WHY USE ADJUSTABLE FREQUENCY CONTROL FOR MOVABLE BRIDGE DRIVES

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ABSTRACT

The evolution of adjustable frequency control will be explained, and why this method of ac motor speed control has become so popular. Also, adjustable frequency control offers many advantages for application as a movable bridge drive. Explanation will be given of how adjustable frequency control can be used to retrofit wound rotor controllers.

The basic designs of adjustable frequency control will be presented. The performance characteristics of each design will be explained, and ac motor considerations will be reviewed.

Similar applications in industry will be reviewed and explanations will be given on how this experience can be utilized on movable bridge drives.

INTRODUCTION

Within the industry, a complete adjustable frequency controller is commonly referred to as an inverter. This is the accepted terminology, even though it is technically incorrect, as explained on page 5. The controller is known by other names also, such as: Adjustable Frequency Drive (AFD), Variable Frequency Drive (VFD), Current Source Inverter (CSI), Six-Step Inverter (SSI), Pulse Width Modulated Inverter (PWM), Variable Voltage Inverter (VVI), and others. In this discussion we will use the term inverter.

The growing popularity of inverters is due chiefly to their ability to provide adjustable speed control with a standard NEMA B design squirrel cage motor. With this system there is an increasing demand to retofit existing installations, in addition to new installations.

The vast majority of motor installations above one horsepower are designed for constant speed operation using a standard NEMA B design squirrel cage motor. When adjustable speed is required, a dc motor, wound rotor motor, or some type of mechanical or hydraulic system is used.

Economically, the squirrel cage motor will cost considerably less than other types of motors. As a comparison with a standard 1200 rpm squirrel cage motor, a dc motor will cost approximately 312% more and a wound rotor motor will cost approximately 200% more.

The squirrel cage motor is considerably smaller, lighter and more readily available. This can be a huge benefit to the user.

For the user, the simpler and more reliable squirrel cage motor means less maintenance. There are no slip rings, commutators or brushes to inspect and replace. These benefits will often justify the use of inverters.

Inverters have been commerically available since the early 1960's, but have become more popular since the mid 1970's. There are several reasons for this increase in popularity.

Dramatic change in available technology.
Emphasis on reducing maintenance costs.
Emphasis on energy savings.
Emphasis on increased productivity.
Emphasis on optimizing process controls with programmable controllers.

The early inverter designs were relatively large, expensive and complicated. Consequently, applications were limited to installations where there were significant advantages in using inverters, such as the textile and fiber industries. With the availability of improved and lower cost logic controls and power switching devices (such as microprocessors, Gate Turn off Thyristors [GTO's] and power transistors), the size, cost and reliability of inverters have improved significantly.

As a result of these improvements, inverters with squirrel cage motors are being applied now for many applications that previously used dc motors, wound rotor motors, or mechanical or hydraulic systems. Less maintenance with the squirrel cage motor is an important consideration in this change.

In designing new machinery or retrofitting old machinery for adjustable speed capabilities to increase productivity, the inverter with the squirrel cage motor is ideal for many installations. Similarly, in a movable bridge installation, being able to attain variable speed with a standard squirrel cage motor in conjunction with programmable controllers, can provide much better control of the system. This is a rapidly growing field for inverters also, and the changes in technology and new applications for inverters are only in the initial phase.

REVIEW OF MOTOR SPEED RELATIONSHIPS

A review of motor speed relationships given below will aid considerably in understanding the operation and application of inverters.

SYNCHRONOUS SPEED

$$\text{Synchronous Speed} \propto \frac{\text{Frequency}}{\text{Number of Poles}}$$

This formula states that the synchronous speed of an ac motor is proportional to the frequency applied to the stator coils, and inversely proportional to the number of stator poles. Synchronous speed is the speed of the rotating magnetic field created by the stator coils when three phase power is applied. The number of stator poles created is determined by the manner in which the coils are wound in the stator.

As an example, for a motor stator wound with four poles and 60 Hertz three phase power applied, the synchronous speed is 1800 rpm.

$$S = \frac{120f}{P} = \frac{(120)\ (60)}{(4)} = 1800\text{rpm}$$

When the frequency is changed to 30 Hertz, the synchronous speed will be 900 rpm.

MOTOR SLIP AND BASE SPEED

The shaft speed of an ac induction motor, when driving a load, will always be less than the synchronous speed. This is a fundamental principle for induction motors. The difference in synchronous speed and shaft speed is called slip. As an example, a four-pole motor with 60 Hertz power has a synchronous speed of 1800 rpm. However, the motor shaft, driving a full load, will rotate at 1750 rpm. The slip speed is 50 rpm or approximately 2.7% of 1800 rpm. Motor slip is usually expressed in percent - such as, "The slip of an ac standard NEMA B design motor is 2% to 3%."

The speed of the motor shaft, with rated voltage and line frequency applied at full load, is called base speed. By changing the frequency to the motor above or below 60 Hertz, the motor can operate above or below base speed.

VOLTS-PER-HERTZ RATIO

This term describes a relationship that is fundamental to the operation of motors using adjustable frequency control. An ac induction motor produces torque by virtue of the flux in its rotating field. Keeping the flux constant will enable the motor to produce full load torque. Below base speed, this is accomplished by maintaining a constant voltage-to-frequency ratio applied to the motor when changing the frequency for speed control. For 460 and 230 Volt motors, the ratio is 460/60 = 7.6 and 230/60 = 3.8. If this ratio rises as the frequency is decreased to reduce the motor speed, the motor current will increase and may become excessive. If it reduces as the frequency is increased, the motor torque capabilities will decrease. There are some exceptions to this rule which are described below.

