6.2.2
SINGLE-UNIT ADJUSTABLE-SPEED ELECTRIC DRIVES

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In past years, the electric motor industry has been dominated by the use of essentially single and constant speed motors when line fed. There were many mechanical methods used to achieve adjustable speed using a single-speed prime mover. There was also widespread use of dc motors for adjustable speed over the last century because only the voltage must be adjusted for speed change. Although operation at speeds well below synchronous can be accomplished through adjustment of the secondary resistance in wound-rotor induction motors, the ubiquitous squirrel-cage ac induction motor requires the adjustment of the frequency to change speed. This was not so easily accomplished until the recent utilization of pulse width modulation (PWM) inverters with insulated gate bipolar transistors (IGBTs) for power transistors plus microprocessors.

Electric drives are available featuring a single rotating element and some associated control for performing the adjustable-speed driving function. The use of a single rotating element differentiates this type of drive from the eddy-current coupling motor, hydraulic coupling motor combinations, and adjustable-speed belt drives, all of which are tandem drives.

The speed of the single-unit adjustable-speed drive is controlled through the interaction of the control and the motor. For this reason, one must consider these two elements as a drive and not consider the motor alone.

Subsection 6.1.1 described motors that will be further discussed in this subsection. Previous discussions of control were limited to that required for starting and protection; this subsection will also describe specific controls required for speed control. The discussion will cover the following types of drives:

- Ac adjustable-voltage drives
- Wound-rotor induction motors with several different types of secondary controls
- Adjustable-frequency drives

- Modified Kraemer drives
- Dc motors with silicon-controlled rectifier (SCR) power supplies

All have physical features, operating characteristics, or prices that make them particularly valuable in some specific segment of the pump driver spectrum.

ALTERNATING-CURRENT ADJUSTABLE-VOLTAGE DRIVES

This drive consists primarily of an adjustable voltage, constant frequency control, and a motor (M) conveniently configured as shown in Figure 1. The motor must possess high slip characteristics and other characteristics that allow it to work successfully with the associated control. The motor is designed for operation and tested with its associated control. Because the motor has high slip characteristics, insulation is of Class F rating.

The fundamental parts of the control are a circuit protective device, such as a circuit breaker, an SCR assembly, and firing circuitry, identified as FC in Figure 1. Other parts are required to complete the control but serve as auxiliaries. The main function of this control is to provide a voltage to the motor at a level that will ensure a desired motor speed. The control also protects the motor under abnormal operating conditions and the motor cable under short-circuit conditions and provides a current-limit function so the motor draws a maximum of some preselected value, such as 150% of normal, under all operating conditions.

The SCR receives impressed voltage, usually at 60 Hz. The SCR can be turned on (or become conducting) by means of current pulses received from the firing circuits that energize the circuits at different points on the sinusoidal wave. After conductance starts, it continues until voltage disappears at the end of the half-cycle. The SCR must be pulsed again in order to become conducting. This occurs while the voltage is in the negative phase of its sinusoidal generation and is performed by an SCR connected in parallel to the first and having reverse polarity. The negative loop conductance continues until the voltage again returns to zero. The firing controls are designed to turn the SCR on repetitively sometime during each voltage half-cycle. Figure 1A shows the shape of the applied voltage between the SCR and the motor for the wave illustration shown. In this case, the SCR is turned on at the beginning of each half-cycle.

By delaying the firing, or turning on, of the SCR until later in voltage generation, shorter intervals of applied voltage and lower levels of voltage appear across the motor. The solid line of Figure 1B illustrates applied motor voltage when the voltage half-wave is half-completed. Figure 1C illustrates the motor-applied voltage when the half-waves are approximately 75% completed. Notice in these illustrations that the frequency of the voltage applied to the motor does not vary; only the voltage magnitude does.

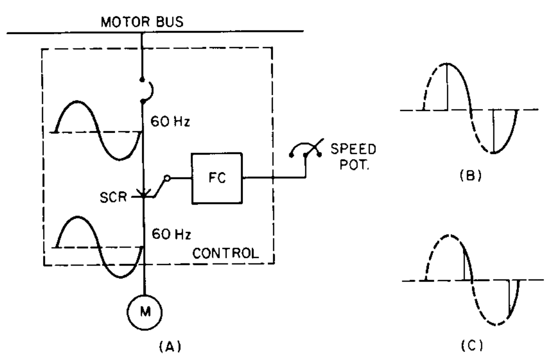

FIGURE 1A through C Block diagram for ac adjustable-voltage drive (General Electric)

The exact point in the half-wave when firing occurs is controlled by a low-energy electronic signal that may come from a potentiometer, as in Figure lA, or from some process instrument signal. By increasing the signal level, voltage applied to the motor increases; on the other hand, a decrease in signal level decreases the voltage level.

Figure 1A shows the SCR on the utility side of the motor as a convenience in illustration. In reality, the SCR is generally placed at the motor neutral point. This reduces voltage from the SCR to ground and allows the motor impedance to protect the SCR somewhat from damage caused by transient voltage spikes entering from the electric utility line. However, placing the SCR at the motor neutral point does require the use of six motor conductors instead of the conventional three.

