ADJUSTABLE FREQUENCY DRIVES

FOR OVERHEAD

MATERIAL HANDLING APPLICATIONS

Keith O. Jurkowski, Director of Engineering

Electromotive Systems, Inc.

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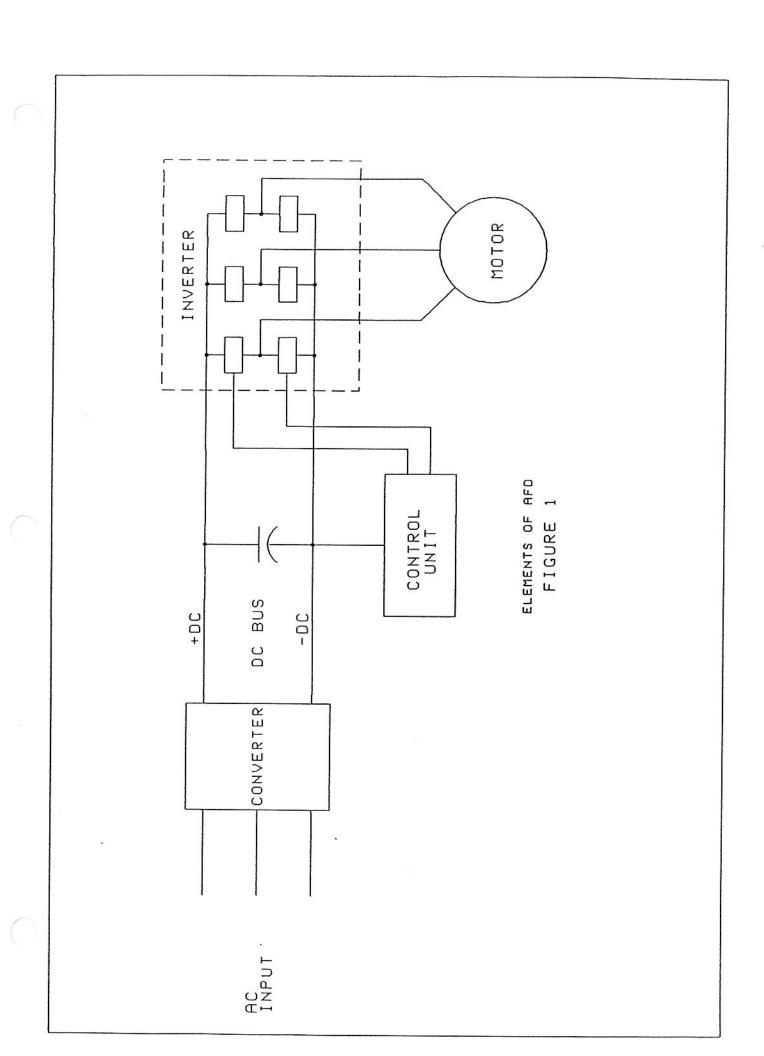
ADJUSTABLE FREQUENCY DRIVES FOR CRANE CONTROL

1.0 Adjustable Frequency Drives

The Adjustable Frequency Drive (AFD) of today provides the ability for precise control of all crane motions. Overhead cranes typically feature one or two speed speed motor controls as standard equipment. Therefore, if operators need to move loads more slowly than the preset speeds they must "jog" the load into place by rapidly turning the control on and off. AFD controls avoid this damaging practice by providing crane operators with the ability to select precise operating speeds and soft acceleration and deceleration for smooth, controlled movement of loads. The degree of control found in AFD was previously available only in AC wound rotor or DC control. The motor most often used with AFD control is a squirrel cage induction motor.

1.1   AFD Basics

The basic elements of the AFD are (1) the Converter or Rectifier, (2) the DC Bus, (3) the Inverter and (4) the Control Unit. Their relationship is shown in <u>Figure 1</u>.

In essence, the AFD works as follows: The Converter section converts the single or three phase input power to Direct Current voltage which is fed to the DC Bus. The DC Bus is a set of Capacitors that hold a high capacity DC Charge. The Inverter section consists of a set of six transistors with free wheeling diodes. All of the current entering or leaving the motor must pass through this section. The Inverter section takes the voltage from the DC Bus, converts it to a simulated AC voltage waveform and places it on the three motor leads, allowing current to flow into the motor. When energy is being fed back from the motor (as in deceleration) the current from the motor passes back to the DC Bus through the free wheeling diodes. The control section is responsible for all the timing, Pulse Width Modulated (PWM) wave generation as well as the sensing and reporting of Fault conditions.

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AC INPUT

CONVERTER

+DC

DC BUS

-DC

CONTROL UNIT

INVERTER

MOTOR

ELEMENTS OF AFD

FIGURE 1

1.2   Volts/Hertz Ratio

The AFD controls the speed of the motor by changing the frequency of the voltage to the motor. The synchronous speed of the motor is described by the following relationship:

$$N = \frac{120 \times f}{P}$$

Where: N = Motor Synchronous speed
f = Frequency of power source
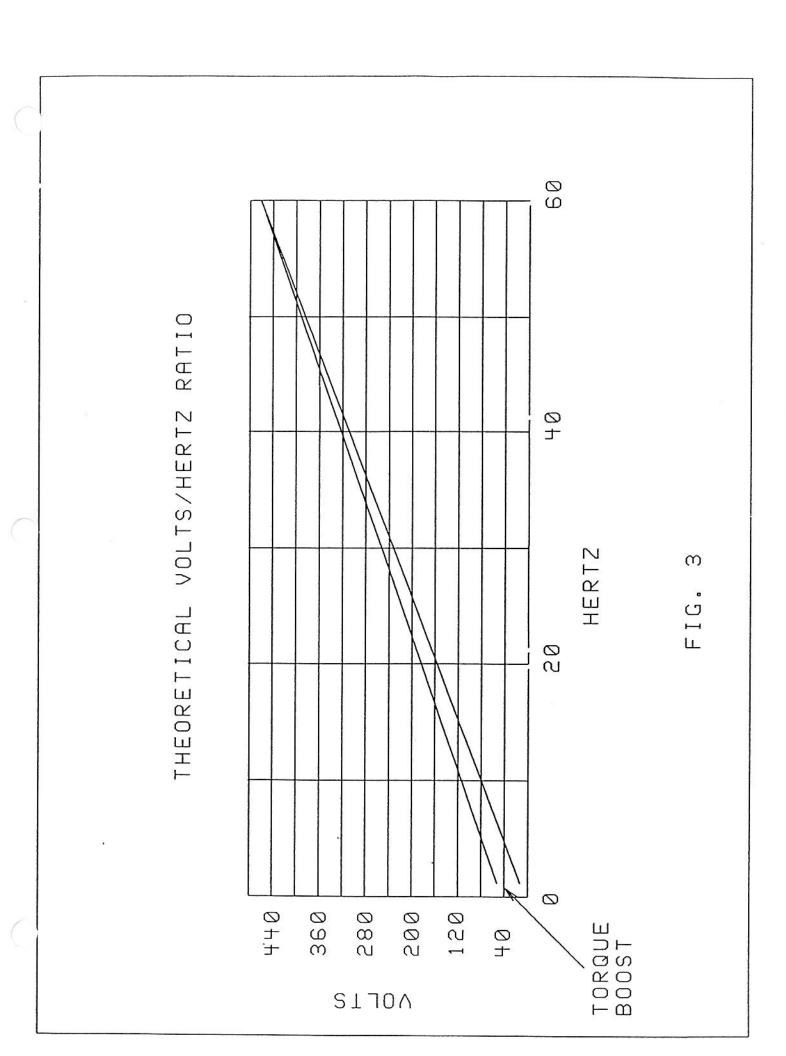P = Number of Poles in Motor

The torque of the motor is described by the following ratio:

$$T = k \times (V/F)^2$$

where: V = Applied voltage amplitude
f = frequency of power source
k = a constant

This V/F ratio must be maintained throughout the working range of the motor to maintain rated torque. The ratio is easily determined by dividing the voltage rating of the motor by the rated frequency. For most industrial motors in the United states this ratio is 460 volts/60 hertz or 7.67:1. This means that at a given frequency the theoretical voltage to be supplied to the motor is 7.67 times the frequency. To determine the voltage to be supplied to the motor at 6 hertz we must multiply 6 hertz by 7.67 volts/hertz. This would yield a theoretical voltage of 46 volts.

As seen from Figure 2 the theoretical volts per hertz pattern is a straight line. Torque is proportional to current in this motor. To maintain the required torque we must correctly control the voltage. In practice, because of resistive and inductive losses in the motor, more voltage is required to produce the necessary current to produce the torque required to control or move the load. This is most apparent at low frequencies where the voltage is also low. The voltage drop across the resistive losses subtracts from the required voltage at the motor terminals. The resultant voltage is lower than it should be, starving the motor of the current required. At this point additional voltage above the theoretical voltage is required. This additional voltage is sometimes referred to as boost. Some AFD controls will allow only a fixed boost at a minimum frequency, as seen in Figure 3. This may provide the necessary voltage at the low frequencies but will provide a higher than needed voltage at all the frequencies up to 60 hertz. The additional current generates undesired heating in the motor

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THEORETICAL VOLTS/HERTZ RATIO