Above base speed, this ratio will decrease when constant voltage (usually motor rated voltage) is applied to the motor. In these cases, the torque capabilities of the motor decrease above base speed.

At approximately 20 Hertz and lower, the Volts-per-Hertz ratio is not always maintained constant. Depending on the type of load, the voltage may be increased to give a higher ratio, in order for the motor to produce sufficient torque, especially at 3 Hertz. This adjustment is usually called "Voltage Boost".

At base speed and below, the Volts-per-Hertz ratio can be adjusted lower to minimize motor current when the motor is lightly loaded. This adjustment, which lowers the voltage to the motor, will reduce the magnetizing current to the motor. Consequently, the motor will produce less torque which is tolerable.

SPEED TORQUE CHARACTERISTICS

Speed torque characteristics of a standard NEMA B design squirrel cage motor are illustrated in Figure 1.

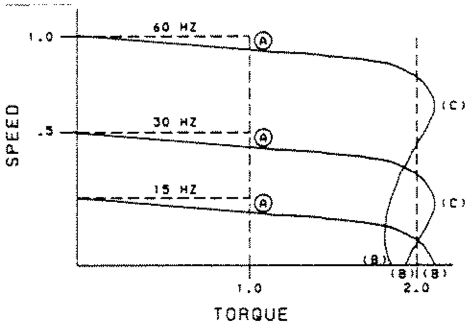

Figure 1

Motor curves are shown for 60 Hertz, 30 Hertz and 15 Hertz. The slip (A) remains the same as the frequency is reduced. However, the breakway (locked rotor) torque (B) will increase and approach pullout torque (C) at zero speed. The maximum value of locked rotor torque will be determined by the magnitude of harmonics in the current to the motor. The harmonics are a result of the distorted sine waves inherent with inverter control. With fewer harmonics, the motor can develop more torque. At line voltage 60 Hertz, locked rotor torque is approximately 150% to 180% of full load torque, and peak torque is approximately 200% to 250%, depending on a specific motor design.

INVERTER FUNDAMENTALS

The type of solid state adjustable frequency controller that is currently most popular consists of two basic functions - a converter section and an inverter section, as shown in Figure 2. Despite the inaccuracy, the complete controller is commonly called an inverter.

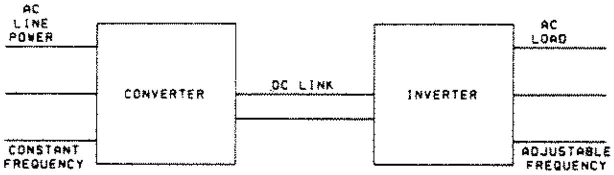

FIGURE 2

The converter section changes ac 60 Hertz line power into dc power. This circuit is sometimes called the dc link. The inverter section is then used to change the dc power into adjustable frequency ac power for the motor. There are various types and combinations of converter and inverter circuits, which will be discussed next.

TYPES OF CONVERTERS

The converter section of an adjustable frequency controller is sometimes called the front end. It consists of power switching devices and logic controls. The converter is used to control the voltage to the inverter section to maintain the constant Volts-per-Hertz ratio from the inverter. There is one exception to this, which will be explained later. For certain designs, the converter is the same as an adjustable speed controller for a dc motor. There are three popular methods of converting ac power into dc power for adjustable frequency controls:

1. Rectifier (diode front end)
2. Rectifier with dc chopper
3. Silicon Controller Rectifier (SCR)-sometimes called thyristors.

Rectifiers (diodes)

The circuit shown in Figure 3 is a three phase full wave bridge rectifier using diodes to produce a constant voltage in the dc link. With this type front end, in order to maintain a constant Volts-per-Hertz ratio to the motor, the voltage is changed in the inverter section along with the frequency. Hence, this type front end can be used only with a constant voltage source inverter (PWM), which will be discussed later.

RECTIFIER (DIODE)

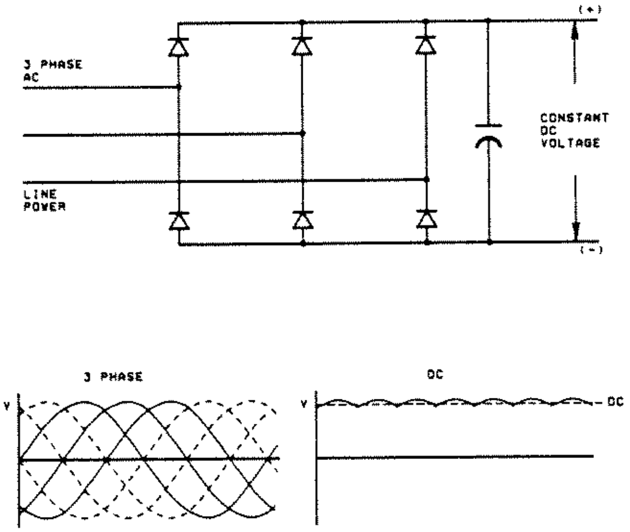

FIGURE 3

The use of diodes only for the front end is the simplest and least costly of the three designs. It provides the advantage of a high line power factor at all speeds. In addition, there is less occasion for line noise to affect the diode operation, or for disturbance from the diode to affect other systems connected to the line.