Figure 2 illustrates representative motor speed-torque curves at rated and other voltages as well as a pump speed-torque curve varying as the square of the speed. The motor possesses approximately 10% slip under rated torque and voltage conditions. Note that motor torque does not break down at speeds lower than breakdown torque speed. These various characteristics help to identify the motor as one designed to operate specifically for this application. Note that by reducing applied motor voltage, motor torque decreases, causing the pump to operate at lower speed.

Ratings of these drives are limited essentially to low power levels. Figure 3 provides a guide to those available in open construction only. All ratings with maximum rated speeds existing within the solid envelope are available. Some, but very few, are available outside of this envelope. Totally enclosed motors are more restricted in supply than open motors and are limited to approximately 40 hp (30 kW) maximum. In addition to these restrictions, load torques must not exceed values varying as the square of the speed; thus this drive is not a candidate for driving a constant-torque load. Table 1 gives some pertinent application information.

WOUND-ROTOR INDUCTION MOTORS

Liquid Rheostat Controls This form of drive consists primarily of a full-voltage, nonreversing (FVNR) starter, a wound-rotor induction motor, and a liquid rheostat, all of which integrate into a configuration as illustrated in Figure 4. The FVNR starter switches power to and from the motor stator as well as provides generally accepted protection to

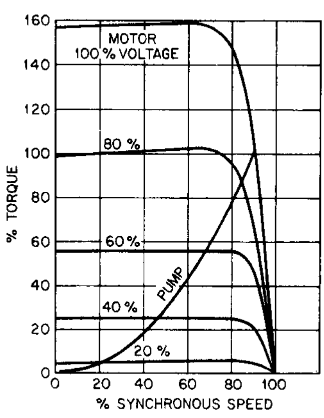

FIGURE 2 Torque versus speed for ac, adjustable-voltage drive (General Electric)

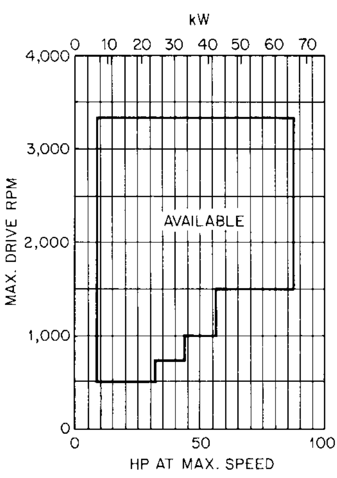

FIGURE 3 Availability of ac adjustable-voltage drives

TABLE 1 Alternating-current adjustable-voltage drive data

Drive element	Power rating[a]	Voltage rating	Max rated speed, rpm	Speed range, %	Enclosure	Mounting	No. of speed points
Motor	See Figure 3 for open frame ratings; limited availability outside these limits	200 230 460	1640 1095 820 655 545 & others	100	Vertical: shielded drip-proof; TEFC not generally available	Vert. or horiz.	Infinite
	Totally enclosed ratings limited as shown under Enclosure				Horizontal: drip-proof, TEFC to 40 hp (30 kW) approx.		
Control	5–150 hp (3.7–112 kW)	200 230 460	. . .	. . .	NEMA 1 NEMA 12	Wall or floor	Infinite

[a]Drive is capable of operating with power varying as the cube of speed maximum. Specifically, these ratings are not suitable for constant-torque applications.

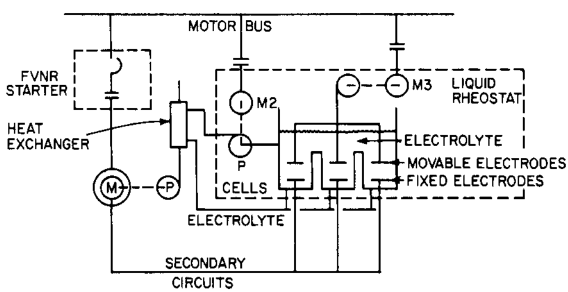

FIGURE 4 Block diagram for wound-rotor induction motor with liquid rheostat secondary power (General Electric)

the motor from short circuits, overloads, and so on. Secondary cables connect the motor rotor and fixed electrodes in the liquid rheostat. The fixed electrodes exist in separate cells of the rheostat, one for each phase. Movable electrodes, one located in each cell, are suspended from a horizontal bar, and this bar, the vertical-electrode suspension bars, the movable electrodes, and the electrolyte filling the cells complete the Y, or common point in the external motor rotor circuit. When the upper electrodes are moved up or down, the secondary circuit resistance of the drive varies and this causes a change in the motor speed-torque characteristic.

As already pointed out, the motor starter provides the normal protective functions for the motor. Control circuitry allows the motor to be started with maximum secondary resistance in the rotor circuit, thus drawing minimum motor current from the power supply.

Figure 4 illustrates a motor (M3) operating a pulley that changes the position of the movable electrode. This motor could be controlled manually by a push button or automatically through a controller position providing either a raise-lower or modulated voltage signal. If desired, a pneumatic cylinder may substitute for motor M3 to provide power to move the electrodes.

The electrolyte receives the drive slip losses dissipated in each of the cells, and of course this heat must be removed into some heat sink capable of dissipating it. In some installations, an electrolyte pump driven by motor M2 circulates the electrolyte through a heat exchanger before returning it to the individual cells. Returning cooled electrolyte reenters the cells under the fixed electrodes and passes through holes in the electrodes before passing vertically through the cells. The heat exchanger primary coolant can be tap water or mill water, which provides a good means of passing drive slip losses as heat directly out of the station, or it can be the pump discharge water, which conveys heat directly away from the building, as illustrated in Figure 4.