VOLTS

| 440 |
| 360 |
| 280 |
| 200 |
| 120 |
| 40 |

0   20   40   60

HERTZ

FIG. 2

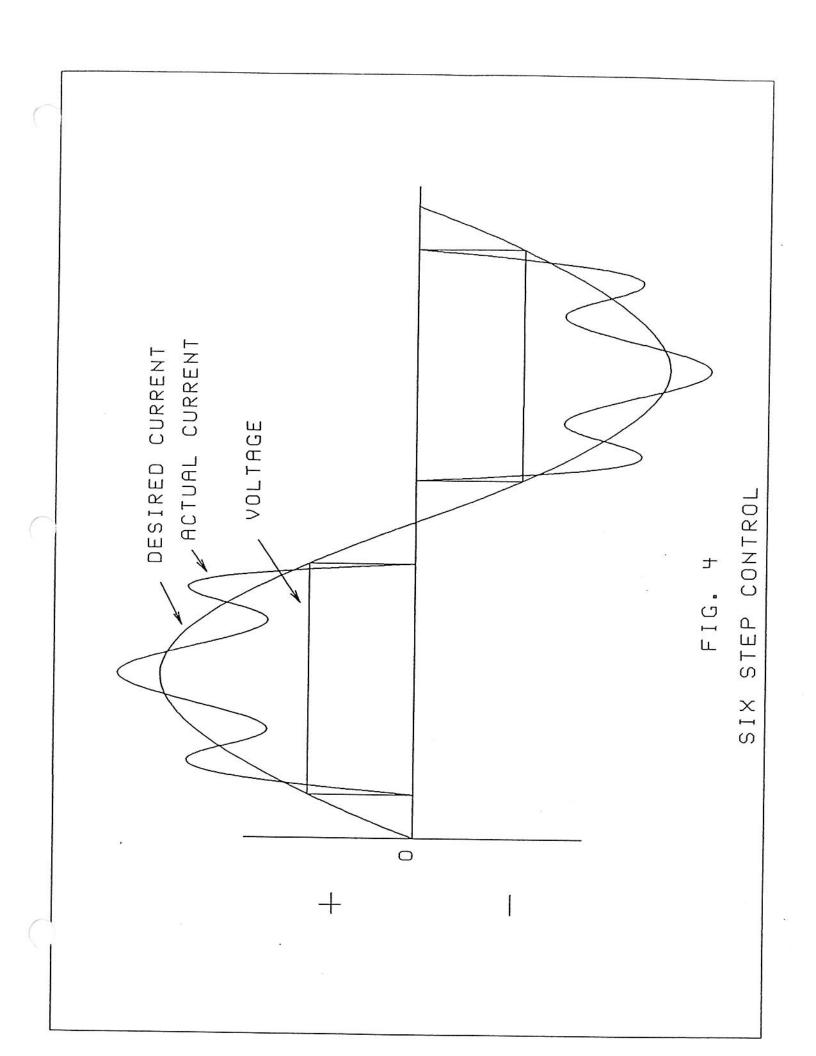THEORETICAL VOLTS/HERTZ RATIO

FIG. 3

windings which reduces motor life and performance. A solution to this problem is discussed in the Special Features section.
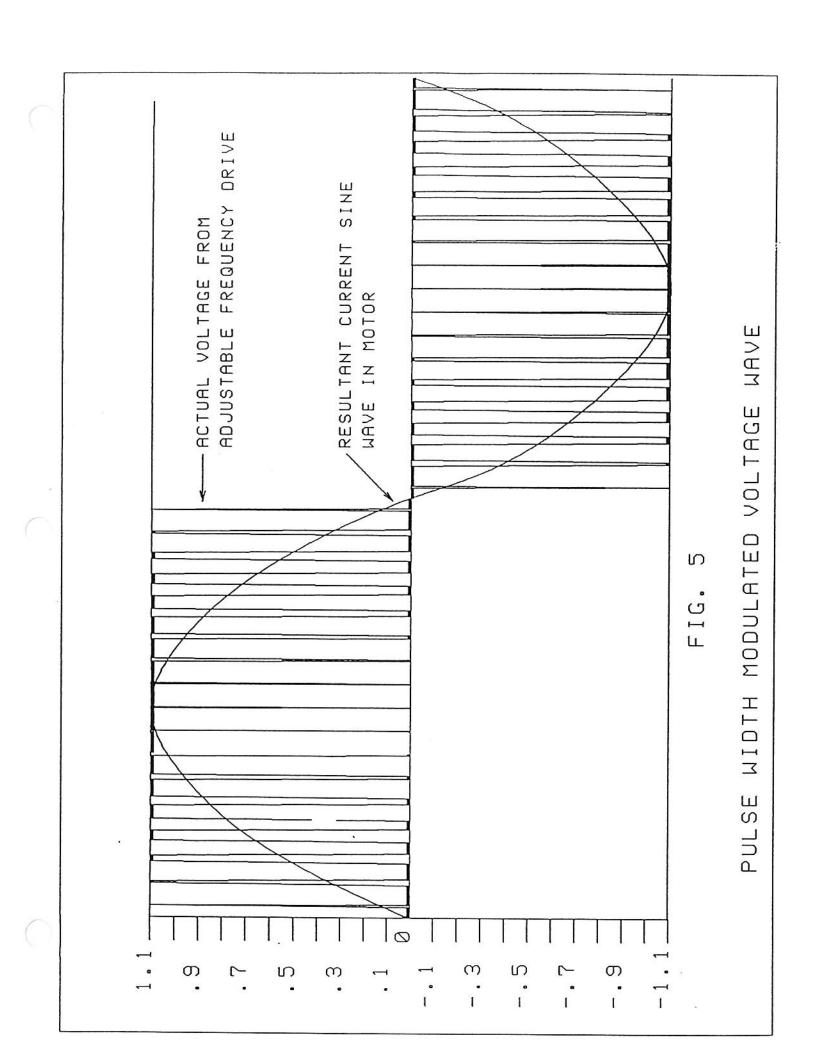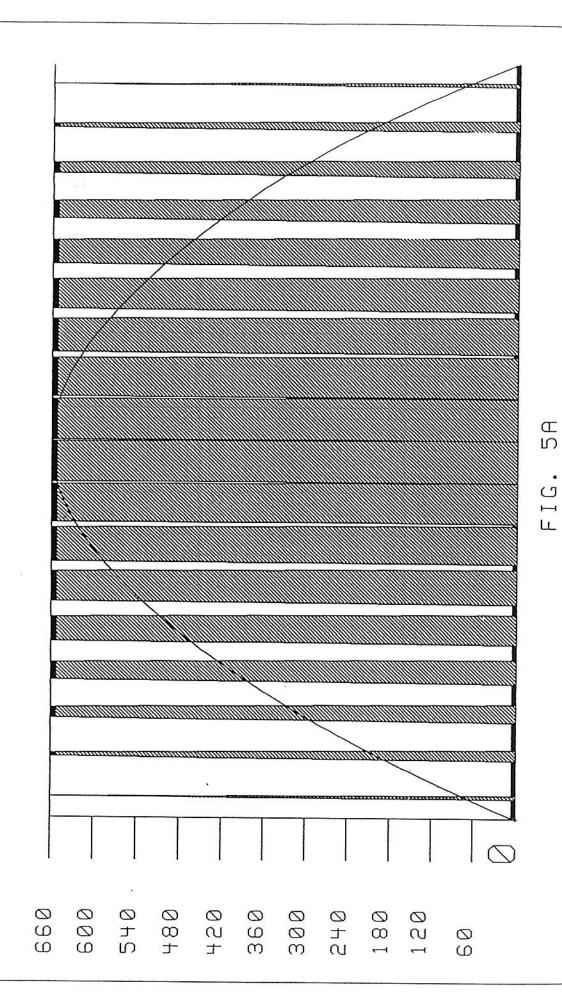

1.3   Six Step -vs- Pulse Width Modulation

In the early days of AFD, many different attempts were made with the knowledge and technology available at that time. Most of these did not work well in crane and hoist applications. The results ranged from excessive motor heating to nuisance trips and poor reliability. These past problems have been addressed by a few responsible AFD suppliers, that have specialized controls for this market.

The earlier AFD controls turned each Solid State Device on once per cycle. This type of control is called Variable Voltage or Six Step Control. Each phase would have one positive square wave and one negative square wave voltage pulse per cycle. The resulting current peaks appeared as three pointed spikes per half phase or six per phase as shown in Figure 4. The non-sinusoidal peaks caused undesired heating in the motor. These peaks do not add any usable current and generally require increased motor horsepower. The Pulse Width Modulated (PWM) AFD allows the crane to be operated at peak efficiency and control through a wide speed range and varying torque demands. Figure 5 shows one full line voltage sine wave with the equivalent PWM voltage superimposed on it for demonstration purposes. Figure 5A shows one half cycle wave from one phase of the AC power line and the equivalent PWM voltage waveform. The PWM wave ,shown as shaded in Figure 5A is composed of constant magnitude voltage spikes of varying width. The voltage magnitude is that of the DC Bus for the drive. This is usually calculated at 1.35 to 1.4 times the RMS source voltage. The DC Bus voltage for a 230 VAC system is approximately 310 to 325 VDC. It is 620 to 650 VDC for a 460 VAC power system

The narrow spikes will produce a very small equivalent voltage as found in the beginning and at the end of the sine wave. As the spikes become wider the average voltage also increases. When the spikes are very wide, full voltage appears at the output terminals of the drive ,as found at 90 degrees in the figure. Because the PWM wave more closely follows the equivalent AC voltage form, less power is lost through motor heating. This greater efficiency reduces the need for a larger motor or drive.

