An additional advantage of this type of drive is that a bypass arrangement is inherent in the design. The normal starting sequence is to bypass the drive and connect it in once the motor reaches a minimum control speed. Therefore, if the drive malfunctions for any reason, it can be bypassed and isolated. In this way repair can be accomplished without shutting down the process.

Other Drive Types. There are other types of ac drive systems used for specialized applications. One of these is the *cycloconverter* drive. This drive is normally applied to low-speed, high-torque, high-performance applications. These include metal rolling mills, large grinding mills for ore or in cement applications, and ship propulsion. All these applications require precise speed and torque control to optimize the process.

The cycloconverter is effectively a separate frequency converter on each phase of a synchronous or induction motor. This allows for a more precise fabrication of the voltage waveform to the motor. This, in turn, results in a current wave shape that very closely approximates a sine wave. Consequently the torque produced by the motor is very smooth throughout the speed range.

The design of the cycloconverter is such that its output frequency cannot exceed one third of the line supply frequency. So, for a 60-Hz system, the maximum output frequency is 20 Hz. A 12-pole motor, which would normally have a synchronous speed of 600 r/min on a 60-Hz system, cannot be run up to only 200 r/min with a cycloconverter drive.

Another type of relatively exotic drive is the supersynchronous converter cascade. This is used for matching frequencies from a variable-frequency generator, e.g., a hydropower station with varying head and speed.

157. Harmonic Impact of Drives on Electrical Networks. *All* drives result in some harmonic distortion in the electrical network to which it is connected. This is due to the fact that the power semiconductor devices "chop up" the incoming sine wave and reconstruct it at another frequency. By definition, this chopping up of the waveform results in distortion from a pure sine wave.

Harmonic distortion can have effects in several areas. Electronic equipment such as computers can malfunction due to changes in zero-crossing points in the supply waveshape. Motors may run hotter due to harmonic currents.

Many factors affect the magnitude of the distortion. The type of rectifier section on the drive has a major effect. Uncontrolled diode bridges will typically produce less distortion. Thyristor rectifier bridges will be somewhat higher since the firing angle is greater than zero.

The short-circuit capacity of the system at the point of connection is the major factor in determining distortion. The distortion can be estimated based on Fig. 20-79. These curves clearly indicate that if the drive is connected to a relatively strong system, i.e., one whose short-circuit capacity (SCC) is substantially higher than the converter rating, the total harmonic distortion seen by the network may not exceed the limits established by IEEE 519.

Connecting to the network with a 12-pulse configuration (through a 3-winding transformer) has a great impact on the distortion. The connection effectively eliminates the fifth and seventh harmonics and all multiples of them. Since the magnitude of the harmonic is inversely proportional to the order number, these are the greatest contributors to distortion.

If multiple drives are connected to the same bus, distortion can be further minimized by phase shifting the primaries of the drives to effectively create a 24-pulse connection. This is only feasible with drives utilizing a diode rectifier. This is due to problems with timing of the device firing on thyristor-type rectifiers.

If the type and configuration of the drive do not limit the harmonic distortion to an acceptable level, filters can be installed on the bus to further reduce their effect. These filters are configured with reactors, capacitors, and resistors to "trap" the unwanted harmonics. Typically they are "tuned" to a specific order number, i.e., there is normally a fifth, seventh, and eleventh harmonic filter. These filters need to be properly coordinated with the drive supplier and the electrical network to ensure that resonances are not created that could interact with other equipment.

158. Impact of Drives on Mechanical Systems. Careful consideration should be given to the *mechanical* system when applying a drive. One key point may be the natural critical speed or resonance point of the motor. When applied as a constant-speed machine, the motor may operate above or below its natural frequency with little problem. However, if the critical speed is within the desired speed control range, problems can occur. These can be addressed in several ways. Critical speeds can be changed somewhat via bearing or base configurations. Or, the drive