The liquid rheostat is factory-assembled with the rheostat, electrolyte pump, and its motor and electrode-positioning assembly packaged in a single steel enclosure suitable for control lineups except for ratings above 700 hp (522 kW). The heat exchanger may be of the sleeve (or wrap-around) type, as illustrated in Figure 4, and comes as a separate device to be attached to station effluent piping. Other forms of exchangers, such as liquid-to-air or shell- and-tube heat exchangers, are available.

Changing the position of the movable electrode results in a change in motor speed-torque relations, as shown in Figure 5. Each curve shown (except the pump curve) represents a motor characteristic for a discrete secondary resistance. Notice the number associated with each curve; it represents the percentage of secondary resistance external to the motor rotor; 100% ohms provide 100% motor torque at zero speed. In examining individual curves, note that as the percent resistance increases, the slope of the motor speed-torque curve decreases, thus allowing the motor to slide down the pump speed-torque curve and assume a lower speed.

This drive utilizes resistance only in the motor secondary circuit as a means of controlling speed. Reactance is available as a substitute for resistance in other forms of secondary controllers, but its use reduces the drive power factor and thereby increases motor current, reduces efficiency, and increases motor heating. As a further effect, the additional motor current may require the use of a larger motor frame to accommodate it.

Figures 6A, B, and D provide clues to the availability of enclosed vertical and horizontal wound-rotor induction motors. Figure 6A illustrates the point that vertical, totally enclosed wound-rotor induction motors are not generally available but may be available in random powers and speeds. Totally enclosed water-to-air-cooled (TEWAC) construction becomes available at some minimum point as illustrated. In large ratings, shown on the right, TEWAC construction becomes very important as it provides a convenient way of capturing motor losses and expelling them in cooling water external to the building. Both curves of Figure 6A terminate at 1800 rpm synchronous speed because higher speed ratings are generally unavailable.

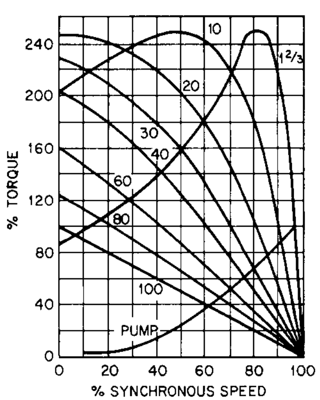

FIGURE 5 Torque versus speed for wound-rotor induction motor with variable secondary resistance (General Electric)

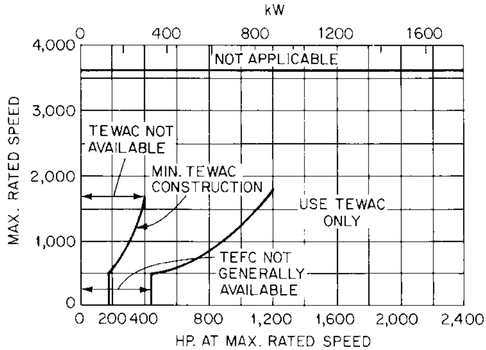

FIGURE 6A Approximate availability of totally enclosed vertical wound-rotor induction motors (General Electric)

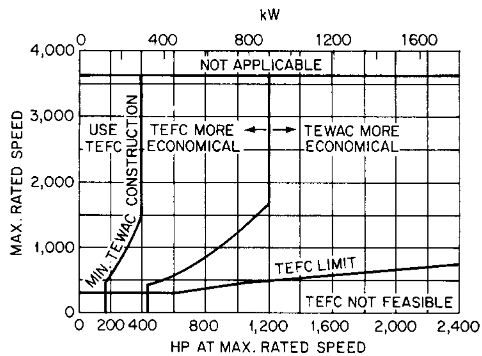

FIGURE 6B Approximate availability of totally enclosed horizontal and vertical squirrel-cage induction motors and horizontal wound-rotor induction motors. Wound-rotor induction motor speeds limited to 1800 rpm maximum (General Electric).

Figure 6B delineates the left side, where totally enclosed fan-cooled (TEFC) construction should be used for horizontal wound-rotor induction motors because it is the only one available, the middle area, where TEFC construction should be used because it is less expensive than TEWAC construction, and, finally, the right side, where TEWAC construction is less expensive than TEFC construction. Again, motor speeds are limited to 1800 rpm synchronous.

Vertical wound-rotor induction motors are not available in explosion-proof construction, as their omission from Figure 6C implies.

Finally, the areas of availability and unavailability are delineated in Figure 6D for horizontal wound-rotor induction motors in explosion-proof construction. Again, the curve terminates at 1800 rpm synchronous speed for reasons already expressed.

Delineation of motor availability is an important criterion in drive selections. Table 2 presents significant data useful in drive selection.

Tirastat II* Secondary Controls This drive utilizes the same wound-rotor induction motor and FVNR starter as the preceding, but substitutes a Tirastat II controller for the

*Trademark of General Electric Co.