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DESIRED CURRENT

ACTUAL CURRENT

VOLTAGE

FIG. 4

SIX STEP CONTROL

ACTUAL VOLTAGE FROM
ADJUSTABLE FREQUENCY DRIVE

RESULTANT CURRENT SINE
WAVE IN MOTOR

FIG. 5

PULSE WIDTH MODULATED VOLTAGE WAVE

FIG. 5A

HALF PULSE WIDTH MODULATED VOLTAGE WAVE

1.4   Speed / Torque Curve

The relationship between the speed and torque of a typical NEMA B motor is shown in <u>Figure 6</u>. It indicates the available motor torque at various shaft speeds based upon a 60 hertz line frequency. With no load on the motor, the shaft RPM will approach synchronous speed, held back only by the torque required to overcome friction and windage.
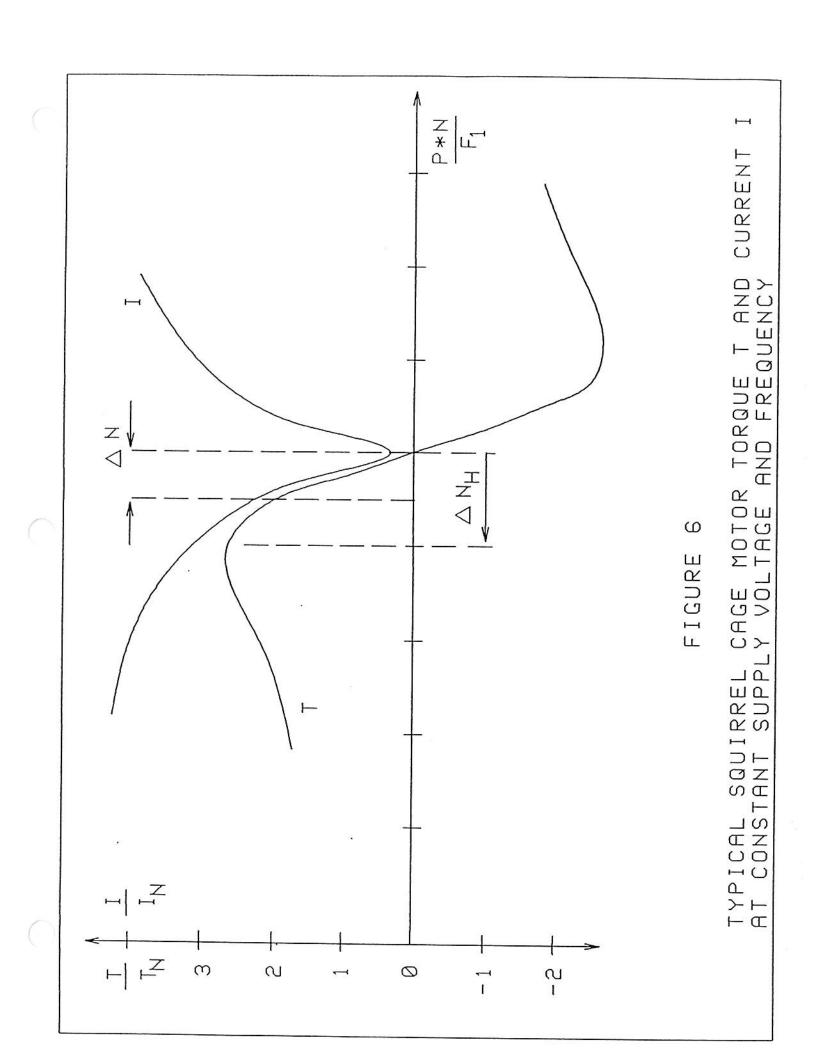
As the torque demands of the motor increase, the speed will decrease to produce the torque required. This reduction in speed divided by the synchronous speed is referred to as slip. Slip is usually shown as a percentage of synchronous speed. Many of today's NEMA B motors are rated at 3% slip at full load. For an 1800 RPM motor this is 54 RPM. At 100% Rated Load, 100% Rated current will be required by the motor. The greater the torque demands on the motor, the more current will be required to produce that torque. The shaft RPM also decreases based upon the characteristics of the speed - torque relationship of the motor.

As the torque demands on the motor increase further, the current also increases. Up to approximately 150% to 200% torque, one unit of torque is produced for every unit of current supplied. At 100% torque, 100% current is required. At 150% torque, 150% current is required. As the torque demands on the motor increase above this point, more than one unit of current is required to produce one unit of torque. Therefore the most efficient operation will occur when the load on the motor never exceeds 150% to 200%. This generally is where the adjustable frequency drive operates.

The curve shown in <u>Figure 6</u> also shows the current as it relates to further motor loading. At approximately 250% torque, 300% of the motor rated current is required. This is the maximum torque the motor can provide. Further torque demands will cause less torque and a greater decrease in speed as the motor stalls. Further increases in current will not increase the torque provided by the motor.

When motors are started across the line, 500% to 600% of rated current must be supplied. This current produces usually only 150% to 200% torque, the rest of the current is used to produce heat. In high activity applications, this heat will require a larger motor of larger frame size.

When the AFD is used, the current needed by the motor rarely exceeds 150% of the nameplate rating. This is because of the characteristics of · Speed-Torque Curve of a motor operated from an AFD. <u>Figure 7</u> shows this relationship to be a family of curves and not just a single curve as before. Because the

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FIGURE 6

TYPICAL SQUIRREL CAGE MOTOR TORQUE T AND CURRENT I
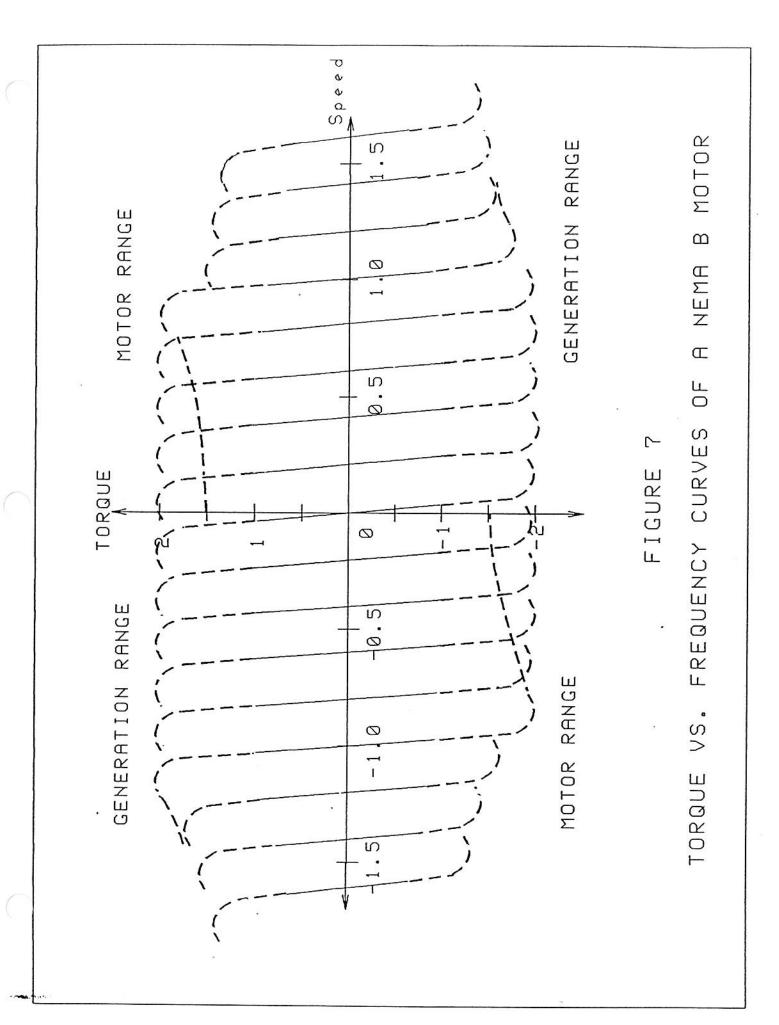AT CONSTANT SUPPLY VOLTAGE AND FREQUENCY

voltage and frequency are being adjusted to maintain a constant volts per hertz ratio, the motor is always operating at it's optimum efficiency. This is always on the steep face of the Speed-Torque Curve for a NEMA B motor. The current required by the motor is used to produce torque. Even while accelerating only a small portion of current results in heat, eliminating the need to use a larger motor.
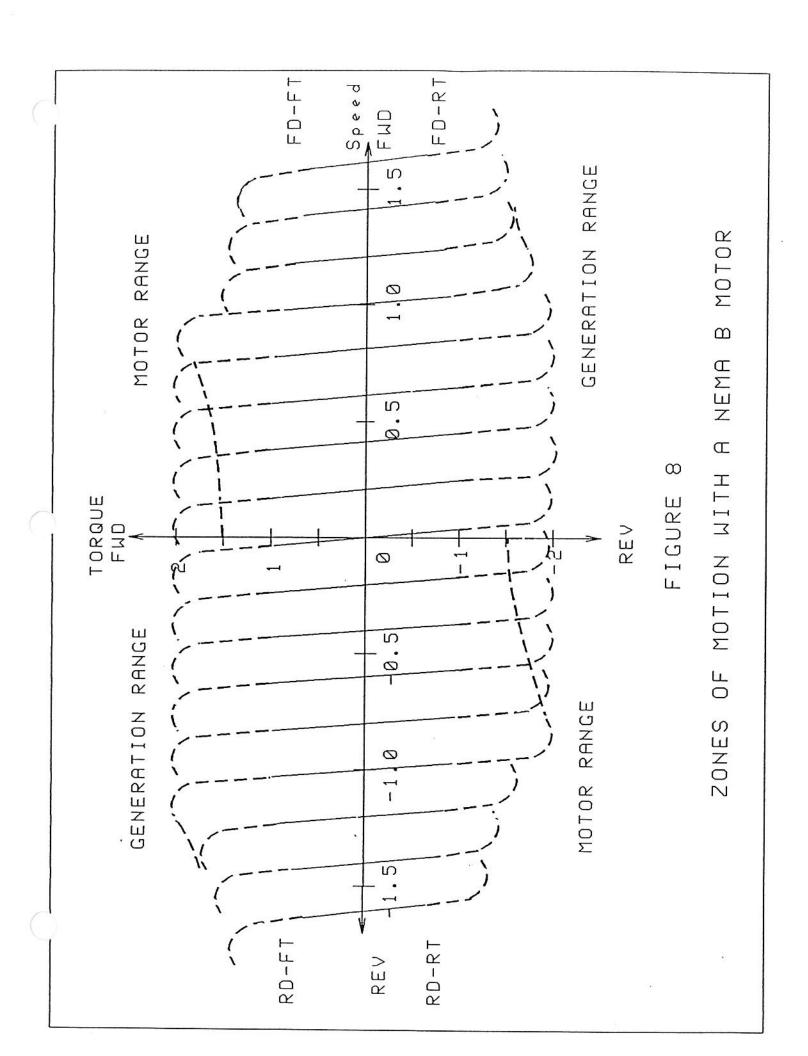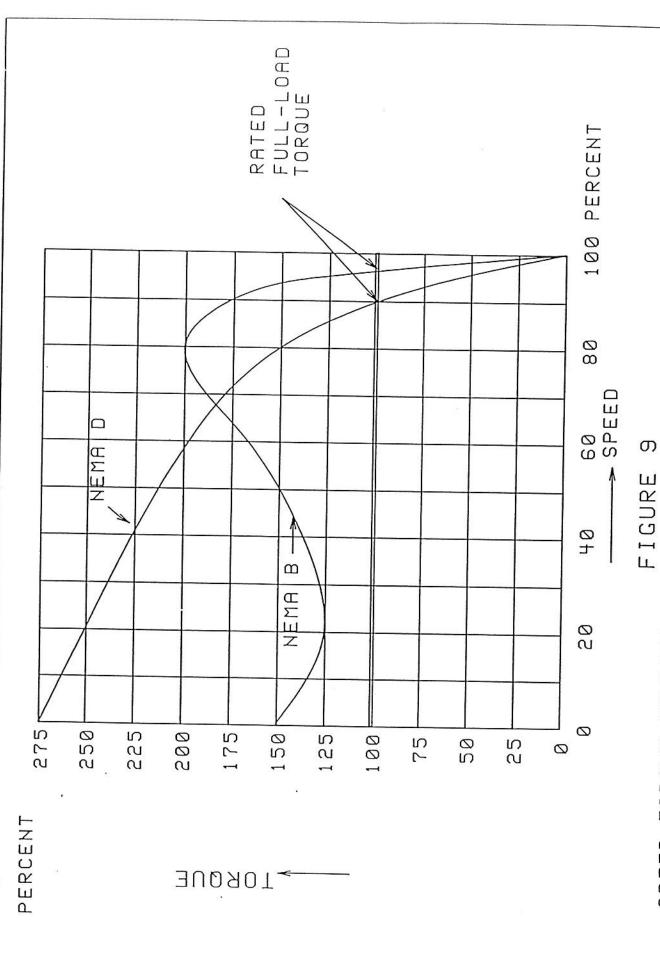

