a rapid deceleration. A braking resistor is placed across the DC link, through an IGBT. Energy returned by the motor is seen on the DC link. When the DC link reaches a predetermined limit the control logic switches on the IGBT, Completing the path from the negative to the positive DC link through the IGBT and resistor. Excess energy is dissipated by the resistor, reducing bus voltage. When DC link voltage is reduced to a safe level the IGBT is switched off, removing the resistor from the DC link. This process allows the motor to act as a brake, slowing the connected load quickly. (Refer back to figure 12)

Rectifier Regenerative Front End

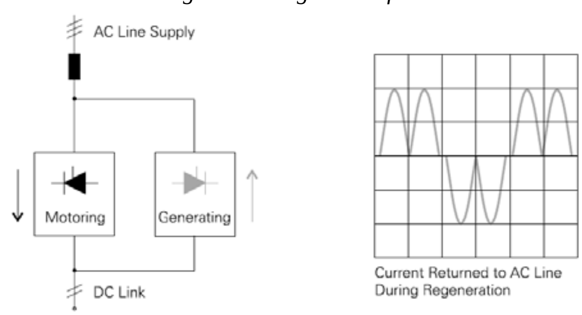
Another method of dealing with excessive regeneration is with a rectifier regenerative front end. Diodes in the converter section are replaced with SCRs and a second regen bridge is added. An SCR functions similarly to a diode rectifier, except that it has a gate lead, which is used to turn the SCR on. This allows the control logic to control when the converter bridge and regen bridge are turned on.

Figure 19: 4 Regen Rectifier



A simplified block diagram provides a clearer view of the regen process. When the motor needs motoring energy to accelerate or maintain speed against the inertia of a load, the converter bridge is turned on. When the motor is in the regenerative mode, it acts like a generator, supplying electrical energy back to the DC link. When the DC link voltage reaches a predetermined level the motoring SCRs are switched off and the regen (generating) SCRs are switched on. This allows the excess energy to be returned to the AC line in the form of AC current.

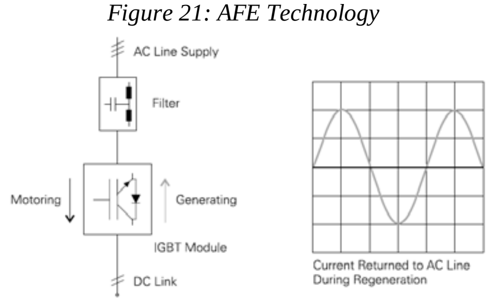
Figure 20: Regen Rectifier



Active Front End (AFE)

An Active Front End (AFE) is another option available to control regenerative voltage. With this option the diodes in the converter bridge are replaced with IGBT modules and a Clean Power Filter. The IGBT, controlled by control logic, operates in both motoring and regenerating modes. In addition, AFE provides low stressing of the line supply. Harmonics are extremely low and the power returned is in the form of sinusoidal current.

Figure 21: AFE Technology



AC/AC Drives vs. DC Common Bus Drive Systems

Stand Alone Drive Systems
Figure 22 shows a configuration stand-alone (AC / AC) drives applied in a multi-axes coordinated drive system. Here each individual drive is connected to the AC line via individual line components (fuses, reactors, contactors and component wiring. Each drive section must deal with its regenerative power individually.

Consider a drive system for a converting line with an unwind, pull roll master section, coater, laminator and rewind. Notice how in this scenario the machine sections that add tension to the web (unwind and laminator) must return their power to the drive, and in turn this energy is subsequently dissipated (wasted) by the regen resistors connected to the individual drives. In this example, 75A of current is wasted as heat.

In some cases a Pseudo-Common DC bus is created with AC /AC drives that have an external bus connection by wiring the bus connections together. However this application can be problematic as the current carrying capability of these bus connections do not always match the drive power rating. Precautions also must be taken to prevent the smaller drives from charging the larger drives. In any case, the added components required to create a Pseudo-Common DC bus add cost and complexity to the system.