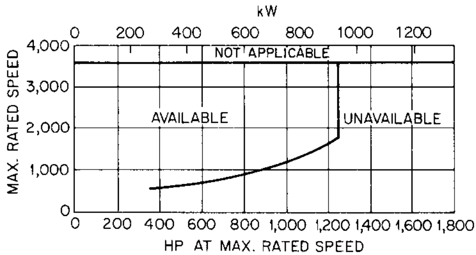

FIGURE 6C Approximate availability of explosion-proof vertical squirrel-cage induction motors (General Electric)

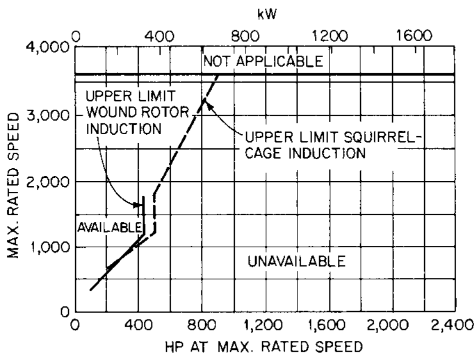

FIGURE 6D Approximate availability of explosion-proof horizontal squirrel-cage and wound-rotor induction motors (General Electric)

TABLE 2 Wound-rotor induction motor with liquid rheostat drive data

Drive element	Power rating[a]	Voltage rating	Max rated speed, rpm	Speed range, %	Enclosure	Mounting	No. of speed points
Motor	No limits for open motors; see Figure 6A, B, D for restrictions by enclosure	Any NEMA standard	All established by number of motor poles and supply frequency	60	Vertical: shielded dripproof, TEFC generally not TEWAC available per Figure 6A Horizontal: dripproof, TEFC, explosion-proof per Figure 6D	Vert. and horiz.	Infinite
Control	25 hp (18.7 kW) min; no stated max	For any motor secondary voltage	. . .	60	NEMA 1	Lineup or singly Floor only	Infinite

[a]Drive may be designed for constant torque or for torque varying at the square of the speed.

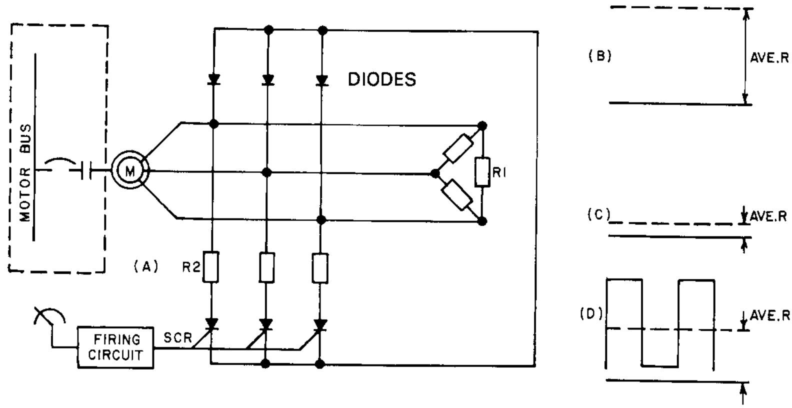

FIGURE 7 Block diagram for wound-rotor induction motor with Tirastat II secondary control power (General Electric).

liquid rheostat. Figure 7A shows the configuration with the wound-rotor induction motor and starter identical to those of Figure 4.

The Tirastat controller in its simplest form consists of the components shown in Figure 7A. Resistors identified as R1 are permanently connected across the motor secondary phases. Additional resistors (R2) are connected across motor phases through SCR and diodes. The SCR are individually turned on (become conducting) by minute current pulses generated by the firing circuit. As the voltage loop across any SCR drops to zero, the SCR shuts off and does not turn on again until the firing circuit refires it. The diodes allow return of the current to the motor but block out current reversals to the SCR.

Drive speed varies as a function of changing controller average resistance. Thus, resistance can be varied by adjusting time on-time off ratios in the SCR to give the desired average resistance. Figure 7B shows controller secondary resistance with the SCR not firing (conducting). In this condition, the controller resistance value equals the resistance of R1. Figure 7C shows controller resistance with all SCR firing continuously. The decrease in resistance is due to additional resistance placed in parallel with resistor R1. Figure 7D shows controller resistance varying from maximum to minimum in approximately equal time periods. The average resistance value then approximates half of the sum of R1 and R2. The time on–time off of the SCR can be varied automatically by the controller to provide the average resistance in the motor circuit necessary to give the desired motor speed.

The motor starter provides normal motor protective functions as well as short-circuit protection of the motor cables and starter. The Tirastat II controller monitors motor current and limits it to some preselected value, such as 150% of normal, under all conditions.

Packaging of the secondary controller is of particular interest. Both packaging and configuration lend themselves to mounting the resistors on or near the control enclosure or removing them some distance from the enclosure. By placing the resistors outdoors or at some indoor location away from the operations, heat losses can be released to the environment with impunity to operators.

The speed-torque ability of this drive would be very close to that illustrated by Figure 5. The comments contained in the text describing that figure apply equally well here. Table 3 presents significant data useful in drive selection.

Contact Secondary Controls Many pump drives utilize a very simple combination of FVNR starter, wound-rotor induction motor, and a form of contact making secondary control. Figure 8 shows the configuration with a motor and FVNR starter identical with those of Figures 4 and 7A.

