LARGE ADJUSTABLE SPEED DRIVES AND THEIR APPLICATION TO A HIGH SPEED CENTRIFUGAL COMPRESSOR

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ABSTRACT

New applications are being found for adjustable speed drives due to: 1) the availability of high current solid-state devices, 2) a simplified inverter design with large scale integrated circuits (LSI), and 3) because of the growing need for energy conservation. Several types of drives and their application to a high speed compressor will be described in this paper. The drives most suitable to high horsepower applications are: 1) the slip recovery drive (Scherbius), 2) the brushless DC system (synchro-converter) and 3) the current source inverter.

CONVERTING DC TO AC (INVERTING)

Inverting is accomplished by connecting a direct current power source to an alternating current load by switches that are operated in sequence. Each phase in a three phase circuit requires that two switches be connected to the DC source; one to the positive and one to the negative circuit. This means that a total of six switching devices are required for a three phase load (Figure 1).

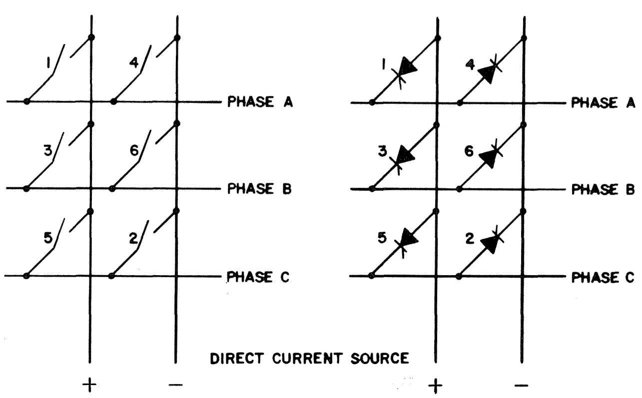

Figure 1. Basic Inverting Circuit.

By sequencing the switches in order 1 through 6 an alternating current can be produced. This has been done for years to position large grinding mills. A DC generator is used for the DC source and DC contactors for sequencing. A motor driven cam is used to pick up and drop out coils in the proper sequence.

In the modern variable voltage, variable frequency drive, thyristors replace switches, a thyristor rectifier converter replaces the DC generator and modern integrated circuits replace the switching control. A simplified schematic of the modern inverter is shown in Figure 2.

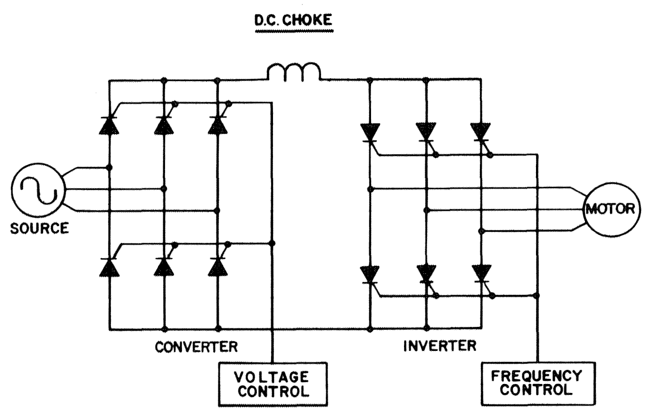

Figure 2. Simplified Modern Inverter.

The driven motor is typically designed to operate at a single voltage and frequency. Motor speed is changed by varying the stator frequency. To allow the motor to operate at different frequencies the voltage must be reduced in direct proportion to the frequency. The basic voltage/frequency changing circuits shown in Figure 2 are used for both the current source inverter and synchro-converter. The major difference between the two inverters is the method in which the inverter thyristors are turned off.

COMMUTATION

Commutation is the transfer of current from one switching device to another. The back EMF (self generated voltage) of the synchronous motor (in the synchro-converter circuit) makes the transfer of current relatively simple in comparison to the current source inverter. The current source inverter requires additional components such as diodes and capacitors that force the commutation of each thyristor switch.

SLIP RECOVERY SYSTEM

The wound rotor motor is a classic variable speed electromechanical drive that has been used for years. Typically, secondary resistance or resistance/reactance has been used for adjusting the shaft speed of the motor. Two shortcomings of this drive that have been eliminated are the reduction of slip losses through energy recovery, and more closely regulated speed control.