1.5   Four Zones of Control

The motion control of an overhead crane has four distinct areas or zones for each motion. Figure 8 shows these areas, which include Forward Direction - Forward Torque, Forward Direction - Reverse Torque, Reverse Direction - Reverse Torque, Reverse Direction - Forward Torque. When a crane is told to move, the direction and torque required are in the same direction. Torque is required to overcome the frictional forces and accelerate the mass of the crane and it's load to be moved. When the crane is up to speed only the frictional forces need to be overcome and thus less torque is required than during acceleration. When the crane is to be slowed, the direction of the torque is now opposite the direction of travel. On cranes without AFD, the reverse torque is supplied by the holding brake or reverse plugging. On other AC systems an eddy current brake is used to provide retarding torque. The energy during deceleration using an AFD is either dissipated in a dynamic braking resistor or placed back on the AC line with a converter. Because of the high cost of the converter a dynamic braking resistor is usually used. The amount of energy dissipated is typically small compared with the total operation and is greatly offset in the reduced maintenance of the holding brake.
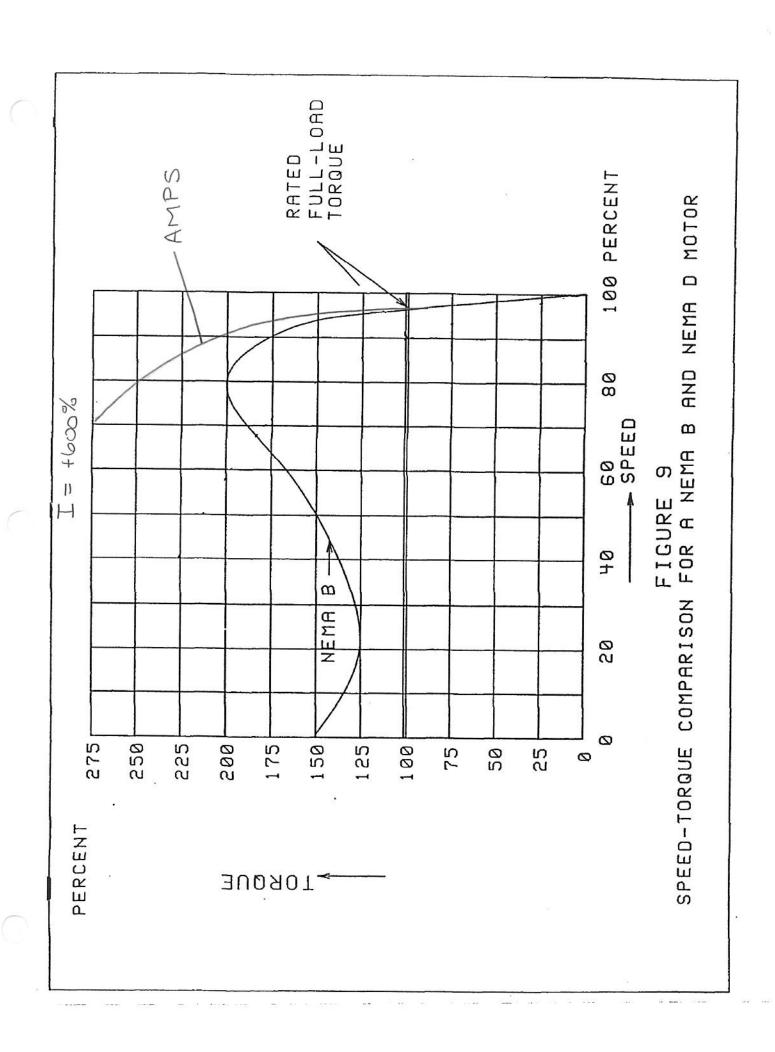

1.6   NEMA B -vs- NEMA D Motors

We have already examined the Speed-Torque Curve for the NEMA B motor. The NEMA D motor has been used for years in the crane industry. As can be seen from Figure 9, the major advantage of this type of motor is the high torque when the motor is started across the line. As we have seen earlier in our family of curves for the NEMA B controlled from an AFD, starting torque is no longer an issue. The NEMA B now can provide equal or greater starting torque as compared with the NEMA D. There are two disadvantages found when using the NEMA D instead of the NEMA B motor: First, the speed range is limited. Secondly, the motor is very inefficient.

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TORQUE VS. FREQUENCY CURVES OF A NEMA B MOTOR

FIGURE 7

FIGURE 8

ZONES OF MOTION WITH A NEMA B MOTOR

FIGURE 9

SPEED-TORQUE COMPARISON FOR A NEMA B AND NEMA D MOTOR

FIGURE 9

SPEED-TORQUE COMPARISON FOR A NEMA B AND NEMA D MOTOR

The speed range is limited because of the high slip with load. If we superimpose the Speed-Torque Curves of the two motors, as in Figure 9, this becomes more apparent. For a given torque requirement, the NEMA D motor will always produce a lower shaft RPM. The NEMA B will be more efficient because one unit of torque will be produced for each unit of current in the normal working range of the motor. The NEMA D will produce less torque for each unit of current and therefore is less efficient.

The NEMA B motor is essentially a constant speed motor having only a 3% to 5% change in speed from no load to full load. The NEMA D motor could have 5% or 8% or more slip at full rated load. At 60 hertz 3% slip is equal to 36 RPM for a 1200 RPM motor. This means that a rated load would be held within 36 RPM of the synchronous speed of 1200 RPM either raising or lowering up to a full rated load. In reality this 36 RPM is constant for all synchronous speeds produced by the adjustable frequency drive. At 30 hertz the synchronous speed of the motor is 1200/2 or 600 RPM. The possible variation in speed is 600 RPM + or - 36 RPM. If we are lifting a full load with a NEMA B motor, what is the speed range lowering and raising assuming a 40:1 frequency range? If we take 1/40 of 1200 RPM we now have a synchronous speed of 30 RPM at an applied frequency of 1.5 hertz (60/40 = 1.5). We have determined that the motor will slip back a total of 36 RPM at full load. Therefore, if we attempted to raise a rated load at 1/40 frequency, with a 1200 RPM NEMA B motor, the rotor RPM would be -6 RPM (30 RPM Synchronous - 36 RPM slip). It is obvious if the load were off of the ground, it would lower at 4 RPM. If the load were on the floor it could not be lifted. Thus the lifting synchronous RPM of any motor, must be greater than the slip RPM to lift a load. Thus the choice of the motor as well as the AFD limit the minimum lowering speed for a given gear ratio.

In this case, the minimum synchronous frequency to be applied to this motor to raise the load at 1 RPM is 37 RPM. If the AFD were to generate a frequency of 1.9 HZ [(37RPM/1200RPM)*60Hz.] this frequency would be generated. While raising a full rated load, the motor RPM can be controlled from 1 to 1164. This is a range of 1164:1. The calculations for lowering are similar except now the slip RPM must be added to the synchronous speed. The minimum frequency of a good AFD is 1.5 hertz. This is 1/40 the standard 60 hertz full speed. At 1.5 hertz the synchronous speed of a 1200 RPM motor is 30 RPM. When lowering a full load, we must add the slip RPM which will yield a minimum lowering speed of 66 RPM (30 + 36). At sixty hertz the load will be lowered at 1236 RPM (1200 + 36). When lowering a full load the

speed can be controlled from 66RPM to 1236RPM. This is a speed range of 18.7:1.

The NEMA D motor has long been the motor of choice for hoist suppliers because it produces maximum torque when started across the line. With the AFD this may change. If the calculations above are repeated, this time for a NEMA D motor, the results will be quite different. This type of motor has a slip of 5% to 8% or more depending upon the rotor construction. Assuming an 8% slip, the 1200 RPM motor would lose 96 RPM at full-rated load with a frequency of 60 hertz applied. The actual change in RPM from no load to full load is constant at all synchronous speeds provided by the AFD. Therefore, the shaft RPM at full load can always be predicted if the frequency being generated by the AFD is known.

If a frequency that will yield a synchronous speed of 97 RPM is applied, the rated load will be lifted at 1 RPM (97 sync. - 96 slip). This RPM would be achieved by applying 4.8 hertz [(97RPM *(60 Hz./1200RPM)] to the 1200 RPM NEMA D motor. At 60 hertz, the full load would be raised at 1104 RPM (1200 sync. - 96 slip). While raising a full-rated load, the motor RPM can be controlled from 1 to 1020. Although this is a range of 1020:1, it must be remembered that only 85% of the synchronous speed can be achieved, with 60 hertz applied. The calculations for lowering are similar except now the slip RPM must be added to the synchronous speed. At 1.5 hertz the synchronous speed of a 1200 RPM motor is 30 RPM. When lowering, a full load, the slip RPM must be added yielding a minimum lowering speed of 126 RPM (30 + 96). At sixty hertz the load will be lowered at 1296 RPM (1200 + 96). When lowering a full load the speed can be controlled from 126 RPM to 1296 RPM. This is a speed range of 10.3:1.