The disadvantage of this type front end is its inability to regenerate power back into the ac line due to the diodes. When regeneration is required into the line, SCR's must be used in addition to the diodes.

RECTIFIER WITH A DC CHOPPER

The circuit shown in Figure 4 is a three phase full wave bridge rectifier using diodes to produce a constant dc voltage, as explained previously. However, with this type front end, an additional power switching device is used, which may be an SCR, a power transistor, or other type switching device. This device will control the magnitude of dc voltage to the inverter section. This circuit is commonly referred to as a chopper.

RECTIFIER WITH DC CHOPPER

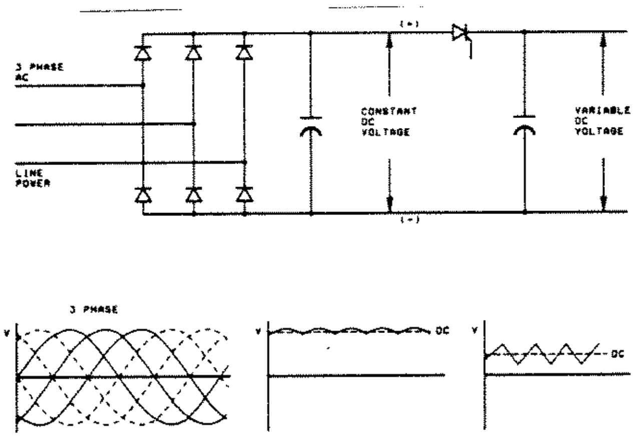

FIGURE 4

The chopper acts as a switch to permit the dc voltage to rise to a predetermined value. The chopper is then de-energized and the voltage will decrease. By controlling the rate at which the chopper is switched on and off, the dc output voltage can be varied from minimum to maximum. In this manner, the converter can control the voltage to the inverter section as the frequency is changed, to maintain a constant Volts-per-Hertz ratio to the motor.

For the larger horsepower motors, this type front end, having a rectifier with a dc chopper, is slightly more complex and costly than the other two types of front ends. The main advantages and disadvantages are the same as described for the front ends using only rectifiers.

SILICON CONTROLLER RECTIFIERS (SCR'S)

The circuit shown in Figure 5 is a three phase full wave bridge rectifier, using SCR's to control the magnitude of dc voltage to the inverter section. This is accomplished by controlling the conduction time of various SCR's in the circuit. Logic circuits will control this output voltage to vary from minimum to maximum. In this manner, the front end can control the voltage to the inverter section as the frequency is changed, to maintain a constant Volts-per-Hertz ratio to the motor.

SILICON CONTROLLER RECTIFIER

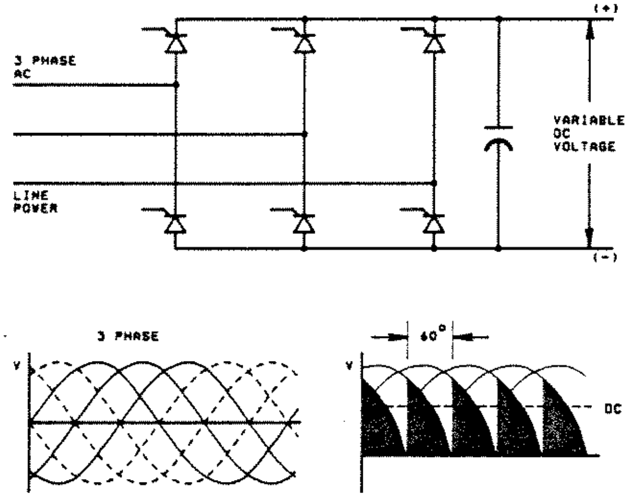

FIGURE 5

With this type front end, the power factor will decrease as the frequency, and consequently the speed is reduced. This may be a disadvantage, depending on the particular installation. In addition, the converter is more sensitive to line disturbances, and may create additional line disturbances, unless special protective circuits are included. However, the significance of these disadvantages will be determined by a manufacturer's specific design and specific application conditions. The advantage of this type front end is its ability to regenerate power back into the ac line, when properly applied.

TYPES OF INVERTERS

The inverter section of an adjustable frequency controller consists of power switching devices and logic controls that are considerably more complicated than those required for the front end (converter). Although there are numerous variations in inverter section designs, there are basically three types that are most popular:

1. Variable Voltage Source Inverters - sometimes called six-step or Voltage Source.
2. Current Source Inverters.
3. Constant Voltage Source Inverters - sometimes called pulse width modulation or PWM.

Each of these basic designs has variations which manufacturers emphasize for their particular market and application objectives. There are various combinations of front end designs that may be used with each inverter section also. The basic inverter designs will be discussed separately next.

SIX-STEP INVERTER (VARIABLE VOLTAGE SOURCE)

A simplified circuit for a six-step inverter is shown in Figure 6. A converter using SCR's is included to illustrate the total circuit. However, a rectifier with a dc chopper for the front end may be used instead.