Common DC Bus Architecture
True common DC bus drive systems are far more efficient than the system composed of stand-alone AC/AC drives in several ways. When drive systems utilize a common DC bus design, a shared rectifier section is used to convert the AC power supply into a DC bus which is common to the parallel connected motor modules (inverters).

Power sharing is now permitted between each different drive sections linked on the DC bus. When power sharing occurs on the DC bus between drives that are motoring and generating simultaneously, the drive system now uses less power from the rectifier as the generating drive sections can return their power to the DC bus to be shared by the motoring or consuming drive sections.

Additionally, the line components (i.e. contactor, reactor, fuses,) and rectifier can be sized based on the maximum current draw of the system not the summation of the individual motors. This also results in a more size optimized and energy efficient design as losses are realized in each individual line component and rectifier. In the common DC bus example in figure 23, the drive system will use almost 75A less than the AC / AC drive system in figure 22.

Figure 22: Stand-Alone AC / AC Drive System

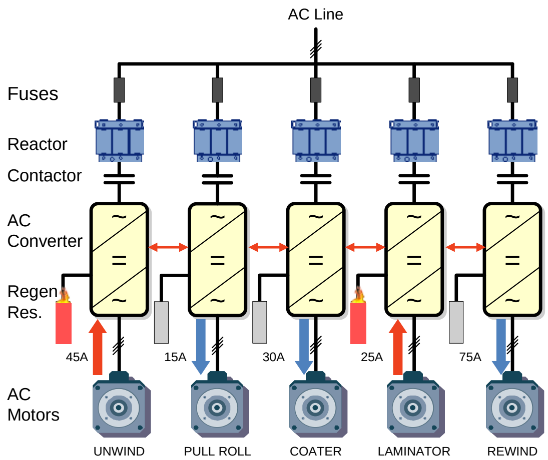
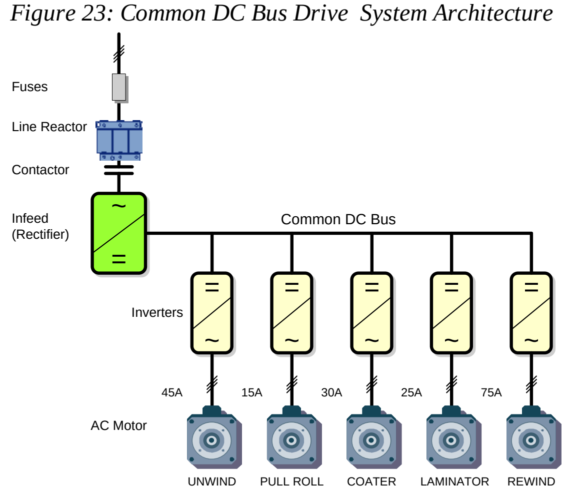


Figure 23: Common DC Bus Drive System Architecture



Drive Control Modes

V/hz Mode

The V/f control characteristic is the simplest way to control an induction motor. The stator voltage of the induction motor is set proportional to the stator frequency. This procedure is used for many standard applications where the dynamic performance requirements are low, for example: Pumps, Fans, Belt drives

V/f control aims to maintain a constant flux Φ in the motor whereby the flux is proportional to the magnetizing current ($I\mu$) or the ratio of voltage (V) to frequency (hz). $\Phi \sim I\mu \sim V/hz$

The torque (M) generated by an induction motor is proportional to the product of the flux and current (the vector product $\Phi \times I$). $M \sim \Phi \times I$

To generate as much torque as possible with a given current, the motor must function using the greatest possible constant flux. To maintain a constant flux (Φ), therefore, the voltage (V) must be changed in proportion to the frequency (f) to ensure a constant magnetizing current ($I\mu$). V/f characteristic control is derived from these basic premises.