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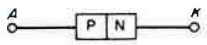
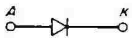
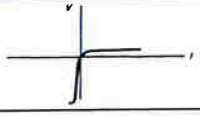
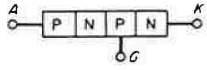
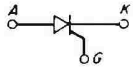
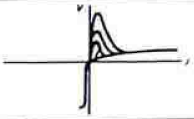
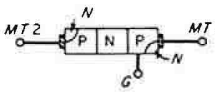
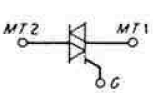
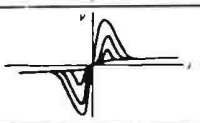
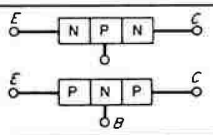
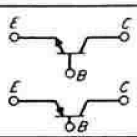
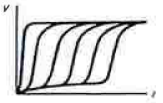
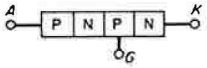
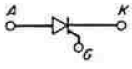
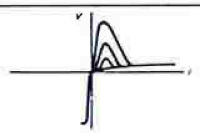
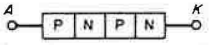
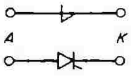
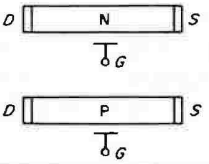
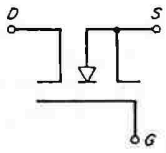
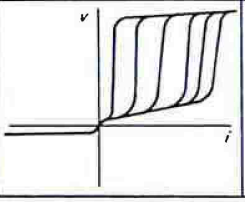
Device name	Structure	Symbol	V-I characteristic	Principal
Conventional rectifier				Rectifier
Thyristor				Controlled turn-on switch
Triac				Bidirectional controlled turn-on switch
Transistor				Controlled turn-on and turn-off switch
Gate-controlled switch				Controlled turn-on and turn-off
Reverse breakdown thyristor (RBDT)				High di/dt breakover switch
Power MOSFET				High speed controlled turn-on and turn-off

FIG. 22-11 Semiconductor switching devices.

In addition, Fig. 22-11 summarizes the junction symbols, circuit symbols, and main terminal *VI* characteristics of the most common power devices.

POWER RECTIFIERS

By JEROME B. BREWSTER

10. Rectifier Average Current Rating. Signal diodes and power rectifiers conduct in one direction and block in the reverse direction. A rectifier conducts as soon as the potential in the forward direction exceeds the barrier potential, about 0.7 V. Power rectifiers are considered to include devices with current ratings from 1 A up.

Power rectifiers are characterized with an average current rating applicable for power frequencies of 60 to 400 Hz. This rating applies for a half-sinusoidal current waveform, as shown in Fig. 22-12.

For this waveform, the root-mean-square (rms) value of the current is 1.57 times the average value. The maximum average current rating of a rectifier is generally the first rating to be seen on a data sheet.

This rating reflects an rms current limit or may represent the thermal limit of a properly

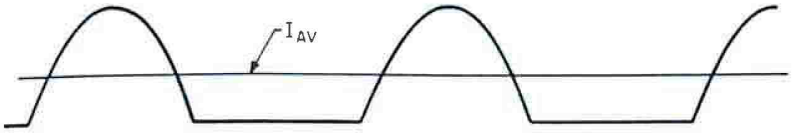


FIG. 22-12 Half-sinusoidal current wave used for rectifier current rating.

cooled rectifier. An rms limit can exist for lead mount wires or wires bonded to the rectifier die. Average current ratings for lead-mounted rectifiers depend on ambient temperature. As ambient temperature rises, the current capability of the device falls because of its thermal limit.

RMS limiting also can apply to existing stud-mounted devices. Pigtail rectifier leads may limit rectifier current rating, and hence the rms limit for stud-mounted devices should be closely observed even if maximum junction temperature is held lower than rated maximum by effective cooling.

Flatpack, hockey puck, or press-pack rectifiers are thermally limited rather than rms-current-limited. The design rationale for a thermally limited rectifier is that as ambient temperature rises, rectifier current is progressively reduced to keep junction temperature within the device less than the rated $T_{J,\max}$. Maximum junction temperatures range from 125 to 200°C for rectifiers.

The actual operating current rating of a rectifier is determined from its power losses as a function of average current. A sample loss curve is shown in Fig. 22-13.

The losses are shown for the most common waveforms found in rectifier systems. These are the 180° half sine wave, the 120° rectangular wave, and the 60° rectangular wave. They occur in resistively loaded half- or full-wave rectifiers, inductively filtered, 3-phase, full-wave rectifiers, and inductively filtered, 6-phase star rectifiers, respectively. The current waveforms are shown in Fig. 22-14.