The main difference between this drive and the two described previously lies in the construction of the secondary controller and the characteristics of the drive. Resistor R in

TABLE 3 Wound-rotor induction motor with Tirastat II controller drive data

Drive element	Power rating[a]	Voltage rating	Max rated speed, rpm	Speed range, %	Enclosure	Mounting	No. of speed points
Motor	No limits for open motors; see Figure 6A, B, D for restrictions by enclosure	Any NEMA standard	All established by number of motor poles and supply frequency	60	Vertical; shielded dripproof, TEFC generally not available, TEWAC available per Figure 6A. Horizontal dripproof, TEFC, explosion-proof per Figure 6D.	Vert. and horiz.	Infinite
Control	5 hp (3.7 kW) min. 600 hp (448 kW) max.	For any motor secondary voltage	. . .	50 70	NEMA 1, NEMA 12	Lineup or singly	Infinite

[a]Drive may be designed for constant torque or for torque varying as the square of the speed.

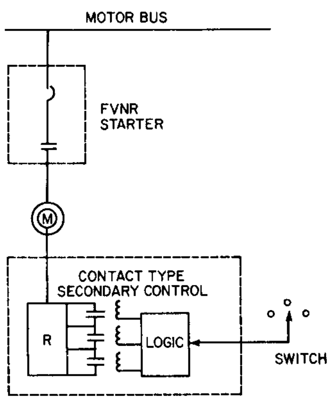

FIGURE 8 Block diagram for wound-rotor induction motor with magnetic secondary control power (General Electric)

Figure 8 is a three-phase resistor connected across the slip rings of the motor. Its resistance rating is selected to provide minimum motor torque at standstill or adequate torque at minimum speed. Contacts in the form of magnetic contactors, drum, cam, or dial switches are closed by a logic device (generally magnetic) to short-circuit part or all of the resistor. Thus, instead of a modulated or infinitely variable resistor as encountered with the other two drives, this drive modifies secondary resistance in discrete steps, providing discrete speed-torque curves instead of an infinite family. The number of speed-torque curves the control generates will depend directly on the number of contacts provided in the secondary-control circuit.

Either a manual switch or some automatic contact-making device actuated by the process can be utilized to actuate the control logic.

Secondary controls are normally packaged in the factory with resistors and contact-making secondary controller integrally assembled.

TABLE 4 Wound-rotor inductions motor with contact-type secondary control drive data

Drive element	Power rating[a]	Voltage rating	Max rated speed, rpm	Speed range, %	Enclosure	Mounting	No. of speed points
Motor	No limits for open motors; see Figure 6A, B, D for restrictions by enclosure	Any NEMA standard	All established by number of motor poles and supply frequency	60	Vertical; shielded dripproof, TEFC generally not available, TEWAC available per Figure 6A. Horizontal dripproof, TEFC, explosion-proof per Figure 6D.	Vert. and horiz.	
Control	No limits	For any motor secondary voltage	. . .	75	NEMA 1	Lineup or singly	Discrete only

[a]Drive may be designed for constant torque or for torque varying as the square of the speed.

The speed-torque capability of this drive would be very close to that illustrated in Figure 5, with the exact number of curves determined by the number of contacts of the contact-making secondary controller and the shape of the curves determined by the resistance selected. Table 4 presents significant data useful in drive selection.

ADJUSTABLE-FREQUENCY DRIVES

Until recently, the most significant step in the improvement of adjustable drives was to replace the autotransformer and rectified variable voltage power supply with SCR drives. Although dc motors are seldom used for pump drives, except in automotive applications and other special cases, the SCR and PWM adjustable speed dc drives are very highly developed and available from a number of suppliers.

Pulse Width Modulation Frequency Inverters Adjustable-frequency drives consist of an adjustable-frequency inverter control and a constant-speed motor, as shown in Figure 9. The inverter control has generally been built in either pulse width modulation or square wave construction. An inverter control consists fundamentally of a circuit-protective device, a diode bridge, and an inverter section having an SCR and a firing-control (FC) section for the SCR, all packaged in a steel enclosure. Special power supplies, motor protective devices, and electrical protective devices complete the package.

Only low voltages are used to energize the motor bus. A diode bridge rectifies voltage and an inverter inverts the direct current into an adjustable-frequency adjustable voltage that varies linearly with frequency. This voltage is not necessarily sinusoidal; it can also consist of a number of dc pulses of positive or negative polarity, as shown between the inverter and the motor in Figure 9. The firing controls modulate the width of the pulses and the number of pulses per half cycle to vary the apparent frequency and to maintain motor voltage at a constant volts-per-cycle. The firing controls automatically introduce additional pulses or withdraw pulses as bandwidths reach their limits.

Firing circuits composed of solid-state devices trigger the SCR in accordance with logic controlled by the setting adjustment of a speed potentiometer (Figure 9) or the signal from the process. The control provides normal protection of the motor as well as short-circuit protection of the control, motor, and cables. Also, the control monitors and limits current drawn by the motor under all conditions to a preadjusted value, such as 150% of normal.