6 - STEP INVERTER (VARAIBLE VOLTAGE SOURCE)

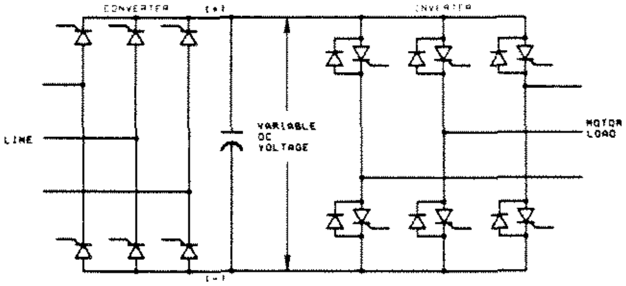

Figure 6

This inverter section has six power switching devices and 6 diodes illustrated in Figure 6. The six power switching devices, performing as switches, are switched on and off in a predetermined sequence to produce a six-step three phase voltage wave for the motor (one phase only illustrated in Figure 7). The distorted current wave illustrated contains harmonics which are usually not deterimental when the inverter and motor are properly applied.

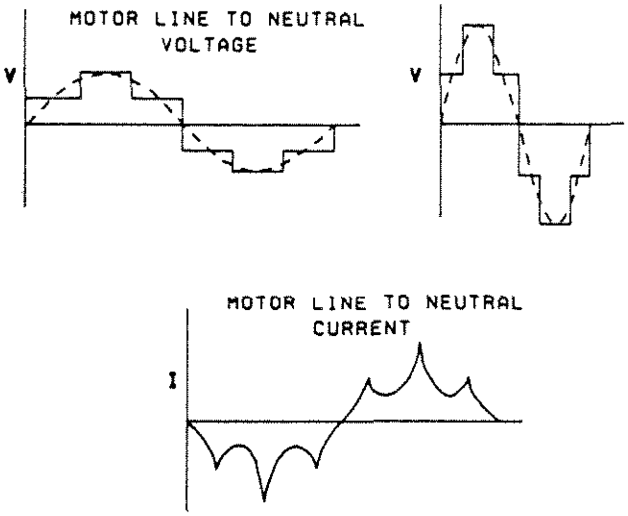

Figure 7

To change the frequency to the motor, the conducting time of the power switching devices is either increased or decreased for each of the six steps, as illustrated in Figure 7. This will result in a cycle time that is either longer or shorter. As explained previously, the dc voltage from the converter is changed accordingly to maintain the constant Volts-per-Hertz ratio to the motor as the frequency is changed.

The circuit for the six-step inverter is characterized by the use of capacitors in the dc link. When SCR's are used for the inverter section, illustrated in Figure 6, relatively complex commutating circuits are required. The commutating circuits are illustrated in Figure 6, but are reviewed below.

To perform the predetermined sequencing, the SCR's are switched on by the logic controls for the inverter. The SCR's however, require additional power circuits in order to be switched off. These additional circuits are called commutating circuits, and may include capacitors, reactors, diodes, and additional SCR's. These add to the complexity and cost of the inverter.

Newer technology devices such as power transistors and GTO's do not require commutating circuits. These are being used instead of SCR's for many designs as they become available with higher ratings.

CURRENT SOURCE INVERTER

A simplified circuit for a current source inverter is shown in Figure 8. A front end using SCR's is included to illustrate the total circuit. However, a rectifier with a dc chopper for the front end may be used instead.

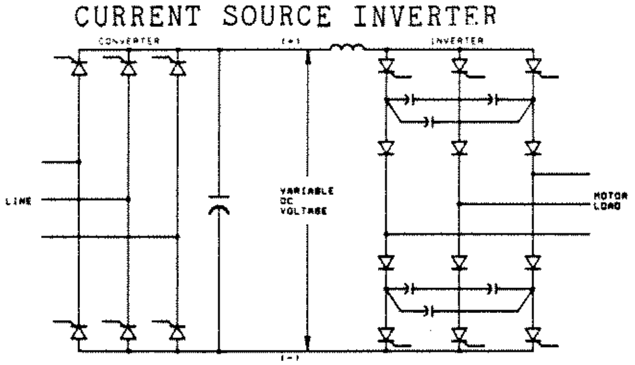

Figure 8

This inverter section has six power switching devices. Unlike the six-step inverter, the current source inverter will use SCR's most of the time and will usually be applied for larger horsepower sizes only. There is little advantage in using power transistors for current source inverters. The six SCR's, acting as switches, are switched on and off in a predetermined sequence to produce a six-step three phase current wave for the motor (one phase only illustrated in Figure 9). Like the voltage source inverter, the distorted current wave contains harmonics which are usually not detrimental when the inverter and motor are properly applied. The voltage wave, however, is unlike the six-step inverter and is generated by the counter emf of the motor. It contains voltage spikes that are caused by commutating the SCR's off.

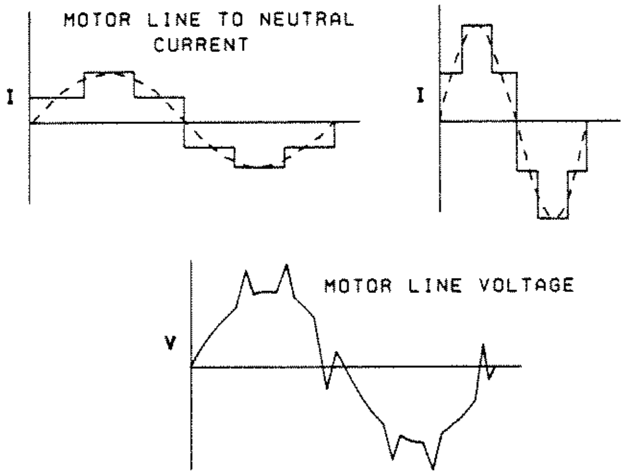

Figure 9

To change the frequency to the motor, the conducting time of the SCR's is either increased or decreased for each of the six steps, as illustrated in Figure 9. This will result in a cycle time that is either longer or shorter. As previously explained, the dc voltage from the converter is changed accordingly, to maintain the constant Volts-per-Hertz ratio to the motor as the frequency is changed.