From Fig. 22-13, it may be concluded that as the rms/avg ratio (form factor) of a rectifier current waveform increases, rectifier power dissipation increases. The information from Fig. 22-13 may be used to generate a rectifier rating curve from

$$T_{C,\max} = T_{J,\max} - P_{\text{av},\max} \times \theta_{JC}$$

The maximum allowable rectifier case temperature ($T_{c,\max}$) is determined as the maximum junction temperature ($T_{J,\max}$) minus the average junction power dissipation ($P_{\text{av},\max}$) times the thermal resistance, junction-to-case (θ_{JC}). Maximum operating junction tempera-

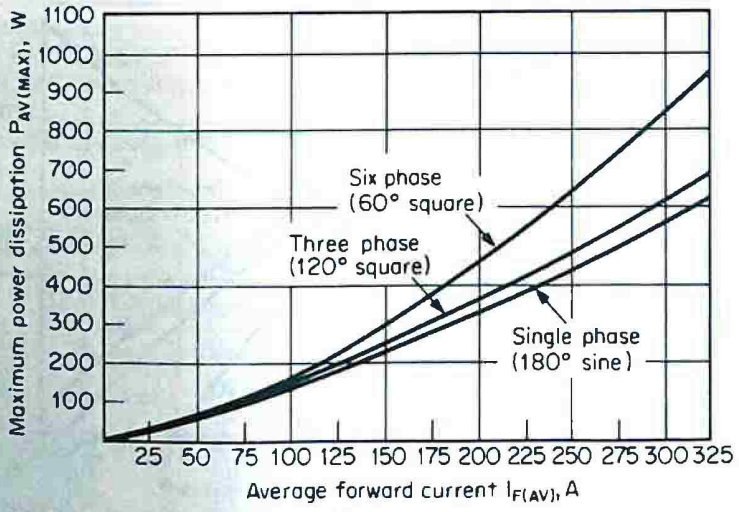


FIG. 22-13 Typical rectifier conducting loss curves. *(Westinghouse Electric Corp.)*

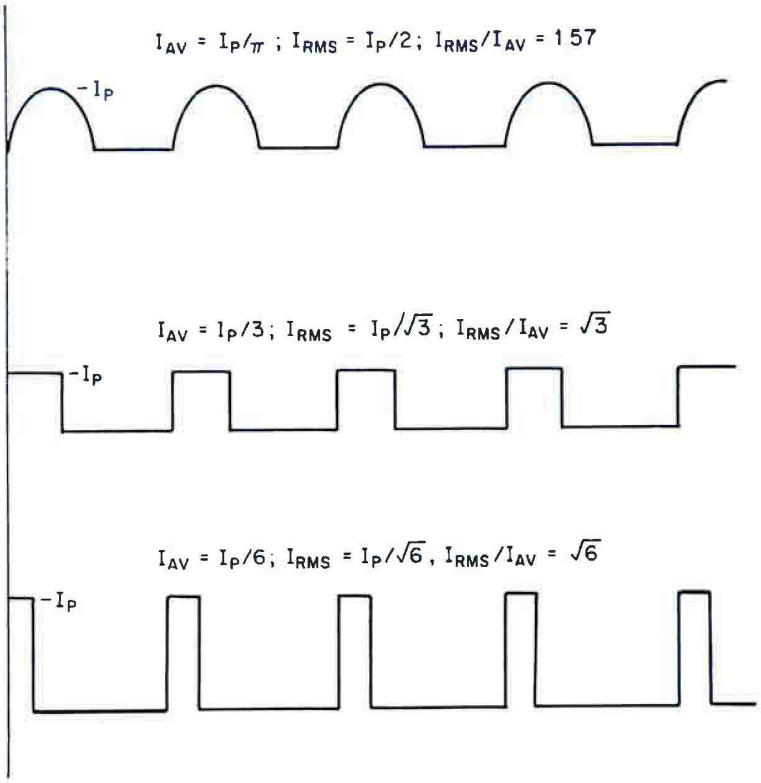


FIG. 22-14 Some typical rectifier current waveforms—two-pulse with resistance load, three-pulse and six-pulse with infinite inductance load.

ture and steady-state junction-to-case thermal resistance are data sheet specifications. Maximum rectifier power dissipation as a function of average current is presented for any rectifier in curves such as Fig. 22-13. From the equation for $T_{C,max}$, manufacturers generate rating curves for maximum case temperature as a function of average current. A typical curve is shown in Fig. 22-15. Manufacturers also publish guaranteed maximum rectifier