A typical slip recovery circuit is shown in Figure 3. The voltage at point 1 is a function of the slip (motor synchronous speed minus motor operating speed). The DC voltage at point 2 is controlled by the firing angle of each thyristor in the inverter bridge. When the voltage at point 2 is reduced to a level below that of point 1 current will flow and the motor will accelerate. If the voltage at point 2 is higher than that of point 1 the motor will decelerate due to the motor load. The inverter portion of the slip recovery drive is a DC converter run in a regenerative (power pump back) mode.

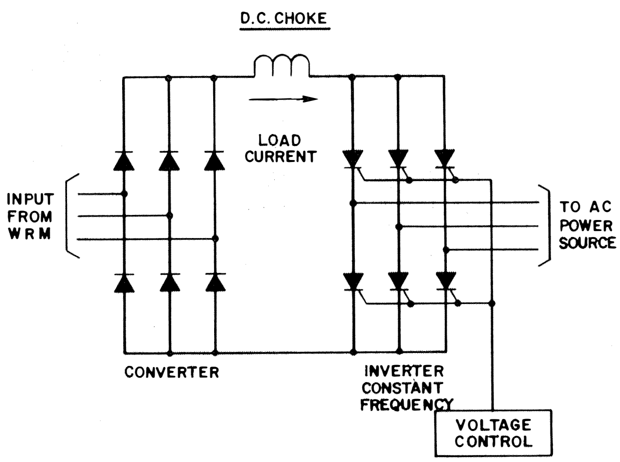

Figure 3. Slip Recovery Circuit.

CURRENT SOURCE INVERTER

The basic inverter looks a great deal like the inverter circuit shown in Figure 2 with the addition of the commutation circuit required to turn off the inverter thyristors (Figure 4). Generally a standard induction motor is used with the current source inverter. However, in the design of the drive system electrical properties of the motor need to be checked to see if they are compatible with the current source type drive. If a new motor is being supplied the following items may be improved: 1) the insulation may be upgraded to protect from surge voltages, 2) the winding reactance decreased to improve thyristor commutation, and 3) the temperature rise decreased to improve motor performance. The surge voltage is caused by high speed switching. The reactance is decreased to effect more efficient commutation.

Additional motor heating and torque ripple are the result of the harmonic content of the square-type current waveform. The harmonic content of the current output affects motor electromagnetics and produces torque ripple which can result in a forcing function to set up drive line torsional vibration. Drive line torsional vibration should be analyzed carefully, particularly on high inertia loads, with respect to torsional critical speeds to insure that premature shaft and/or bearing failure is prevented.

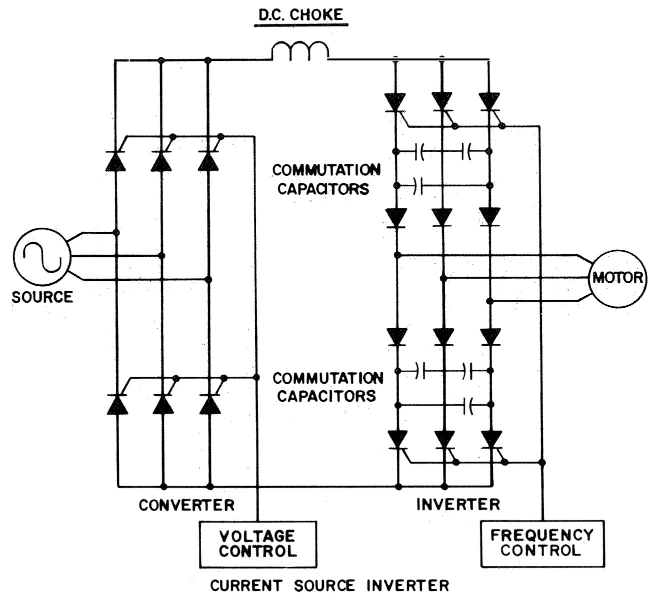

Figure 4. Current Source Inverter.

To improve the current waveform and reduce harmonic heating the number of output switching thyristors is increased in increments of six. The outputs of each set of six thyristors is added through the use of phase shifting output transformers. For a twelve-pulse system, Figure 5, the windings of these transformers are phase shifted by 30 electrical degrees. (A typical rule of thumb is from 0-500 HP use six-pulse systems, from 500-1000 HP use twelve-pulse systems, from 1000-1500 HP use 18-pulse systems, etc.)