Vector Control Mode

- Compared with vector V/f control, vector control offers the following benefits:
- Stability for load and setpoint changes
- Short rise times for setpoint changes (→ better control behavior)
- Short settling times for load changes (→ better response to disturbances)
- Acceleration and braking are possible with maximum settable torque
- Motor protection due to variable torque limitation in motor and regenerative mode
- Drive and braking torque controlled independently of the speed
- Maximum breakaway torque possible at zero speed

Vector control can be used with or without an encoder. The following criteria indicate when an encoder is required:

- High speed accuracy is required
- High dynamic response requirements
  - Better command behavior
  - Better disturbance characteristic
- Torque control is required in a control range greater than 1:10
- Allows a defined and/or variable torque for speeds below approx. 10% of the rated motor frequency (p0310) to be maintained.

Servo Control Mode

This type of closed-loop control enables operation with a high dynamic response and precision for a motor with a motor encoder.

- Drives with highly dynamic motion control requirements
- Drives with high speed and torque accuracy (servo synchronous motors)
- Angular-locked synchronism (Electronic Gearing & Camming)

Connectable Motors:		
Vhz	**Vector**	**Servo**
• Induction	• Induction	• Induction • Synchronous • Reluctance

Basic Drive Safety

More and more, integrated drive safety is becoming an important part of every machine and control system. As the requirements for machine flexibility and productivity continue to increase, new safety requirements must still be met. Conventional safety technology is at its limits in this respect. Integrated safety technology can be an asset in meeting design and performance criteria and still satisfying today's and future safety requirements.

In modern drives, safety functions are becoming increasingly integrated. Using drives with integrated safety technology can result in the elimination of previously required electromechanical components and their associated wiring. The transmission of safety-relevant signals are done via standard field buses, which reduces the complexity and the overhead of wiring. This considerably simplifies the implementation of safety concepts. In addition, they allow for considerably more efficient safety concepts, both in terms of functionality and in terms of response times. This commonly relates to increases in productivity.

Benefits of integrated Safety

- Highly effective safety: - Integrated through all safety components, sensors, drives to the central processor.
- Cost Savings: - Due to reduced hardware and installation costs
- Easy system engineering and maintenance: - By means of safety-related communication via standard field buses
- Effective and fast diagnostics: through a high degree of safety data availability
- Increased productivity: - Fast troubleshooting and comprehensive diagnostics functions reduce downtimes

The following list outlines commonly available integrated safety functionality for drive systems.

Functions to stop a drive:

- Safe Torque Off (STO): Torque is safely switched off (Stop Cat. 0)
- Safe Stop 1 (SS1): Active braking, then STO (Stop Cat. 1)
- Safe Stop 2 (SS2): Active braking, then SOS (Stop Cat. 2)

Motion monitoring functions:

- Safe Direction (SDI): Safe direction of rotation
- Safely Limited Speed (SLS): Speed is safely limited
- Safe Speed Monitor (SSM): Check back signal if speed falls below a limit
- Safe Brake Control (SBC): Brake is controlled safely

Position monitoring functions:

- Safely Limited Position (SLP): A traversing range is safely limited
- Safe Cam (SCA): Safe software output cams
- Safe Operating Stop (SOS): The drive position is safely monitored

Conclusions

There are multiple choices available today when selecting and designing a drive system for converting machine applications. Different drive technologies may have seemingly subtle differences, yet in operation may provide quite different results. Choosing a drive depends upon many factors. Understanding the strengths and deficiencies of alternate drive technologies is paramount to machine performance, maintenance support costs.

Asynchronous motors still receive the majority of usage in converting applications however; synchronous motors are rapidly gaining in popularity and are a good choice for high performance applications. Common DC bus architecture is well proven technology, well suited for converting lines and provides the optimum system efficiency and lowest system costs. Integrated drive safety is now a component of even the most basic of drives and the advantages of its functionality should be considered.

References

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