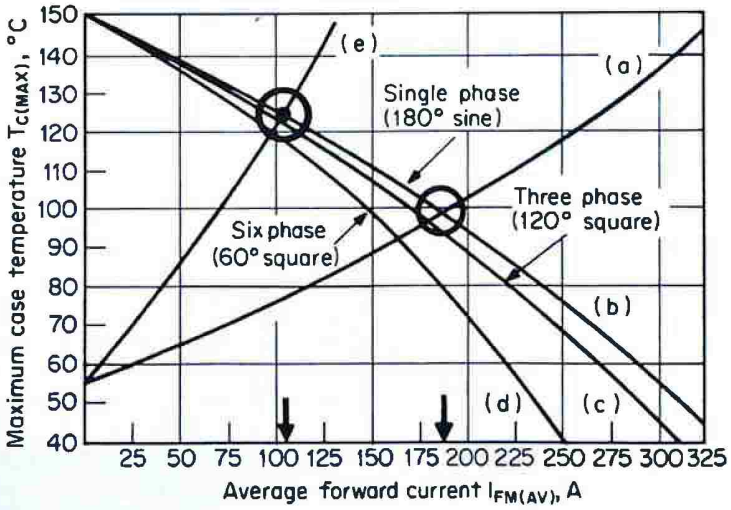


FIG. 22-15 Permitted case temperature versus current for rectifier [(*b*), (*c*), and (*d*)], together with case temperatures versus current for two different heat sink conditions (*a*) and (*e*). *(Westinghouse Electric Corp.)*

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conducting drop, V_{FM}, at a specified peak 60-Hz half-sine-wave current pulse (I_{FM}), and junction temperature. It is assumed that if a device is within the V_{FM} limit, then the loss curve of Fig. 22-13 will be met. A proper rectifier V_{FM} level indicates proper chip design, mounting, and bonding. These factors also affect thermal impedance and losses.

All points of Fig. 22-15 which lie below the appropriate curve are acceptable operating points. To determine where a particular cooling system will operate, the following equation must be considered.

$$T_C = T_A + P_{av,max}(\theta_{CS} + \theta_{SA})$$

where T_C is the case temperature of the device in question, T_A is the ambient temperature in degrees celsius, $P_{av\cdot max}$ originates from Fig. 22-13, θ_{CS} is the device thermal impedance from rectifier package to sink (published in the device data sheet), and θ_{SA} is the thermal impedance of the heat sink chosen by the designer to remove heat from the device. Using this equation, the designer can achieve a desired current rating by choosing the appropriate heat sink to complement the rectifier. As an example, Figs. 22-13 and 22-15 are typical for a 250-A average-current-rated stud-mounted rectifier for which $\theta_{CS} = 0.10$°C/W. A heat sink suitable for this size device shows the following thermal resistances:

Heat sink thermal resistance θ_{SA}, °C/W	Airflow
0.60	Convection cooled
0.20	Forced air, 500 linear ft/min
0.10	Forced air, 1000 linear ft/min

If this heat sink is used with $\theta_{SA} = 0.1$°C/W, curve *a* can be plotted on Fig. 22-15 for half-sine-wave current if T_A is assumed to be 55°C. The intersection of the calculated curve and the manufacturer's curve, curve *b*, indicates that an average current of 187 A may be achieved with this system at a 55°C cooling ambient. A 105-A rating is obtained for a convection-cooled sink, shown as the intersection of curve *e* with curve *b*.

The calculations and their graphical presentation do not completely define a rectifier cooling system. After design, the calculated result must be checked by an actual heat run where the case temperature of the rectifier is measured using thermocouples. In rectifier systems, heating caused by other components or rectifiers can be influential in determining the final case temperature. The top rectifier in a convection- or fan-cooled stack should be carefully checked, because this device is subject to the greatest temperature rise. Measured data from a heat run may then be used to determine the intersection with the maximum permissible case temperature curve. Measured thermal checks need not be carried out at the maximum anticipated ambient temperature, since data can be adjusted by adding to each data point the temperature difference between the actual and maximum ambient temperatures.

The increase in rating obtained from better package configurations is shown in Table 22-3.