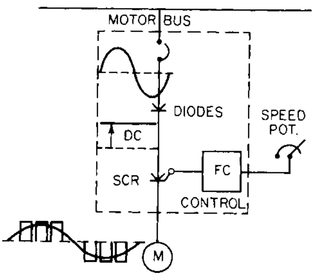

FIGURE 9 Block diagram for ac adjustable-frequency drive (General Electric)

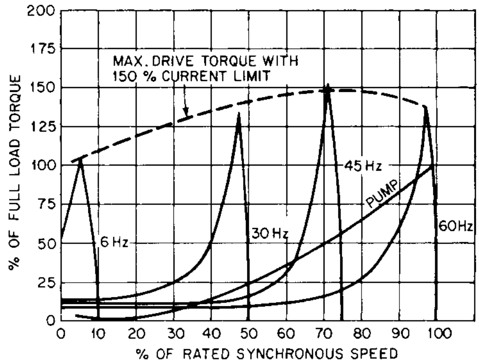

FIGURE 10 Torque versus synchronous speed for adjustable-frequency drive (General Electric)

TABLE 5 Adjustable-Frequency Drive Data

Drive element	Power rating[a]	Voltage rating	Max rated speed, rpm	Speed range, %	Enclosure	Mounting	No. of speed points
Motor	All NEMA ratings for open motors; see Figure 6B, C, D for restrictions by enclosures	460 or 230	All established by number of motor poles and supply frequency	100 plus limited over-speed	Vertical shielded dripproof, TEFC per Figure 6B, explosion-proof per Figure 6C. Horizontal: dripproof, TEFC per Figure 6B explosion-proof per Figure 6D.	Vert. or horiz.	Infinite
Control	Up through 800 hp (597 kW); higher ratings available as custom-built units	460 or 230	Capable of producing 150% of rated frequency but at reduced torque	150	NEMA 1 or NEMA 12	Floor	Infinite

[a]Drive may be designed for constant torque or for torque varying as the square of the speed.

Figure 10 displays some representative speed-torque characteristics of the drive utilizing a squirrel-cage induction motor and a representative centrifugal pump. Note that each characteristic intersects the zero-torque point at a different speed value. This differs from those of other drives, illustrated in Figures 2 and 5. The steepness of the slope of each characteristic as it rises from its zero-torque value indicates its low-speed regulation and provides a clue as to its ability to maintain speed with little fluctuation as load torque varies slightly. Motor speed is a function of frequency adjustment; the voltage is adjusted only to accommodate moderate changes in motor impedance. Table 5 lists significant application data.

Solid State Adjustable Frequency Inverters The opportunity for adjustable speed for ac induction motors has been realized by the development of the adjustable frequency control as well as the more recent vector drives. Similar adjustable speed drives are now available for the control of switched reluctance (SR) and permanent magnet (PM) brushless motors. These three technologies are well suited for pump applications that can benefit from adjustable speed.

There are many manufacturers that offer variable frequency with constant or variable voltage IGBT-driven PWM inverters for reliable and performance programmable adjustable speed control of ac induction motors. These drives are available in power up to the hundreds of horsepower (kilowatts). They offer many standard features that can be useful for driving pumps. Some of these are summarized as follows:

- Wide input voltage range allowing standardization of motors.
- Dual frequency operation (50 or 60 Hz)
- PWM output for sine wave voltage at selected output frequency
- Constant or variable torque
- High starting torque at programmable linear acceleration/deceleration
- Over-current protection
- Phase to phase and phase to ground short circuit protection
- Maximum output frequency of 120 Hz for double motor speed
- External contacts for other uses
- Analog speed output proportional to frequency

The use of these types of adjustable speed drives provides pump speed ranges up to nearly twice the base speed of the ac motor. The details of an actual selection of a system should be discussed with an application from a supplier in order to select the right product and size for the pump. An example of a low-power ac inverter is shown in Figure 11.

These classes of solid state adjustable ac motor drives take the 50 or 60 Hz ac line voltage from the grid (wide voltage tolerance range OK) and first rectify it into a dc voltage. Some filter capacitors are sometimes used to attain a smooth dc voltage. Then the dc is converted into sine waves, one for each phase, at a frequency that is selectable to achieve the speed of the motor and pump according to the number of poles in the motor. The drive

FIGURE 11 Low-power AC inverter (motor controller) for three phase motors with sine wave outputs and an output frequency range from 1 to 120 Hz (courtesy of Leeson Electric Corp.)