The circuit for the current source inverter is characterized by the use of a large reactor in the dc link, and realatively simple commutating circuits with capacitors for the inverter.

To perform the predetermined sequencing, the SCR's are switched on by the logic controls, and switched off by commutating circiuts. Unlike the numerous additional devices and circuits required to commutate SCR's for the six-step inverter, the current source inverter requires only simple capacitor circuits and the diodes.

PWM INVERTER (CONSTANT VOLTAGE SOURCE)

A simplified circuit for a PWM inverter is shown in Figure 10. A converter using diodes is included to illustrate the total circuit.

PWM INVERTER (CONSTANT VOLTAGE SOURCE)

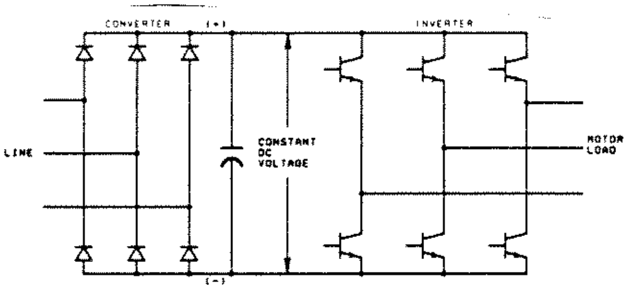

Figure 10

The inverter section has six power switching devices. Power transistors, illustrated in Figure 10, or GTO's are usually used because of their fast switching characteristics required for PWM. The six power devices, acting as switches, are controlled on and off in a predetermined sequence to produce a series of pulses. These pulses will be varied in width to produce a square, three phase voltage wave for the motor (one phase only illustrated in Figure 11). The distorted current wave illustrated contains harmonics which are usually not detrimental when the inverter and motor are properly applied.

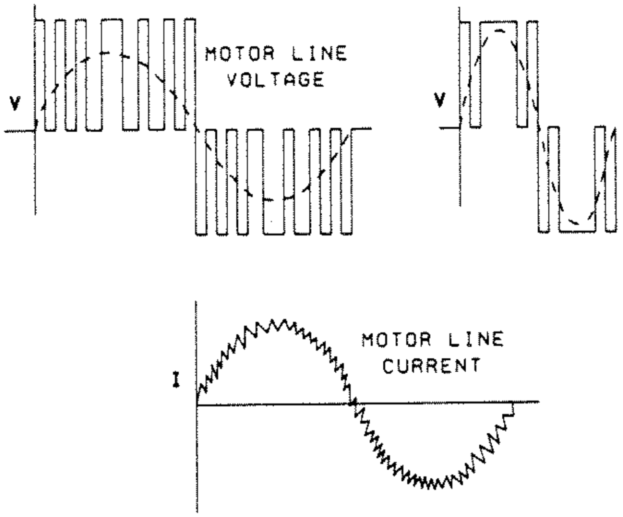

Figure 11

To change the frequency to the motor, the number of pulses and the width of the pulses are either increased or decreased for each half cycle, as illustrated in Figure 11. This will result in a cycle time that is either longer or shorter. For each specific frequency, there is an optimum number of pulses and pulse widths that will produce a minimum amount of harmonics in the current wave to closely simulate a pure sine wave. In practice, the number of pulses and widths used are usually compromised with other design requirements.

The voltage change required to maintain a constant Volts-per-Hertz ratio as the frequency is changed is controlled by increasing or decreasing the widths of the pulses.

The power circuit for the PWM inverter is characterized by its simplicity - a diode front end, the use of capacitors in the dc link and elimination of commutating circuits when using power transistors or GTO's.

To perform the predetermined sequencing, the power switching devices are switched on and off by the logic controls for the inverter. The logic circuits for PWM are considerably more complicated than six-step. However, microprocessors or large scale integration (LSI) chips are usually used for PWM, which simplifies the control.

INVERTER COMPARISONS

Various combinations of the three front end designs and three inverter section designs are used by manufacturers for specific markets or applications. The chart below lists the items for consideration when designing or applying the various inverter designs.

C -indicates an item for special consideration.
NC -indicates no special consideration required beyond the normal application considerations.
( ) -numbered footnotes provide additional information.

ITEMS FOR CONSIDERATION	SIX-STEP INVERTER	CURRENT SOURCE INVERTER	PWM INVERTER
MOTOR			
(1) Horsepower Rating	NC	C	NC
(2) Special Data	NC	C	NC
(3) Voltage Stress	NC	C	C
(4) Noise	NC	NC	C
(5) Heating	C	C	C
INVERTER			
(6) Commutation Circuit for SCR's	C	NC	C
(7) Short Circuit Protection	C	NC	C
(8) Open Circuit Condition	NC	C	NC
(9) Reactor	NC	C	NC
(10) Noise	C	C	C
(11) Efficiency	C	C	C
(12) Power Factor	C	C	NC
LOAD REQUIREMETNS			
(13) Low Speed	C	C	NC
(14) Breakway Torque	C	C	C
(15) Regeneration	C	C	C

MOTOR CONSIDERATIONS

(1) Motor Horsepower Rating - When paralleling motors with a single current source inverter, it is important to properly match the inverter horsepower rating with the total motor horsepower rating. For example, with a 100 horsepower inverter controlling five 20-horsepower motors connected in parallel, no more than two of the motors should be disconnected, leaving three 20-horsepower motors connected to the inverter. To ensure a proper application for multi-motor installations, the inverter manufacturer should be consulted.