TABLE 22-3 Current Comparison for Stud and Disk Rectifiers

	Stud-mounted rectifier	Disk-type rectifier
I_{av}	250 A	400 A
V_{RRM}	1400 V	1400 V
I_{FSM}	4500 A	4500 A
I^2t	85,000 $A^2 \cdot s$	85,000 $A^2 \cdot s$
V_{FM} @ 800 A	2.0 V	2.0 V
θ_{JC}	0.17°C/W	0.095°C/W (double-sided cooling)
θ_{CS}	0.10°C/W	0.025°C/W (double-sided cooling)

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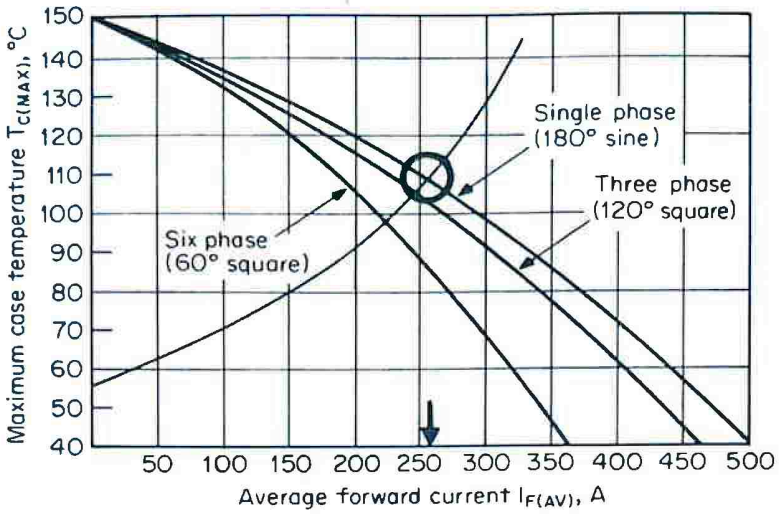

FIG. 22-16 Another example of permitted case temperature and heat-sink-developed case temperature curves for θ_{SA} = 0.05°C/W and θ_{CS} = 0.03°C/W. *(Westinghouse Electric Corp.)*

For the disk type rectifier, assume that a heat sink is chosen such that θ_{CA} of 0.08°C/W is achieved. The disk device rating curves are shown in Fig. 22-16. Note that power dissipation curves for the stud- and disk-mounted rectifiers would be the same.

11. Surge Current Rating. The surge current rating of a rectifier presumes the device to be operating at maximum rated junction temperature, carrying rated average current before the surge, and blocking rated reverse voltage in the interim half-cycle periods. After a repetitive reverse voltage pulse, the rated surge current I_{FSM} is applied for half a cycle, followed by one half cycle of nonrepetitive surge voltage level, then followed by rated average current and voltage until the device cools to rated maximum junction temperature. Thereafter the surge current may be repeated, up to 100 times, in a similar fashion. A rectifier should not be designed to operate at the surge level, and the single-cycle surge is characterized only to define a fuse-blowing level after a short circuit develops and control of current has been lost. Although JEDEC defines the surge current test with the intent that a rectifier tolerate this at least 100 times, it is not good practice to intentionally exercise devices at this level. The single-cycle surge current defines a half cycle fusing I^2t for 8.3 ms pulses as follows:

$$I^2t = I^2_{FSM}(T/2) \qquad A^2\cdot s, \text{ where } T/2 = 8.3 \text{ ms}$$

A rectifier data sheet will publish both the rectifier single-cycle surge rating and the I^2t corresponding to this 8.3-ms pulse. At this I^2t level[3], the rectifier will survive a single-cycle surge. The rectifier will be adequately protected if it is serially connected with a fuse which is rated to clear with an I^2t less than the rectifier I^2t rating. The rectifier fuse need only be used if available fault current exceeds the single-cycle surge rating of the rectifier before a breaker or a "slow" fuse would open.

The multiple-cycle surge rating is the level of an integral number of current pulses (n) needed to produce the same junction temperature by the series of n pulses as was produced by the single-cycle surge pulse.

12. Transient Thermal Impedance. The main objective of power rectifier rating systems is to be certain that maximum operating junction temperature is not exceeded. For continuous trains of current conduction pulses, analysis using steady-state cooling parameters is appropriate. However, for current pulses of short duration, or short pulse trains, transient thermal impedances must be considered. Figure 22-17 shows a transient thermal impedance curve for a rectifier. The curve arises because of thermal capacity effects. When a rectifier experiences a step power pulse, the rise in junction temperature begins immediately, but the

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