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MINIMUM SPEED LOWERING

NEMA B MOTOR		:	NEMA D MOTOR	
AFD HZ. 1.5	MOTOR RPM 30 SYNC. +36 Slip --------- 66 ACTUAL	: : : : : :	AFD HZ. 1.5	MOTOR RPM 30 SYNC. +96 SLIP --------- 126 ACTUAL

MAXIMUM SPEED LOWERING

NEMA B MOTOR		:	NEMA D MOTOR	
AFD HZ. 60	MOTOR RPM 1200 SYNC. +36 SLIP --------- 1236 ACTUAL	: : : : : :	AFD HZ. 60	MOTOR RPM 1200 SYNC. +96 SLIP --------- 1296 ACTUAL

SPEED RANGE

NEMA B MOTOR	:	NEMA D MOTOR
1236/66 = 18.7 : 1	:	1296/126 = 10.3 : 1

FIGURE 10

The motor of choice for hoists using an AFD should be the NEMA B
motor. The most important characteristic of hoist control is
usually the amount of control when lowering. As can be seen from
Figure 10, the NEMA B motor, when lowering, will not only allow
a good speed range (18.7:1) -vs- (10.3:1) but will allow a lower
slow speed 66 RPM -vs- 126 RPM.

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2.0   Types of Control Available

There are a few types of control available for the Adjustable Frequency Drive. All other things being equal the choice of the type of control may well determine the degree of success achieved with the AFD application.

2.1   Analog

The Analog control of the AFD was the first available. It is based upon operational amplifier circuits which operate on voltage levels. The controls are characterized by the many potentiometers (pots) found on the circuit boards. These pots are used to change the gain and offsets of many of the critical circuits on the control board.

Unfortunately, these circuit's gain and offset values can change with fluctuations in temperature and over time from vibration found on cranes. The pots are then adjusted to compensate for current conditions only to be readjusted, some time later, for the same reason. After a while, the control is detuned to the point of noticeable performance degradation. At this time, a readjustment and calibration is required to bring the system back to its original settings. The cycle begins again, with the system at any given point operating in a sub-optimal condition.

2.2   Digital

There are two types of digital control circuits currently being used in AFDs. They are LSI and Microprocessor based systems.

2.2.1 LSI Large Scale Integration

LSI circuits are digital or mostly digital in nature. They allow the advantages of digital control and remove many of the disadvantages of the analog control. The major problem with this type of circuit is that it is standard for all of the applications, in which the general purpose drive will be used. Once programmed it may not be changed, modified or enhanced. The design of the chip is fixed and only an expensive redesign will change its characteristics. The crane and hoist applications require superior performance not required with the main stream world of fans and pumps.

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2.2.2 Microprocessor

The microprocessor has many advantages in the control of AFDs. The major advantage is that all settings are digital and do not change with time, vibration or temperature. The microprocessor communicates with many types of memory. The basic algorithms for control are stored in Read Only Memory (ROM). The ROM retains this information indefinitely. If special features are required to make the AFD behave in a new way, a new ROM is prepared. This ROM then replaces the old one, and the drive has taken on new characteristics. Although new ROM's are not trivial to generate, it does provide flexibility and has been done by those companies interested in tailoring the AFD to a specific market. This allows performance and safety features not available from general purpose AFD suppliers.

The AFD can be set up or tuned for the application by entering data through a Keypad Display Unit (KDU). Figure 11 shows a typical example of a contemporary microprocessor based AFD with a KDU. All set-points are entered through this unit. These set-points are then stored in nonvolatile memory. The user can then examine the current set-points at any time and change them if required. The set-points will not change with temperature, time or vibration. An example of a typical user changeable set-point is the acceleration time. As received from the supplier this value may have been set for too long a time. The qualified maintenance person can change this value and verify the change before returning the crane to operation. The maintenance person may now lock the set-points by entering a special code or password.

The KDU can be used to display operating conditions such as the frequency and amplitude of the current being supplied to the motor. A good AFD can also display coded messages on the display to indicate current or pending fault conditions. The best drives will have sufficient detail to help locate the faulty component or unacceptable operating condition. The microprocessor based AFD provides many operational advantages over previous designs and offers some functions not otherwise available. An example would be the ability to communicate with a computer to report status or accept new set-point information.

3.0 Special Features

Special features are what separates AFDs tailored to an industry from general purpose AFD's. Some of these features are related

Figure 11

to performance others are related to operator interface while others are related to safety. The following is only a partial list of features available.
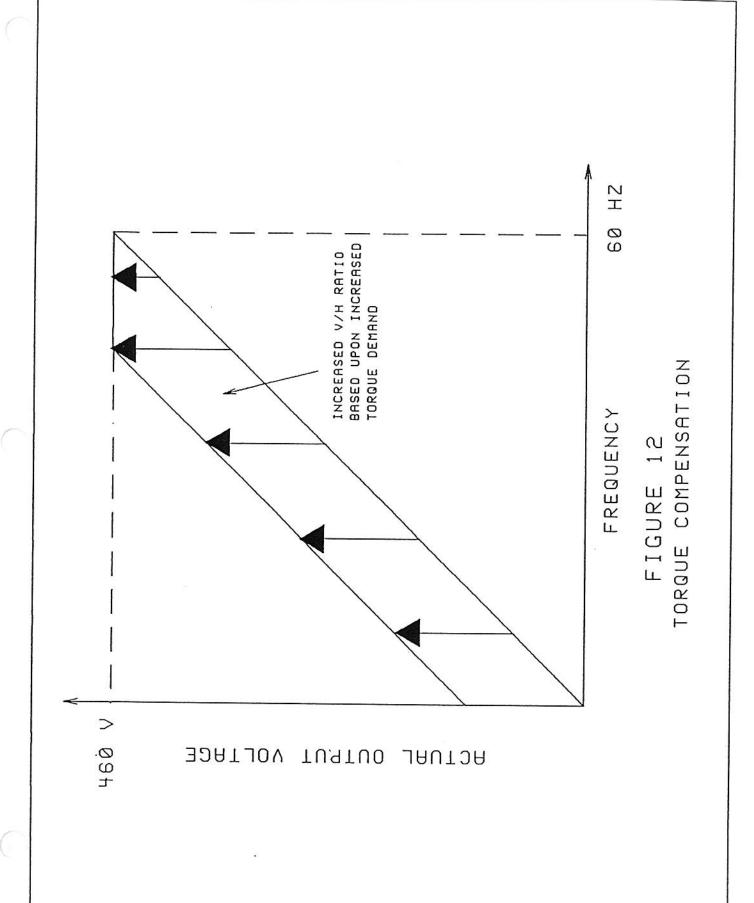
3.1   Torque Compensation

For example, in a squirrel cage NEMA B motor, as the load on the motor increases and the rotor begins to slip back in RPM the impedance of the motor changes. More current is taken from the power source in response to the torque demand. Some of this current will generate flux and some is consumed in winding and iron losses. If the AFD has a mathematical model of the motor in its memory, the current required to produce torque and that which will be consumed through losses can be calculated. The volts/hertz (V/H) pattern can be increased to insure that enough current is left, after losses, to produce the required flux to meet the changing torque demand. Figure 12 shows this feature and the ability to dynamically change the V/H ratio with load. When the load is reduced the V/H pattern is reduce to the appropriate level. The effect of this feature can be dramatic.

When a non-standard type motor is used, the performance of the drive and motor system is very sluggish and inefficient. The motor may be a low slip, high-efficiency motor and appear to operate worse than one with standard characteristics. The AFD with a good torque compensation algorithm and an accurate model will provide superior performance. By supplying the perfect current match to torque required, the motor will run cool and be very responsive. The accurate model is achieved by determining the important motor parameters for the motor to be used and loading these parameters into the AFD's mathematical model. Now the drive is matched or tuned to the motor. We have seen surprising performance improvements when this tuning had been performed. Some of the best motors do not work well only because the drive is responding to an incorrect model or no model at all.

3.2 Minimum Voltage Boost

There are times that even Torque compensation can not correct for all of the losses at the lowest voltage levels. This can occur on hoist and trolley motions when the length of the wiring between the AFD and the motor is very long. There are many instances when this length exceeds 150 to 200 feet. Even if the wire is sized from traditional table values, when a large current is being supplied to the motor at these distances, a

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INCREASED V/H RATIO
BASED UPON INCREASED
TORQUE DEMAND

460 V

ACTUAL OUTPUT VOLTAGE

60 HZ

FREQUENCY

FIGURE 12
TORQUE COMPENSATION

relatively large voltage drop will occur. Torque Compensation takes care of the losses within the motor but assumes that the wiring loss to be minimal. A minimum voltage boost will compensate for this loss. This boost is seldom required above 3 or 4 hertz. As we discussed earlier, if this boost has only one setting, additional heating will result in the motor at all frequencies up to 60 hertz.