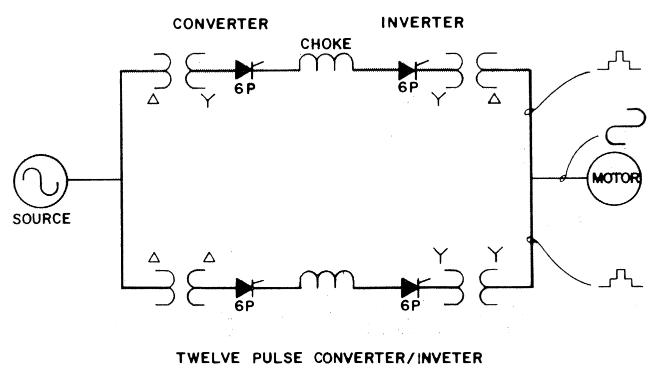

Figure 5. Twelve-Pulse Converter/Inverter.

Phase shifted isolation transformers can be added to the input side to reduce harmonic currents and decrease voltage distortion at the power source. Increasing a six-pulse converter to a twelve-pulse unit decreases the fifth and seventh harmonic to almost zero. Theoretically, the fifth harmonic is 20 percent and the seventh is 14 percent of the fundamental current.

For operation above motor base speeds it is only necessary to switch the inverter thyristors on and off at a higher rate. Other important considerations are the mechanical strength of the motor and the commutating speed of the thyristor/motor combination.

SYNCHRO-CONVERTER

The basic circuit for the synchro-converter, although similar to the current source inverter, does not require the commutation circuits. The back EMF (self generated motor voltage) turns off the thyristors at speeds greater than six percent of motor speed. Below six percent speed the stator field is rotated by 1) turning on the DC source, then 2) a set of thyristors of the AC source, and finally, 3) turning off the DC source. Increasing the speed at which steps 1, 2, and 3 are accomplished will accelerate the motor to a speed at which the motor back EMF shuts off the thyristors. A sample circuit is shown in Figure 6.

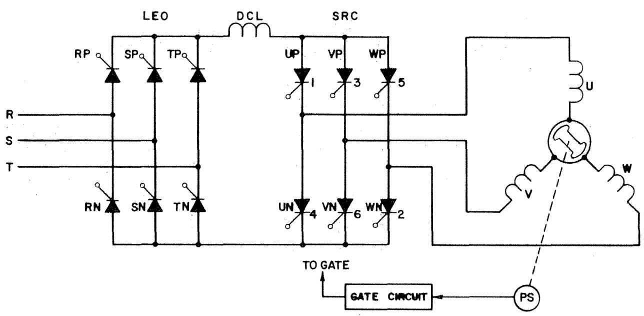

Figure 6. Synchro-Converter.

Again the motor is semi-standard. The synchronous motor is designed with a leading power factor and fitted with a field pole position sensor that is used during initial starting.

Depending on the design philosophy of the drive manufacturer, the motor may not be suitable for use with back-up across-the-line starting. Since back EMF (turn-off) is critical to the operation of the thyristors, the motor may be built more like a generator and therefore have little starting torque available. The square wave characteristic of the stator applied voltage can cause winding heating. This is due to the induced currents in the cage winding which is due to time varying flux in the motor air gap. This can also be considered as one of the drawbacks of using a standard synchronous motor. If, however, the cage winding was eliminated, the torque ripple component would increase.

MAINTENANCE

Rotating Equipment

The squirrel cage motor is used with the current source inverter. Since the mechanical and electrical design is simple, this motor has the highest reliability and requires the least maintenance. The synchro-converter is used with a brush-type or brushless synchronous motor. Wound rotor motors are applied with slip recovery systems. Synchronous and wound rotor motors are only slightly more complex than induction motors and they do require some brush maintenance.

Adjustable Speed Controls

Since the current source inverter requires commutating components, it is the most complex of the three. The slip recovery system is the simplest. When considering which drive to apply, the following must be determined:

- Existing Motor
- Speed Range
- Mechanical Performance
    - Load inertia (WK squared)
    - Drive Lineup Torsional Characteristics
    - Speed vs Load Torque Requirements
    - Starting/Stopping/Running/Overload Characteristics
- Environmental Characteristics for Motor and Control Location(s)
- Drive Complexity
- Power System Characteristics
- Multiple Drives
- Harmonics
- Power Factor Correction.

DRIVE MOTORS

The application of the adjustable speed drive may be to upgrade a drive on an existing single speed installation. With an existing motor, it may not be advisable to replace it at the time the decision is made to add adjustable speed capability. Since the output waveform of the drives increases motor heating, it is necessary to check with the manufacturer to determine the motor's thermal capabilities. All drives generate torsionals; therefore, the motor shaft mechanical strength and bearings should be checked. If the driven equipment (load) is centrifugal in nature, such as a fan or pump, operation at reduced speeds may not be a problem.