(2) Motor Special Data - With a current source inverter, in many cases, specific motor data (leakage reactance) may be required to ensure proper commutation.

(3) Motor Voltage Stress - With a current source or a PWM inverter, there is some additional stress on the motor insulation. With current source inverters, high voltage spikes are usually limited to acceptable levels with clamping circuits; however, too much clamping can cause a reduction in inverter response. With the PWM inverter, additional stress also occurs in the motor insulation due to the rapid change in voltage pulses. These voltage stresses, however, are usually not detrimental.

(4) Motor Noise - With PWM inverter, the motor will produce more noise than normal.

(5) Motor Heating - The distorted current wave produced by all three types of inverters contains harmonics. These harmonics will not develop productive torque, but will cause additional motor heating. The amount of additional motor heating produced with six-step and current source inverters is predictable and will vary over the speed range from approximately 5% to 15% additional heating. This be considered along with the other application considerations when applying motors with inverters. The additional heating with PWM inverters may be approximately the same as six-step, depending on a manufacturer's specific design.

INVERTER CONSIDERATIONS

(6) Inverter Commutation Cirucits for SCR's - With the six-step and the PWM inverters that use SCR's, the commutation circuits will be considerably more complex than those for current source advantages. However, when GTO's or power transistors are used with six-step or PWM inverters, there are no commutation circuits and the inverter power circuits are the simplest.

(7) Inverter Short Circuit Protection - The current source inverter will inherently limit short circuit currents, thereby minimizing the number of fuses required in the controller. Six-step and PWM inverters usually require fuses or additional electronic protective circuits.

(8) Inverter Open Circuit Condition - With a current source inverter, an open circuit condition such as disconnecting the load, will result in an excessive voltage rise in the inverter circuits, due to the large amount of stored magnetic energy in the dc link reactor. Unless special circuits (sometimes called "crowbar") are employed to discharge this energy, an open circuit condition could cause inverter failures.

(9) Inverter Reactor - The current source inverter requires a relatively large and heavy reactor, which adds to the cost and installation considerations for the larger horsepower sizes.

(10) Inverter - All three types of inverters may generate some noise in the controller due to resonance in the power switching devices. With the current source inverter, additional noise can be generated in the large dc reactor, depending on its construction. Also, additional noise is generated when rectifiers with a dc chopper are used for the front end.

(11) Inverter Efficiency - In comparing the efficiency of the three types of inverters, there are many variables involved that will influence the efficiency ratings, such as horsepower sizes, speed ranges, power switching devices, types of loads, etc. As an example, the use of power transistors vs SCR's will eliminate the commutating losses and provide a higher efficiency in six-step and PWM inverters. Because of the many variables, it is not practical to state specific efficiencies for the three basic types. The efficiency for each type should be determined for a specific manufacturer's design for specific conditions.

(12) Inverter Power Factor - With the six-step and current source inverters, the power factor will be determined by the type of front end used. When SCR's are used, the power factor will be relatively poor at reduced speeds. When diodes with a dc chopper are used, the power factor will be the same as a PWM inverter, which is relatively high at all speeds.

LOAD CONSIDERATIONS

(13) Load Low Speed Requirements - With a six-step and current source inverter, cogging will be noticeable at speeds below approximately 10 Hertz. Cogging is a jerky rotation of the shaft due to the badly distorted current wave at these speeds. With a PWM inverter having an optimized design, the current wave at speeds below 10 Hertz is less distorted and smoother shaft rotation is possible. However, not all PWM inverter designs are optimized, and some will produce cogging at low speeds also.

(14) Load Breakaway Torque Requirements - With an optimized design PWM inverter, the torque (per amp) capabilities of the motor will be greater than that with a six-step or current source inverter. This is due to the capabilities of the PWM inverter to produce a truer (less distorted) sine wave at the very low frequencies. However, there are other considerations involved with breakway torque requirements that are explained under Application Considerations.

(15) Load Regeneration Requirements - When it is desirable or required to regenerate motor power back into the ac line, the current source inverter with an SCR front end can be designed to provide this inherently. This feature, however, is not possible with a current source inverter having a dc chopper front end. With a six-step or PWM inverter, an additional SCR front end is required to regenerate power back into the ac line. However, in some cases, to avoid the necessity of an additional converter, dynamic braking is achieved within the dc link by using a chopper and resistors. Also, to a limited degree, by virture of the capacitance in the dc link and the motor losses, some small amount of braking is provided. This type of braking is frequently call regeneration also, although technically it is not correct. This method of providing retarding motor torque is usually acceptable for smaller horsepower sizes where the amount of energy is not significant.

INVERTER APPLICATIONS CONSIDERATIONS

Probably one of the major causes for many inverter malfunctions is mis-application. To ensure proper inverter application, it is recommended that the subjects listed below be reviewed. Fortunately, many inverters, especially for the most popular types of loads, will not require extensive application considerations. This will be explained in more detail in this section. The important considerations when using inverters are grouped as follows: electrical system, load and motor.

ELECTRICAL SYSTEM CONSIDERATIONS

Line Voltage - The system voltage should be confirmed to be within the deviation permitted by the specifications for the inverter. This is usually +10% and -5% per NEMA standards. Specific values are given in the manufacturer's literature. Otherwise, the proper Volts-per-Hertz control may not be maintained to the motor, possibly resulting in excessive currents.