The best approach is to apply the voltage boost only at the lowest frequencies, and then return to the traditional Volts/Hertz (V/H) pattern for the remainder of the frequencies. Figure 13 shows a typical V/H pattern for Hoist applications. Notice that above 3 hertz, the theoretical V/H pattern is used. Above this point Torque compensation is used to insure the required current is supplied to the motor. Voltage boost is limited to frequencies below 3 hertz.
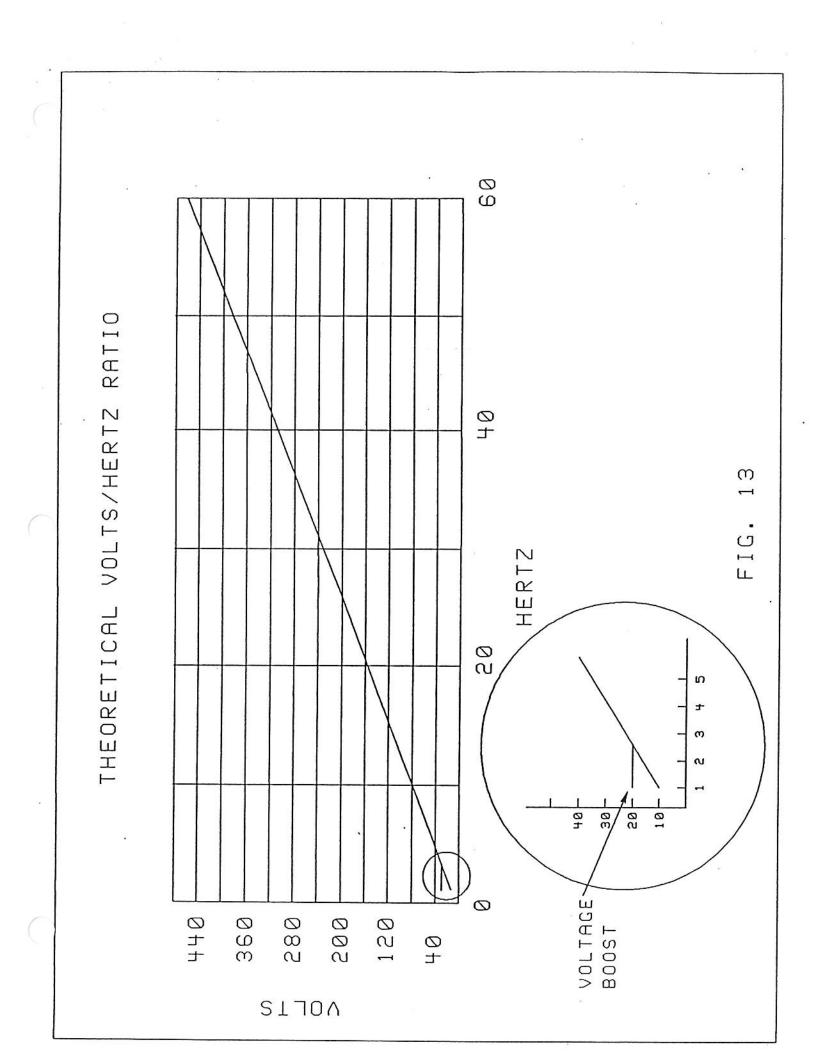
3.3 Stall Prevention

When a motor is used to lift a load, three types of torque are required: holding, friction and acceleration. Holding torque prevents the load from dropping when the holding brake is released. Holding torque is proportional to the weight of the load. Friction torque overcomes the frictional losses in the motor, gearboxes and reeving, and will be considered for our example to be constant. Acceleration torque changes the velocity of the load and is proportional to the mass of the load and rate at which a velocity change is to occur.

In equation form: T(total) = T(hold) + T(friction) +T(accel)

Hoist motors are sized to deliver a specified torque at a specified speed. If a NEMA B motor is used, a peak torque of 200% to 250% of motor rated torque, is available to lift the load. The sum of the three torques described above must never exceed this value or the motor will stall and the load would begin to drop.

Most AFDs are rated to deliver 150% of their rated current for one minute. This is usually ample time to accelerate or decelerate a load. The AFD should be sized according to motor-rated current. A good rule of thumb is to select an AFD whose 150% rated current is sufficient to provide 200% motor current. As the size of the hoists and loads increase, a greater percent of the available current is required for acceleration. If the load is too heavy or the acceleration time too short, the motor could be starved for current, stall, and the load could drop.

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THEORETICAL VOLTS/HERTZ RATIO

FIG. 13

Stall Prevention will keep this from occurring. Because the accelerating torque is proportional to the mass of the load and the rate at which it is to be accelerated, the AFD can maintain control of the load, by controlling the acceleration rate. Stall prevention will allow a maximum current value to be demanded during acceleration. If this value is exceeded, the acceleration rate is reduced or stopped until the current is once again below the set-point. This has the effect of slowing the acceleration rate and automatically compensating for a heavy load. The load is now being accelerated at the hoist's maximum safe rate.

We will assume that the hoist motor has been sized to lift a 100% load at 100% rated motor torque. We will also assume that torque on the drum will be proportional to the force on the rope. Our torque equation from above now can be stated in units of force which will be proportional to the units of torque as:

$$F(total) = F(hold) + F(friction) + F(accel)$$

In Figure 14 we can see the following description in equation form (a). If we assume that 100% force will lift 100% load with nominal acceleration we can also assume that 100% force on the rope will be distributed among the three forces as shown (b). We will now normalize the equation to equate one percent of force equal to one unit of force. As we can see then 100 units of force are distributed over the three force areas (c).

If we now want to lift a load of 125% what will be the required units of force (d)? If we assume the frictional force to be constant and the other forces proportional to load, we see that it would take 122.5 units of force to lift the load at the same acceleration rate (e). If we only want to use a maximum of 120 units of force, what must be done with the acceleration force to compensate (f)? The acceleration force must be limited to 10 units of force.

The acceleration force is equal to the mass of the load times the acceleration rate (h). The mass will remain constant therefore we can only adjust the acceleration rate to limit the force. Using a ratio relationship the new acceleration rate must be reduced to 80% of the original, to limit the force (torque & current) to 120% of rated (i).

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(a)   F(total) = F(hold)   + F(friction) + F(accel)

(b)   F(100%) = F(80%)   +   F(10%)   + F(10%)

(c)   F(100) = F(80)   +   F(10)   + F(10)

(d)   F(???) = F(1.25*80)   +   F(10)   + F(1.25*10)

(e)   F(122.5) =   F(100)   +   F(10)   +   F(12.5)

(f)   F(120) =   F(100)   +   F(10)   +   F(????)

(g)   F(120) =   F(100)   +   F(10)   +   F(10)

(h)   F(12.5) = M * A(1)   F(10) = M * A(2)

(i)   A(2) = (10/12.5) = 0.8 * (A1)

Figure 14

This acceleration adjustment is done automatically and dynamically on contemporary AFDs so equipped. This adjustment is made approximately 50 to 100 times a second in the latest microcomputer based models.

3.4   Parameter Changes and Lockouts

Some AFD's, such as the one shown in Figure 15 must allow the AFD suppliers to make critical adjustments to insure the efficiency and safety of the crane operation. Some of these should only be changed by skilled and experienced personal while allowing the users personnel to change speed and acceleration settings. It is not appropriate for us to discuss these techniques in detail in this paper, but a special key sequence, setting or pass word is usually provided. Customers must look for this feature in their selection of suitable vendors to safeguard their investment. This feature is only available in microprocessor based AFDs as the pots of analog AFDs are always exposed to curious unqualified individuals

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Figure 15

3.5   Speed Reference Options

It is important that the crane manufacturer or service supplier remain up-to-date on the product offerings for control. The way the speed of a crane is selected is one of the variables which must be considered in the selection of an AFD. Some AFDs will provide one, some or all of the selections described below. AFD suppliers with the greatest product offerings provide the best solutions. If only the method of speed control is changed, all of the other connections and settings would be very familiar to the assembly, installation and customer's personnel. This usually results in easier installation and maintenance while continuing to allow a variety of offerings to meet the needs of the end-user. Sometimes suppliers can provide interface modules that enhance the AFD and provide a more suitable match to the crane builders existing pendant stations.

3.5.1 Analog

This interface is characterized by a voltage level or current level determining the frequency output of the AFD. The most standard interfaces are 0-10 VDC or 4-20 DCMA, although others are available. Usually for crane operation, a Forward or Reverse discrete input is used to determine direction and the analog signal used for speed. This interface is used when a potentiometer is required to set the desired speed. This type of interface may also be used in conjunction with automated cranes interfaced to a computer or programmable logic controller. Because this interface is based upon a voltage or current magnitude, the user must insure that the system remains calibrated. Care must be taken to insure that time, temperature or vibration does not effect the reference level sent to the AFD.

3.5.2 Digital

This type of interface is sometimes used to interface automation controllers to AFDs. The speed reference is sent to the AFD in either binary or binary coded decimal (BCD) of one to four digits. If eight bits of binary are interfaced to the AFD one of 256 different speed selections from 0 to full speed can be made. In three digits of BCD one of 999 speed points can be selected. If the controller is far from the AFD there may be too many wires of low potential signals to be practical for crane use.

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3.5.3 Discrete

This type of interface is usually used from pendant stations or automated systems. It is characterized by having one input for each function or speed selection. A typical four-speed crane motion interface would include a single wire for forward motion and the minimum speed point. A second wire is used for a reverse motion input and the minimum speed set-point. Three additional signal wires are used for the remaining second, third and fourth speed selections. The AFD can be programmed to provide a different frequency for each of the four settings. A typical application would have the slowest speed at 5 hertz, a second speed at 15 hertz, the third speed at 30 hertz and the full speed set to 60 hertz. Because these speeds are programmed into the AFD memory they will not change with time, temperature or vibration and can be changed when needed through the Key Pad of the microprocessor based control. This provides a very repeatable, predictable crane operation, with a relatively simple interface.

3.5.4 Infinitely Variable.

This type of interface uses discrete inputs from a pendant station to provide infinitely variable operator selectable speeds. When the direction input is supplied to the AFD, the minimum speed in the direction request is sent to the motor from the AFD. A second step on the same button is used to accelerate the crane to the desired speed. When that speed is achieved, the operator will reduce pressure on the button back to the first position. The crane will continue to operate at that speed until the operator removes pressure from the button. When pressure is removed from the button, the AFD will decelerate the crane to stop and set the brake. This type of control using a two step button is used for horizontal motions.

A similar interface is available for Hoist motions. This requires a three-step button. The first position will select minimum speed. The second position will hold the speed selected and the third position will increase the speed. When the operator desires to reduce the speed of the hoist he will allow the button to move to the first position, the AFD will slow the crane at a predetermined rate. When the crane has slowed to the desired speed the operator will move the button to the second position to hold the current speed. When the operator removes his finger from the button the holding brake is immediately set, for safety reasons.

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3.6   Over-speed (Field Weakening)

This feature is provided by some AFD suppliers to enable the crane to operate beyond its normal maximum speed. Up to 60 hertz (50 hertz in Europe) the crane motors are operated in a constant torque mode. The drive will be able to provide full-rated torque between 1.5 hertz and 60 hertz. Above 60 hertz the motion is considered to be in the constant horsepower range. Although the motion can be operated above this frequency the motor can no longer provide full-rated torque. Horsepower is proportional to a specified torque at a specified RPM. This RPM is usually 1800 or 1200 for crane operation. When the frequency is increased above the specified rating of these motors, torque is reduced. At 90 hertz the torque available will be 50% or less of that available at 60 hertz. This is equivalent to the field weakening operation used with DC Drive systems.