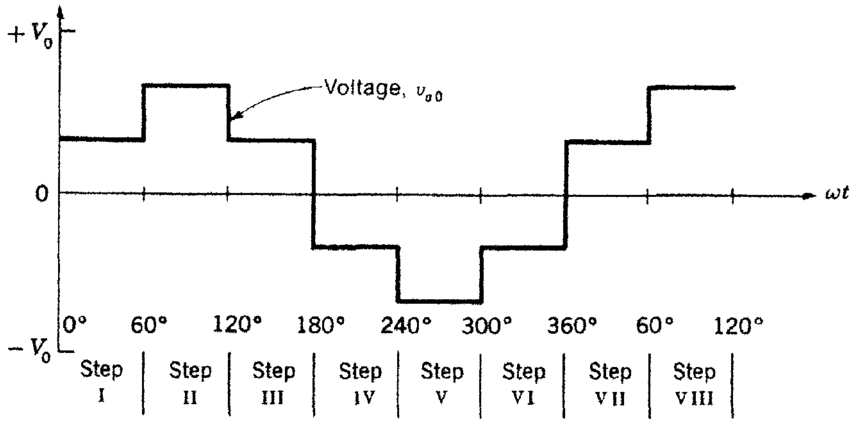

FIGURE 12 AC inverter (6) step simulated sine wave shown for one phase

is designed to maintain a constant volts/Hz relationship. Speed can be controlled to about 10% by inputting the frequency setting. The sine waves can be approximated, as shown in Figure 12, by the use of a simple six-step transistor switching method. Alternatively, they can be very precisely generated using a PWM switching topology at a high carrier frequency to achieve a very low-distortion sine wave. The dynamic response of these systems is sufficient for many pump applications. However, if there are sudden load changes and speed must be accurately maintained, such as for metering pumps, a higher dynamic response will probably be needed. For applications that require high acceleration, the constant volts/Hz algorithm will not allow a fast enough dynamic response because the system bandwidth will likely be too low.

Another problem with these drives is that they usually need a voltage boost at low speeds because of the low frequency. This would be a problem only for metering pumps run over a wide speed range, which is very rare.

Flux Vector Drives The highest performance class of solid-state adjustable speed drives for ac induction motors are known as *flux vector drives.* The rectification requirement of the incoming ac power is the same as is the regeneration of sinusoidal currents for each of the three phases to power the motor. The very important difference between them is that the phases are controlled in a closed loop fashion. The control block of the flux vector drive must receive rotor pole angular position feedback information. With this information, the inverter driven ac induction motor can be made to operate like a servomotor. Most flux vector drives utilize a digital signal processor (DSP) for all of the control functions using the software commands programmed by the supplier (user or supplier can modify). These include the various control loops such as speed (within 0.5% if required), acceleration (linear or to a function), current, torque, power, and several more over a very wide speed range. Drives of this type are available for high power with output frequencies of 800 Hz from several suppliers and up to 3 kHz from a few suppliers.

Flux vector drives can achieve a dynamic response in the 10-millisecond range and very smooth speed regulation, down to zero with ordinary induction motors. The concept of the vector control is to observe the present position of the rotor poles and formulate the control to achieve a dc servomotor performance. The control scheme synthesizes the two currents in the motor. If the calculation is done correctly, one of the synthesized currents controls the flux in the motor and the other controls the torque. In other words, one current vector in the stator phases lies along the vector of the rotor flux and the other current vector lies in quadrature or at 90° out of phase. The DSP constantly receives rotor pole position information and constantly recalculates this relationship at all speeds in spite of load changes.

An important feature of flux vector drives is that with simple and minor software modifications they can easily be used to drive PM brushless motors. The drive has transistor gate drivers controlled by the commands from the DSP that receives shaft angle position information from a shaft sensor such as an encoder, resolver, or hall sensors. The poles on the rotor do not move with respect to the shaft and rotor current (true synchronous operation without “slip”) as do the poles in the induction motor. It is actually much easier to use this vector flux vector inverter for a PM brushless than for an ac induction motor. This is because there are seldom any calculations to required to run the brushless motor unless phase advance is needed. However, for pump drives, this requirement seems unlikely.

MODIFIED KRAEMER DRIVES

Kraemer drives have been used as heavy industrial drives for many years. Although functioning very successfully, each has three rotating units requiring maintenance, and each has significant losses.

In recent years, the advance of semiconductors has simplified the drive configuration to that of Figure 13, which involves an FVNR starter, a wound-rotor induction motor, a solid-state converter, and an acceleration section. The acceleration section and contactors 1 and 2 can be omitted if the converter rating is large. The FVNR starter switches power to the motor and protects both the motor and the converter. Contactor C2, if, provided, serves as a synchronizing contactor between converter and power line and is closed only when converter and line frequencies and voltages are compatible. This contactor may be placed on either aide of the converter unit.

Under running conditions, rotor slip energy of low voltage and frequency (Figure 13B) flows to the low-frequency aide of the converter, The converter unit inverts this voltage to a fixed line frequency. Thus all motor rotor slip energy except converter unit losses are returned to the power source, thereby improving drive efficiency.

Under starting conditions, acceleration occurs with contactor C2 open and C1 closed. Accelerating contactors progressively and automatically short-circuit the resistor H to allow the motor to accelerate to some preselected speed. When converter output voltage and frequency match line values, contactor C2 closes and C1 opens automatically. The drive then operates as already described.

The converter generally consists of a diode bridge and SCRs with their firing circuitry for inverting. Required auxiliaries, such as special power supplies, complete the package.

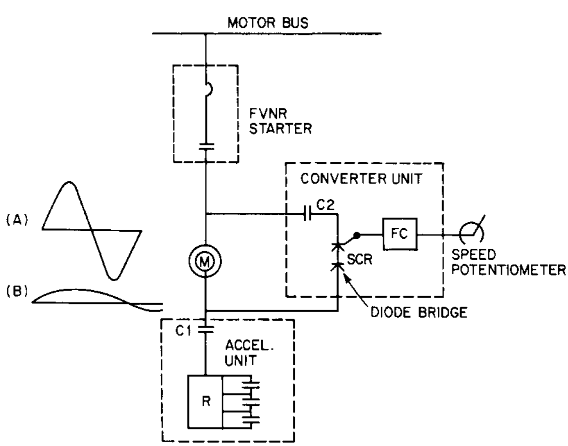

FIGURE 13 Block diagram for modified Kraemer drive

Generally all control materials are packaged in a single lineup to facilitate building and installation.