Line Inrush Current - Limitation of the line inrush current is usually not a negative consideration when applying inverters. In fact, inverters provide the best control for inrush limitation. Most squirrel cage motors require approximately 5 to 6 times full load current when started at line voltage. Synchronous reluctance motors require approximately 10 to 12 times full load current. When these motors are controlled by inverters, the inrush current can be limited to values much less than with conventional reduced voltage starters, to develop the same torque. For example, with a 150% current limit setting for an inverter, 150% motor torque at locked rotor can be developed. With conventional starters to develop 150% torque at locked rotor, the inrush current would be close to full voltage inrush - probably 400% to 500% - depending on the specific motor design.

For variable torque loads, the current limit can be set for slightly higher than the 100% full load current rating of the motor, and still provide the necessary accelerating torque. For constant torque loads, the current limit must be set higher than motor full load current, usually 150%, depending on the acceleration time required and the motor-load inertia. These subjects are reviewed in more detail later.

Line Power Factor - With inverters having diode front end, the power factor commonly understood is relatively high and the subject is generally not an important consideration. However, when a specific power factor is specified or limitations are imposed for an installation, a more through review of the subject as described below should be undertaken.

Power factor is a subject that is often misunderstood, especially when dealing with non-sinusoidal wave forms for voltage and current. These distorted wave forms are created when power semiconductors are used in electrical circuits. In summary, the conventional explanation of leading and lagging power factor due to capacitance and inductance applies only when a pure sine wave for voltage and current is involved. When a distorted sine wave is produced, power factor assumes a new dimension. This is usually explained as two distinct components.

A "harmonic component" is introduced which, like the conventional reactive component, produces no useful motor torque. However, the harmonics will produce power losses in the distribution system. The degree of power factor reduction due to harmonics is a function of a particular circuit condition such as the type of distorted wave invloved, etc. This may or may not be significant for an installation - depending on the conditions. The harmonic component is usually not detected with conventional power factor meters, and cannot be corrected with capacitors. It will, however, result in a higher RMS current. This phenomenon is not unique to inverters, but may exist whenever semi-conductors are used.

The other component is frequently called the "displacement component" and results from the conventional reactance in the system, plus any phase control that may be employed with the power switching devices. The displacement component is measurable with conventional meters and can be corrected with capacitors.

The displacement power factor with inverters having diode front ends is relatively high, approaching unity. There is no reduction in displacement power factor at reduced speeds because there is no phase control employed with the diode front end. Inverters using an SCR type front end employ phase control to reduce the voltage in the dc link. This will present a lower power factor to the line at reduced speeds.

Branch Circuit Apparatus - Inverters may be furnished with or without branch circuit apparatus such as cirucit breakers, disconnect switches, fuses, and transformers when specified.

When branch circuit equipment is furnished to separate mounting, the current rating of the apparatus should be based on the input current of the inverter, and not necessarily on the motor full load current. The inverter input current for a specified motor horsepower will be greater than the normal motor full load current. This is a result of the harmonics generated in the line currents, due to the solid state devices and dc link capacitors. The previous paragraph on "Line Power Factor" briefly reviews this subject.

Inverter Efficiency - An inverter's efficiency rating is frequently required, in addition to the efficiency of a motor, to justify an installation for energy savings. The use of standard squirrel cage motor with inverters provides a considerable improvement in efficiency for adjustable speed applications when compared to conventional wound rotor motor controllers or some mechanical systems. A specific motor manufacturer's design, the load, and the speed range will determine the efficiency of the motor for specific conditions. Inverters have relatively high efficiency ranging from 85% to 95% and do not change appreciably with speed or load. When an accurate efficiency rating for an inverter installation is required, it should be confirmed by the manufacturer for a particular size and specific application conditions.

LOAD CONSIDERATIONS

Types of Loads - The type of load that a motor drives is one of the most important application considerations when applying any type of inverter. For some types of loads, the application considerations may be minimal. For other types of loads, extensive review may be required. Generally, loads can be grouped into four different categories:

> Variable Torque Loads - fans, blowers, propellers, centrifugal pumps.
>
> Constant Torque Loads - movable bridges, conveyors, hoists, drill presses, extruders, positive displacement pumps. (Torque load of these pumps may be reduced at low speeds.)
>
> Constant Horsepower Loads - grinders, turret lathes, coil winders.
>
> Impact Type Loads - stamping presses

There are important considerations for each of the above types of loads. The significance of these subjects in the application of inverters is limited to constant torque loads for this paper.

Speed Range - The minimum and maximum operating speed of the motor when controlled by inverters is usually expresses in Hertz - 60 Hertz is 100% base speed, 30 Hertz is 50% speed, 3 Hertz is 5% speed, 120 Hertz is 200% speed. Adjustments in the inverter will permit a specified speed range operation.

Speed Regulation - With standard squirrel cage motors, the inherent speed change is approximately 2% to 3% at no load and full load. An inverter adjustment "slip compensation" will maintain approximately ± 0.5% speed regulation. When no speed deviation is required, synchronous motors are used.

Breakaway Torque (locked rotor) - This is the torque required of the load to start from rest. The motor locked rotor torque characteristics are illustrated and explained on page 5. An inverter adjustment "voltage boost" will permit an increase in the locked rotor torque for normal applications. When a higher-than-normal breakaway torque is required, the inverter components must be sized larger and the current limit set higher to permit the motor to develop a higher starting torque.