If the existing motor is an induction motor, the reactance of windings may have to be checked. The motor load current is necessary to charge capacitor circuits to commutate (turn off) inverter thyristors.

If the motor is synchronous, the field excitation would need to be checked to make sure there is enough motor back EMF to properly commutate the thyristors. An 0.8 leading power factor may be adaptable to an adjustable speed drive whereas the unity machine may not. For starting, a field pole position sensor should be added.

When the existing motor is a wound rotor motor only, the thermal characteristics must be checked. For speed control purposes, it may be desirable to add a tachometer for speed feedback. For emergency operation the wound rotor motor can be soft started with a set of secondary resistors. Inrush voltage/power can be limited by proper resistor selection to 100% of motor nameplate values, or less, if the starting requirements permit.

For a new application each drive should be selected on its own merits and the requirements of the system. For centrifugal type loads, i.e., torque is reduced as the square of the speed, the drive motor may not require external cooling. For constant torque loads the motor may have to be pipe ventilated or have a built-in constant speed fan to provide for rotor and stator cooling.

SPEED RANGE

The slip recovery system is most suitable for 2:1 speed ranges or less. Speed range can be easily extended by using the current source of load commutated inverter with a speed range of 10:1. For those applications that require operation above the basic motor speed, one of the inverters may be the preferred.

MECHANICAL PERFORMANCE

The inertia and torsional sensitivity of the driven load may affect selection. Each drive produces a different spectrum of torsional vibrations. To reduce the torsional vibrations of any of the drives, the number of active components may be increased, i.e., the current waveform to the motor can be improved. Another mechanical solution to the torsionals is to install a torsionally damped type coupling between the motor and load.

When regenerative braking is required, the slip recovery system described in this paper is not applicable as the secondary current can only flow in one direction. Both the current source and synchronous motor drive can return braking energy to the power system.

DRIVE COMPLEXITY

The capability of the maintenance personnel can be of major importance when selecting a drive. (The diagnostics provided on each type of drive are important as well as the basic complexity of the drive.) The most complex of the three drives discussed is the current source inverter. Its complexity is a result of the addition of commutation capacitors and associated circuits. The LCI (Load Commutator Inverter) and slip recovery drive do not require commutating circuits, which means that the thyristors turn off naturally in the latter two drives. The slip recovery drive is the simplest of the three drives.

LRU's (Line Replacement Units) make repairing most of the modern adjustable speed drives relatively easy. LED's and test points are provided so that service personnel can determine which of the LRU's have faulted. Power thyristors and thyristor fuses have increased in reliability to the extent that when properly applied there are almost no failures. For many applications it is advantageous to supply back-up control for the motor if the solid-state drive fails.

POWER FACTOR CORRECTION

All three of the drives discussed may require the addition of power factor correction capacitors. The customer supply voltage variation may increase the necessity for correction. For example, if the specification requires operation at minus ten percent voltage, the synchro-converter and current source inverter will operate at a reduced power factor at normal voltage. As the speed is decreased, the power factor is reduced due to the phase back operation of the thyristors. When using the slip recovery system, the opposite occurs: as the voltage is reduced, the power factor increases. In the case of slip recovery, the power factor approaches zero at the overvoltage point. The power factor of the slip recovery system improves as the speed is reduced, since phase back is reduced, and therefore the inverter voltage increases.

All drives have harmonic currents associated with them and since the impedance of a capacitor is reduced as the frequency increases, the capacitors may overheat due to harmonic currents. A detuning reactor may be used to filter out the harmonics. However, the voltage of the capacitor must be increased because of the overvoltage caused by the reactor.

TORQUE RIPPLE

The output current waveform of an inverter only approximates that of a sine wave. Torque ripple is the result of the influence of the harmonic currents affecting the motor magnetic circuits. The largest torque ripple occurs with load commutated inverters where it is approximately 30 percent of the base torque. The current source inverter and slip recovery system have approximately ten percent each. To decrease torque ripple it is only necessary to improve the current waveform. This is done by increasing the number of inverter components. Increasing the number of output bridges from one to two reduces the torque ripple by one-half. A torsionally damped coupling can be used between the motor and load to further reduce the effects of torque ripple.

EFFICIENCY

At full speed/full torque the efficiencies of all adjustable speed drives are approximately the same. Efficiency is a function of both the motor and the drive. The careful installation of all components is necessary to reduce losses. For example, the installation and sizing of cables can amount to several tenths of a percentage point of drive losses. Other drive elements such as gears, coupling, and output piping or ducting losses should also be carefully considered.