The motor starter provides normal protection of the motor as well as short-circuit protection of control, motor, cables, and converter. In addition, the converter monitors and limits current drawn from the line under all conditions to a preadjusted value, such as 150% of normal.

DIRECT-CURRENT MOTOR WITH SCR POWER-SUPPLY DRIVES

General industries use many dc motors with SCR power supplies. These drives perform very well in the exacting circumstances they normally face. Some of these drives are used to drive pumps. They are configured as shown in Figure 14 and consist of a dc shunt wound motor and an SCR power supply.

The dc power supply unit rectifies motor bus voltage to an adjustable dc voltage level, which in turn energizes the armature of the motor. The second function of the power supply unit is to rectify motor bus voltage and apply this constant dc voltage to the motor shunt field. By adjusting the dc voltage to the motor armature, the speed of the motor can be adjusted to a desired value.

The SCR power supply unit consists primarily of a short-circuit protective device, a switching contactor, SCR power modules, firing circuitry, a speed regulator, and a shunt field rectifier. The firing circuitry responds to a low-energy-level speed potentiometer or some process variable. The SCRs in turn respond to the firing circuitry and translate those signals into the correct dc voltage to be applied to the armature of the motor. Control circuitry is included to monitor motor current and limit it to a preselected value, such as 150% of normal.

The SCR power supply unit comes packaged for easy installation in the field.

Speed-torque curves for the drive and for a representative centrifugal pump are shown in Figure 15. The steepness of the motor torque provides a clue to its stiffness; that is, its ability to resist speed change because of a change in load torque. Motor torques are limited to some ceiling, such as 150% of normal, by the current limit circuitry of the drive. Table 6 provides significant data useful for drive selection.

DRIVE COMPARISONS

When comparing drives, factors to be considered include the following:

- *Drive costs—both initial and operating cost*. Cost considerations must include not only initial (installed) cost but also drive efficiency and power factor effects. Power factor may

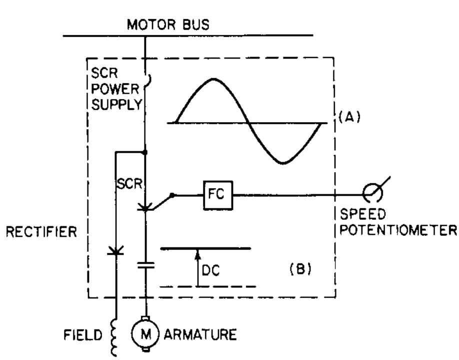

FIGURE 14 Block diagram for dc motor with SCR power supply

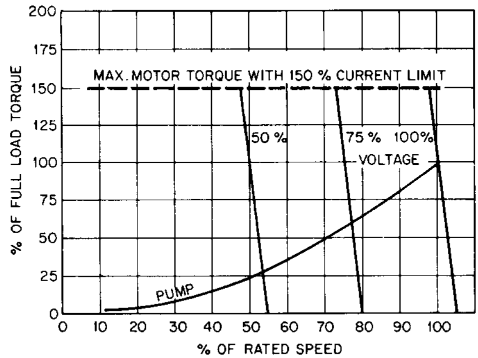

FIGURE 15 Torque versus speed for dc motor with SCR power supply

TABLE 6 Direct-current motor with SCR power-supply drive data

Drive element	Power rating[a]	Voltage rating	Max rated speed, rpm	Speed range, %	Enclosure	Mounting	No. of speed points
Motor	Open horizontal machines can be built at least up to 1500 hp (1120 kW); see Enclosure for other limits	240 500 550	Rating increases inversely with power rating; can match almost all pump speed requirements	At least 95	Vertical: open/dripproof, upthrough 300 hp, (224 kW) totally enclosed up through 200 hp (149 kW) Horizontal: open/dripproof, totally enclosed up through 200 hp (149 kW)	Vert. or horiz.	Infinite
SCR power supply	Can be built at least up to 1500 hp (1120 kW)	Any NEMA ac input voltage; will match motor voltage	. . .	At least 95	NEMA 1; NEMA 12	Floor	Infinite

[a]Drive can power either constant-torque toads or those varying as the square of the speed.

be of critical importance in influencing total costs highly dependent on the terms of the rate structure applied by the power supplier.

- *Operating characteristics.* All the drives discussed in this section compare favorably and all are considered generally suitable to perform functionally as pump drives.
- *Mechanical features* include enclosure, mounting, bearing capabilities, and arrangement (horizontal, vertical). Features are highly application related.
- *Mechanical simplicity* is one of most importance to operations personnel. It can consist of the number of wear points (parts) in rotating and control equipment. The rationale is

based on the concept that parts subject to wear are the eventual causes of failure; the smaller the number of parts, the less cause for failure.

- *Heat emission—removal requirements* can be critical depending on where the equipment is to be located. Heat can be emitted by both the equipment and the drive. If they are located in an enclosed area or building, heat emission can be an important issue.

In the final analysis, no simple routine can be suggested for drive selection. Each drive must be reviewed in the light of the application and its requirements. By reviewing the capabilities and features of the various drives, one has a starting point leading to successful drive selection.

The relative importance of these factors seldom remains stable but changes as application circumstances change.