This feature can be used on a hoist motion to raise or lower an unloaded hook at up to twice the rated speed. Caution must be used when applying this feature because the inertia in the hoist system will exert some load on the hook even though there is no load. A frequency of 120 hertz may not be practical for either the gearbox or motor of larger horsepower. A practical limit may be achieved at 90 or 100 hertz. This will allow improved speed performance when little or no load is on the hook. A safe system will sense the actual load on the hook and limit the maximum over-speed to a controllable level.

3.7 Dynamic Braking

Dynamic braking is used when the AFD is slowing a motor by lowering the applied frequency and voltage, as shown in the V/F pattern discussed earlier. During this period, the AFD is reducing the applied frequency at a specified rate, to provide predictable movement. The motor during this period becomes a generator. The current generated enters the AFD through the free-wheeling diodes on the output transistors. The current entering the AFD causes the DC Bus voltage on the AFD to rise. When the voltage reaches a predefined level one of two things can occur. First, if there is no way to get rid of the energy entering the drive, an Over Voltage Trip will occur. This in turn will stop the controlled deceleration and set the holding brake. A second solution is to use a Dynamic Braking Transistor (DBT) which will turn on above the normal DC Bus voltage level but below the Over Voltage Trip level. The second approach is usually used in crane systems.

When the DC Bus level rises during deceleration the DBT will turn on at a predetermined level. When the DBT is on, the energy being added from the decelerating motor to the bus must be removed at a greater or equal rate or the bus voltage will continue to rise. A Dynamic Braking Resistor (DBR) must be added to the output of the DBT to dissipate the energy being removed from the bus. The size of this resistor is critical. If the ohmic value is too high, an Over Voltage Trip may occur. If the ohmic value is too low too much current may be removed when the DBT is on causing the transistor to fail or large torque shocks to appear in the motor and gearbox. The wattage rating of the DBR must be sized to the expected activity of the crane. If the crane is seldom used more than once an hour, a minimum wattage resistor may be used. If the activity is continuous over periods of time during the day, as in automated cranes or refuse applications, a large wattage rating is in order.

Because the size of this DBR is critical, consult your AFD supplier for selection assistance. A reputable supplier should have calculated resistance values for the activity you require. The RPM rating of the motor must also be known, because each ampere of current removed from the motor of a 900 RPM motor will produce twice the retarding torque of the same horsepower 1800 RPM motor. Incorrect sizing of the DBR in 900 RPM or 1200 RPM motor application, can cause destructive torque shocks in both the motor and gearbox.

4.0   Crane Control with Adjustable Frequency Drives

The AFDs available today allow the crane industry a sophisticated control system in a rugged, reliable, and easy to use package. The features mentioned above help to provide the unique requirements that crane control demands and only an AFD of superior performance can provide. The crane has two groups of motions. The traverse motions, usually described as the bridge and trolley, are related to the horizontal movement of the crane and its load. The hoist motion is related to the vertical movement of the load.

Some features of AFDs used on cranes are related to all motions. Most cranes use a holding brake to hold the crane in position while not in motion. Historically this was a constant source of maintenance problems. Before the AFD, the crane was brought to a stop using this brake. Because a very slow (creep) speed was not available, the operators would rapidly push the motion button on and off many times. This jogging procedure

would produce a slow speed while the crane was alternately
accelerating and stopping. The brake took a beating because it
was constantly being hammered in and out. The brake coil would
heat up with the high inrush currents. The brake shoes would
wear because the were constantly being used to decelerate the
inertia of the motor, gear box and load which was at this time
still accelerating. The AFD has solved this problem by only
allowing the brake to set when motion is stopped. The slow
speeds available have removed the damaging jogging of before.
Even if jogging is attempted the AFD will cause the crane to
smoothly change from acceleration to deceleration on a smooth
wave of motion.

Prior to AFDs, the motor also took a beating. When the jogging
occurred, the current in the motor was always at inrush levels
most of which produced heat. The gear box, being started quickly
from the motor and stopped abruptly by the brake, would also get
hammered. These large torque shocks would help to reduce the
life of the gear box.

The AFD has been shown to reduce maintenance on the brake and
gear box, but it is also easier on the motor. The NEMA B motor
used in traverse motions never sees the 500% to 600% inrush
currents associated with starting and jogging. The motor is
never plugged to slow down as with earlier contactor controls.
The highest currents provided during acceleration and
deceleration are usually limited to 150% of motor rated current.
When accelerating or decelerating the motor speed is changed in
a smooth, continuous manner providing smooth constant torque.
There are no hammering or torque shocks seen by the motor, gear
box or load when properly applied.

4.1   Traverse Motions

The Traverse Motions of a crane are bridge and trolley. They
make up the X and Y coordinate system for the crane. The Bridge
motion usually requires the largest horsepower motors because
the total mass of the crane and load are moved with it. As can
be seen from Figure 16, the mass to be controlled can be very
large with dual girder bridges extended as much as 80 to 100
feet in span. Many of these cranes use multiple motors to help
share the load and reduce skewing. This mass must be
accelerated, held at a desired speed and decelerated when coming
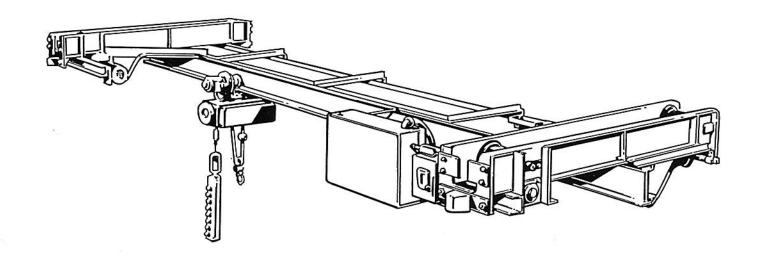into position.

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FIGURE 16

The adjustable frequency drive accelerates the bridge from any speed to the programmed maximum speed in a fixed amount of time. It will also reverse the process during deceleration. Multiple motor systems will be given the same voltage and frequency and tend to share the load. The traverse motions are very predictable and repeatable, regardless of load. A good AFD will use up to 200% rated motor current to follow the accel or decel ramp. This repeatability is good for the operator because he will know what to expect. For automated systems this ability reduces the need for sophisticated closed loop control because the crane will always repeat motions in a defined manner.

The bridge motion, with its large mass, usually exhibits about the same load for the AFD with or without load. The trolley is usually small compared with the bridge. The loaded trolley will look quite different to the AFD than it does with no load. Because of the features such as Torque Compensation, the control of the trolley will always be consistent. The operator or automation will see the same movement no load or full load or in between.

4.2   Hoist motions

The attributes associated with the traverse motions are the same for the hoist with one exception: if we lose control of the traverse motions the motion will eventually stop. If we lose control of the load on the hoist - the load will free fall to the ground. As we have described earlier in this paper, the torque available from the motor is limited. It is either limited by the motor or the drive. Using a NEMA B motor has many advantages but there is one big disadvantage. If the torque required exceeds the pull out or breakdown torque, the hoist will lose the load. There are two ways to attempt to move an uncontrollable load. The first is to lift a load greater than the capacity of the hoist rating. Because of the Stall Prevention feature described earlier, the acceleration rate will automatically adjust to allow the lifting of an over-weight load. The problem is when this load is lowered, the deceleration rate will be fixed. If the torque required for controlling the combination of the weight of the load, the inertia of the motor and gear box and the deceleration of the load mass are greater than the motor and AFD can provide, the load will free fall.

There are two methods of preventing the loss of the load. The first is to monitor the output frequency of the AFD and compare

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it with the RPM of the motor. If the load is too great, the RPM of the motor will begin to be very different from the predicted slip. When the motor RPM deviates from a predetermined safe window, the holding brake is set and the load stopped from entering a free fall mode. A major crane manufacturer provides this feature and has a patent pending, for its Deviation Detection Circuit.

The second method of prevention is to control the hoisting motion within safe limits. This would include a weight sensing device to prevent the lifting of an overweight load. The acceleration and deceleration times would need to be set within a safe operating limit. As an additional feature, an over-speed device could also be installed.

If the AFD size is made large enough, the motor will always be the limiting factor. The AFD selection must always be made on the current rating of the drive and motor. A 900 RPM motor will require almost twice the current of an 1800 RPM motor of the same horsepower. An AFD will have to be at least one or two horsepower sizes larger because of the current rating of the 900 RPM motor.

5.0   Conclusion

The AFD has indeed changed the way we control cranes today. When used with a squirrel cage motor it is a very rugged, reliable, cost effective package. For high performance application special motors can be tuned to provide continuous repeatable performance.

Although the AFDs work best with a new NEMA B motor, many successful retrofit applications have been installed using the existing NEMA D or wound Rotor motors.

To get the most from AFDs, you should consult suppliers who specialize in crane and hoist applications. They will be able provide safe and reliable controls by following good wiring and installation practices. They will supply the AFD and motor combination suitable for your application.

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DC vs AC

ELECTRONIC MOTOR CONTROL FOR OVERHEAD CRANES

For many years both Alternating Current (AC) and Direct Current (DC) electronic motor controls have been available for the overhead crane industry. AC adjustable frequency drives (AFD) with squirrel cage motors are replacing other types of motor control for traverse motions (bridge and trolley). Until recently, AC motor control was used for hoisting applications where speed and load regulation were not as important as maintenance free operation. When precise, well regulated speed control was required, DC control was used.

With the advent of IGBT (Insulated Gate Bipolar Transistor) for the power output devices, 32 bit microprocessors and Digital Signal Processors (DSP) the AFD and FLUX Vector control have many advantages over DC control.

DC CONTROL

DC control has been used for two major reasons in the past:

- It is easy to control motor torque by varying the current to the armature.
- It is easy to control motor speed over a relatively wide, constant torque and constant power range.

It can be seen by the circuit diagram in Figure 1 below that the magnetizing flux and armature current can be controlled separately. This allows the control of torque by varying the armature current .

Torque: $T \propto \Phi \times Ia$ Where: Φ = Flux   and   Ia = Armature current

Because the Field current and the Armature current can be controlled independently. As long as Φ is kept constant (Field current kept constant) then Torque is proportional to the armature current.