TYPICAL APPLICATION

Compressor:

- High speed centrifugal compressor driven by a 4-pole, 500 HP induction motor through a 1:6.35 ratio.

Application:

- Constant volume/variable molecular weight

Special Problems:

- Drive Harmonics
- Voltage
- Torsional Vibrations
- Emergency Operation
- Oil Lubrication During Power Failure
- Cooling

An adjustable speed drive was selected in this application for several reasons: 1) to increase efficiency, 2) to avoid increasing power supply capability (substation size), and 3) to avoid purchasing more than one compressor. Efficiency was increased by avoiding the use of bypass gas to the suction side and throttling the compressor discharge. Without the soft start capability of the inverter, an increased power supply capability was required to avoid excessive voltage dips. Process requirements dictate that the compressor output is constant volume. By varying the speed of the compressor, gases with different molecular weights can be compressed for constant volume delivery.

The speed range is 60% to 110% speed (36 Hz to 66 Hz). Acceleration occurs at a constant rate through the compressor critical speeds to the lowest operating speed point. Because of the varying molecular weight, the motor load torque (current) was designed to be constant over the speed range. The constant motor current necessitated that two auxiliary cooling fans be installed to avoid motor overheating at reduced speeds.

To reduce torsional vibrations two inverters and two output transformers were used to construct a more accurate current waveform. The improved waveform was accomplished by phase shifting two six-step waveforms by 30 electrical degrees and adding these output current components at the terminals of the motor to produce a twelve-pulse output. The addition of two input transformers was logical to reduce harmonics on the power system. Fifth and seventh harmonics were reduced by the resulting twelve-pulse system. The input transformer voltage turns ratio allows for line voltage fluctuations and voltage drops across converter/inverter components. The current rating of the converter/inverter thyristors was minimized by designing the bridges to operate at 500 volts AC.

To provide for emergency operation in the event that any of the drive components fail, three contactors were provided, two to isolate the inverter and one to start the drive across the line. Across the line starting required that the motor be designed for operation at system voltage. Since output transformers were provided on the input and output of the inverter, the voltage match was simple. Typical motor protection that met the customer's specification was provided to operate in conjunction with the bypass contactor (Figure 7).

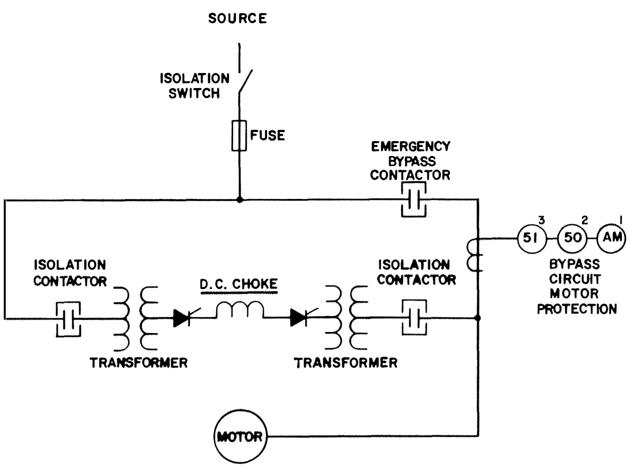

Figure 7. Example Installed Industrial Circuit.

The motor and inverter are protected by the current feedback loop provided within the converter/inverter control. The current limit is adjusted to a setting that limits inrush current and load torque to a level required by the load profile.

If a power failure occurs, the compressor bearings will obtain their oil from an auxiliary oil pump directly coupled to the main motor shaft. As long as the motor/compressor rotates, oil will be provided for bearing lubrication.

SUMMARY

High energy costs are now making it economically justifiable to invest in electronic adjustable speed drive equipment. The highly efficient adjustable speed drives replace such devices as fluid couplings, eddy-current clutches, valves, dampers, and secondary resistance of primary voltage control of motors. The loads that are considered are 500 HP and higher. Three state of the art drives that can handle these larger HP loads are:

- The Current Source Inverter
- The Synchro-Converter or Brushless DC
- Slip Recovery Drive.

There will be a great deal of discussion in the next few years over the application of adjustable speed drives. It is suggested that each drive selection be made on its own merits and that the user select the drive he is most comfortable with for the specific application circumstances. Also, many potential applications for adjustable speed equipment may not be suitable after close scrutiny. Items like payout period, maintenance capability, capital available, energy recovery ratio, etc., may make it impractical.

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