Accelerating Time and Torque - An inverter adjustment will permit short or long accelerating times, which should be adequate for normal applications. When high inertia loads are encountered, the current capabilities of the inverter must be evaluated to determine if the motor can provide the necessary accelerating torque for the required accelerating time.

Decelerating Time and Torque - An inverter adjustment will permit short or long deceleration times, which should be adequate for normal applications. When high inertia loads are encountered, the regeneration capabilities of the inverter must be evaluated to determine if the motor can provide the necessary retarding torque for the required decelerating time.

Before evaluating the above considerations, a brief description and illustration of the constant torque type load are given below.

Constant Torque Load - With a constant torque type load, the torque is not a function of the speed. The torque required for the load will be constant and may be 100% torque, or any reduced value,as illustrated in Figure 12.

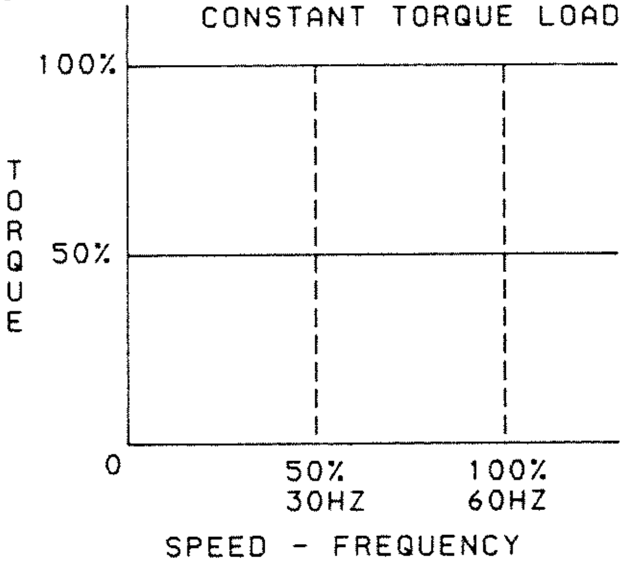

Figure 12

APPLICATIONS CONSIDERATIONS FOR CONSTANT TORQUE LOADS

Speed Range - Minimum speed requirements can vary considerably and can be at 3 Hertz or lower. For speeds below 10 Hertz, the application should be checked to determine if cogging (jerky rotation) will be detrimental. Cogging is a condition that exists with a six-step or current source inverter, but is not likely to exist with an optimized PWM design. Normally, the maximum speed requirememnts should not exceed base speed (60 Hertz at line volts); otherwise, the proper Volts-per-Hertz ratio will not be maintained for a constant torque load.

In special cases, an extended speed range above base speed at constant torque is possible. For example, with a standard squirrel cage motor wound for 230 Volts at 60 Hertz, the Volts-per-Hertz ratio can be maintained constant when 460 Volts is applied at 120 Hertz. The motor will produce its rated torque at twice base speed, and the horsepower output will be doubled.

Speed Regulation - This may or may not be a consideration, depending on the particular installation. In most cases, the inverter slip compensation feature providing ± 1% regulation should be adequate, unless a higher degree of regulation is specified.

Breakaway Torque - The current limit capability of the inverter must be checked to be high enough to enable the motor to provide sufficient breakaway torque for the worst case, such as a motor 100% fully loaded with unusual load conditions. Normally, 150% current limit is available with the inverter to provide 150% torque at locked rotor.

Accelerating Time - The amount of load and its inertia will determine whether or not the current limit capabilities of the inverter will permit the motor to accelerate in the minimum time setting. For a fully loaded condition and high inertia, a larger size inverter may be required. For high inertia loads requiring accelerating time longer than 40 seconds, the thermal rating of the inverter must be evaluated.

Decelerating Time - Similar to acceleratring time, the amount of load and its inertia will determine whether or not the regeneration capabilities of the inverter will permit the motor to decelerate in the minimum time setting. For a fully loaded condition, and high inertia, dynamic braking or regenerative braking may be required.

APPLICATIONS

In the past, ac drives used on movable bridge spans have been contactor or adjustable voltage ac type. The ac motor advantages were not fully utilized, because wound rotor motors were usually required with these control methods. Wound rotor motors have brushes and slip rings that require periodic maintenance, where the squirrel cage motor has none.

In some movable bridge applications low speed motor performance may not be satisfactory with the use of contactor or adjustable voltage ac drives. Therefore many designers specified adjustable voltage dc or hydraulic type devices.

The use of adjustable frequency drives on a movable bridge span offers many advantages. These advantages are summarized below:

1. Can be used with standard squirrel cage Nema B motor or wound rotor motor.
2. Will allow the ac motor to produce 150% breakaway torque with 150% current. This can reduce emergency generator size, and therefore reduce cost.
3. Is speed regulated without the need for motor mounted dc tachometer.
4. Will allow the motor to produce 100% torque at low speeds (5% and above).
5. Provide smooth acceleration and deceleration control.
6. Can provide 100% braking torque with the use of dynamic braking or regenerative braking.
7. Easily mounted in MCC enclosure.

Applications similar in performance characteristics to movable bridge span motions are now using the Class 8804 OMEGAPAK adjustable frequency controller. Our field experience with similar high performance applications has been:

Railroad Turntable
Steel Mill Planer
Ship Unloader
Bridge and Trolly Motions on Cranes
Missile Moving House