The electrical angle between Φ and Ia is kept at 90° mechanically by the brushes and commutator in the motor.

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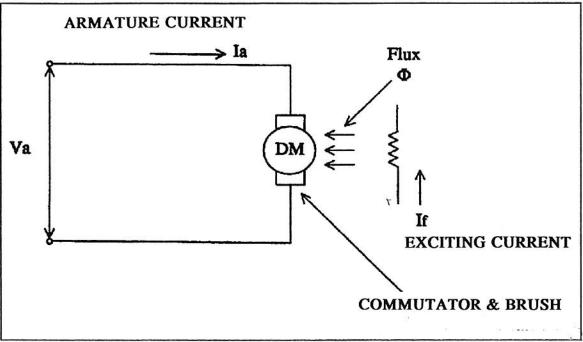

Figure 1   DC MOTOR EQUIVALENT CIRCUIT

The speed of the DC motor is controlled by the voltage applied to the armature, while the flux remains constant. When the motor is running a counter EMF is generated by the motor proportional to the speed of the armature. If this voltage is sensed by the motor controller the approximate motor speed can be determined. This can be used for speed regulation by the drive to allow approximately 5% speed regulation. If tachometer feedback is used this will allow a speed regulation of 0.5 to 1%.

The speed range of the DC application depends mostly upon the construction of the motor. The constant torque speed range is limited, by the commutator and brushes,

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to approximately 200:1. Overspeeding is possible by reducing the Flux (FIELD WEAKENING) by lowering the field current. The speed achieved through field weakening is usually 130 to 200% of the base speed. Field weakening can only be achieved with light loads because of the reduction in torque.

For Overhead Crane applications AC control has surpassed DC. The reduced cost and improved performance with AC Flux Vector (ACFV) and the ability to Float the load, has helped the replacement of DC controls. The construction of the DC motor is more complex than the AC Squirrel cage motors used with AC AFD and AC Flux Vector control. In addition to the bearings, the brushes and commutator of the DC motor require periodic inspection to maintain the performance and life of the motor.

AC ADJUSTABLE FREQUENCY

AC Adjustable Frequency Drives (AFD) have been used in crane traverse motions for over ten years. The AFD has been improved almost every year since the first application. The reasons for its acceptance include:
- A rugged squirrel cage motor can be used.
- It is easy to control motor speed over a relatively wide, constant torque range, by maintaining a constant V/F ratio.
- Because of the rugged motor, the constant horsepower speed range can be 200% or greater of the rated motor speed. The motor is usually the limiting factor.

The AFD is a good speed controller allowing a constant torque speed range of 40:1. If slip compensation is enabled, the frequency will be increased proportional to the current required by the motor. This will have the effect of improving the speed regulation of the motor without the use of a tachometer or pulse generator. Although, through the sensing of load, current the Volts/Hertz pattern can be adjusted to produce more motor current, this drive is not a true torque controller. In general, the current to the motor can be increased or decreased through automatic circuitry based upon the theoretical model of the motor. If the model closely resembles the motor, the response will be predictable and appropriate. If the model does not accurately depict the motor, performance will suffer. The performance may take the form of sluggish

ELECTRONIC MOTOR CONTROL FOR OVERHEAD CRANES

response, motor heating or stalling.

If a step change in torque is required by the motor, the AFD will respond with a voltage boost at that frequency, to force more current into the motor. The AFD can only increase the magnitude of the current, not the phase angle. The motor will take the current delivered and divide it into Torque producing current and Flux producing current. It can be seen from the equivalent circuit in Figure 2 that the equation for torque producing current is:

$$I_T = \sqrt{I_1{}^2 - I_M{}^2}$$

where:

I_T is the Torque Producing Current
I_1 is the Total current per phase
I_M is the Flux producing current

Any current not required to produce torque and flux is dissipated in the motor windings as heat. It is not possible for the AFD to discriminate between the Torque producing current and the flux producing current. This is however adequate for most traverse motions. In hoisting applications where the AFD is sized so that the motor is the limiting element to producing torque, special software can determine if the load on the hook is excessive and stop the hoisting sequence safely.
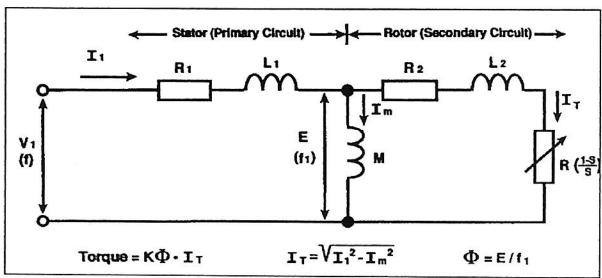

Figure 2   AC MOTOR EQUIVALENT CIRCUIT
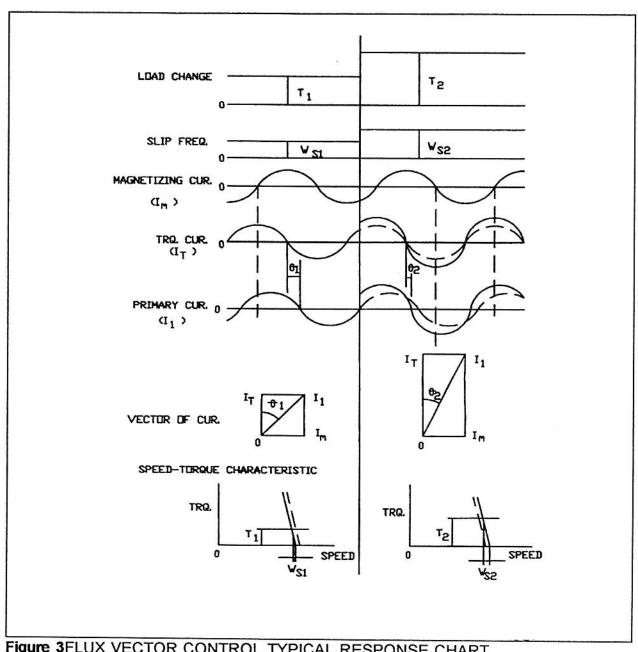
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ELECTRONIC MOTOR CONTROL FOR OVERHEAD CRANES

Figure 3FLUX VECTOR CONTROL TYPICAL RESPONSE CHART
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ELECTRONIC MOTOR CONTROL FOR OVERHEAD CRANES

The magnitude of the output current of the AFD is monitored to allow additional safety and performance possible with special software. Among the features are:

- The use of IGBT output power devices reduce the audible noise from the motor and improve the simulated sinewave to the motor, reducing heat and improving low speed torque.
- Slip compensation to increase the frequency to the motor to improve speed regulation.
- Torque compensation to boost the current to the motor to produce sufficient torque producing current to reduce the chance of stalling.
- Stall prevention to reduce the acceleration rate and/or frequency to the motor to reduce the chance of the motor stalling.
- Phase loss detection to verify that the sum of the currents to the motor phases are correct to insure the motor is not single phased producing high currents in one phase only but not producing adequate torque.
- Load check will detect the current to the motor at various frequencies. If the level of current has exceeded the setpoint, motion in the hoisting direction is halted and lowering allowed only at slow speed.
- Swiftlift⁹ at low currents will allow the motor speed to increase over rated to increase productivity with light loads.

AC FLUX VECTOR CONTROL

The AC Flux Vector Controller is similar to the AFD with a few exceptions which include:

- The use of an improved mathematical model of the motor.
- The use of high speed Digital Signal Processing (DSP)
- The use of encoder feedback for speed and slip frequency sensing.
- The use of high speed microprocessors.
- The utilization of a current regulator.

The typical motor circuit for a squirrel cage motor is shown in figure 2. The current parameters are the same for the AFD as the Impulse Flux Vector Control. The BIG difference is the ability of the Flux Vector Control to change the motor input current to

DC vs AC
ELECTRONIC MOTOR CONTROL FOR OVERHEAD CRANES

independently control the motor torque. The improved mathematical model is required to enable a virtually instantaneous response to a step change in torque demand. This not only improves the performance of the hoisting systems, insures the correct change in current and applied frequency to the motor, but also improves the safety of the system.

Figure 3 shows a change in load torque demand (T_1 and T_2) and the change in the resulting slip frequency. The AC Flux Vector Control (ACFV) responds with a change in the primary current. The primary current is the only parameter the ACFV can control. The applied voltage and frequency are modified so the increased current is sent to the rotor (I_T) without changing the Magnetizing current (I_M).

It is this ability to control the torque producing current without changing the flux producing current that differentiates the ACFV from adjustable frequency and phase vector controllers.

The ability to determine the load on the motor and precise feedback from the encoder allow the speed range of 1000:1 with most squirrel cage motors. This also allows the ACFV to suspend a load at zero shaft speed by producing a counter torque field at the motor's slip frequency at the current load torque condition. The length of time at the very slow or zero shaft speed is limited by the motor characteristics and external cooling provided.

The ACFV requires feedback from motor to obtain the data required for the vector calculations. This data includes current, rotor speed and for linear torque calculations, the motor winding temperature.

CONCLUSIONS

Historically DC Control was the only way to obtain good speed and torque control. The chart below indicate typical characteristics of the types of motor control described above. It can be seen that the Flux Vector Control exceeds DC in all aspects. With the advances in motor control and sensing the AC FLUX VECTOR CONTROL is the best choice for control in overhead cranes.

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ELECTRONIC MOTOR CONTROL FOR OVERHEAD CRANES

AC vs DC DRIVE TYPICAL PERFORMANCE

	AFD	FLUX VECTOR	DC ELECTRONIC MOTOR DRIVE
SPEED RANGE	40:1	1000:1 LOAD FLOAT	100:1
SPEED RESPONSE	30 RAD/SEC	100 RAD/SEC	50 RAD/SEC
SPEED REGULATION	1.5 - 3.0 %	0.01 %	5 % (ARM VFB) 0.5 % (TACH FB)
STALL TORQUE	SMALL	CONTROLLER LIMITED	COMMUTATOR & BRUSH LIMITED
FWD/REV DEADBAND	NONE	NONE	3 MSEC.
POWER FACTOR DISPLACEMENT	98 %	98 %	20 - 85 %