14

Industrial Application

14.1 FIELD OF APPLICATION

Thyristors being utilised in the industry widely, some of them are briefly stated below :

(*i*) **Heating element power control.** Thyristors (or triacs) can be used in heater control circuits as shown in Fig. 14.1.

By proper firing, the average value, rms value of voltage for each half cycle can be controlled and thus heating power is controllable.

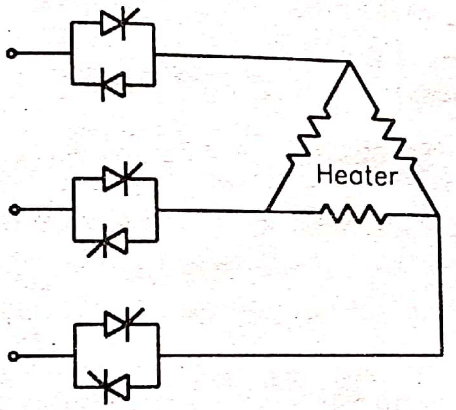

Fig. 14.1. Heat power control using thyristors in antiparallel mode in each phase.

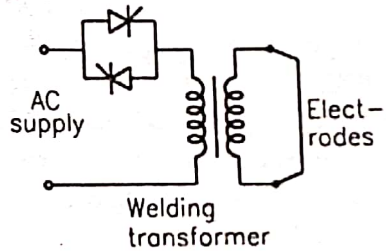

Fig. 14.2. Welding power control using antiparallel thyristors.

(*ii*) **Welding power control.** Antiparallel thyristors, with proper protection circuitry, can control the voltage of the welding transformer (Fig. 14.2) by selecting variable firing delay angles. However, the thyristor PIV ratings must be high enough.

(*iii*) **DC Voltage/power control.** Thyristors can be used as ON/OFF switches in DC circuits thus controlling pulse timings. This action is illustrated in chopper circuits and it is possible to use step up and step down chopper using thyristors.

(*iv*) **Thyristor as a contactor.** Thyristors can be made to switch on a circuit at zero voltage while they can be used to open the circuit at zero current instants. This facilitates the use of thyristors as contactors in smaller AC motor control circuits.

(*v*) **Thyristor as a solid state relay.** Fig. 14.3 shows a thyristorised relay which can be used to close on at zero voltage and switched off at zero current states.

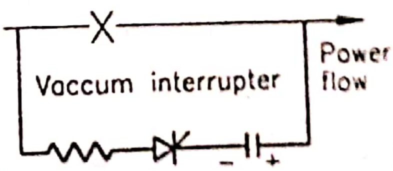

Fig. 14.3. Schematic of a solid state relay.

They do not have any moving contacts and they are very fast in operation. Also there is no possibility of "contact bounce". The switching on at zero voltage and off the zero current eliminates the possibility of radio interference.

(*vi*) **Thyristor as induction heating controller.** An important application of thyristor is induction heating controller in form of series inverter. The series inverter produces a high frequency magnetic field through changing electric current in the induction heating coil. This high frequency magnetic field produces eddy currents in the charge to be melted. The eddy current produces thermal energy. The firing pulses to the thyristor can be supplied from an oscillator.

(*vii*) **Thyristor as Circuit breaker.** Vacuum interruptors can be used in DC circuits for circuit breaking since due to absence of dielectric medium, the arc can-not persist in the vacuum interruptor. The commutation of fault current can be made possible by using another circuit using a thyristor (Fig. 14.5).

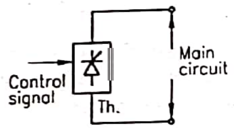

Fig. 14.4. DC Circuit Breaker.

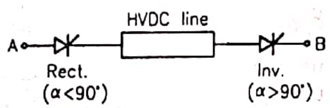

Fig. 14.5. Schematic of HVDC system.

During normal operation, the thyristor is switched off. With actuation of fault, the vacuum interruptor starts tripping and the thyristor is gated on. The capacitor starts discharging in the direction opposite to load current. This commutates the fault current in the vacuum interruptor.

(*viii*) **Thyristors in HVDC power transmission.** HVDC power systems can be used to serve as a link between two ac power sub grids/grids. With reference to Fig. 14.5 it is evident that station *A* can serve as a rectifier with $\alpha < 90°$ while station *B* as an inverter with $\alpha > 90°$.

This causes the power flow from side *A* to side *B*. On the other hand, to make power reversal, $\alpha > 90°$ for station *A* and $\alpha < 90°$ for station *B*. Station *A* serves as an inverter while station *B* as rectifier.

HVDC transmission lines can link two asynchronously operating AC terminals, can facilitate vary fast power reversal, can eliminate stability problem. Details of HVDC transmission is covered in the subject of Electrical Power System*

(*ix*) **Power Electronics in Drive control.** *History of adjustable Speed Control*

Formerly, variable speed conversion equipment was either a motor-generator set used to control a dc motor or an eddy current clutch attached to an ac induction motor. Fig. 14.6 shows these two systems.

The MG set based quipment that most electricians are familiar : an ac machine and two dc machines. Controlling the armature voltage and field current of the dc motor gives the required speed. This method of speed control is expensive—controlling a 250 hp dc motor required purchasing a 250 hp ac motor, a 250 hp dc generator, the controls, plus significant real estate to house the controls.

* Please refer the book ***"A Text Book on Power System Engineering"*** by *Chakrabarti, Soni, Gupta and Bhatnagar.*

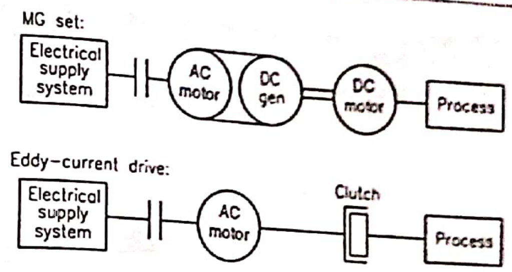

Fig. 14.6. Mechanical adjustable speed controls.

The eddy-current drive uses an eddy-current clutch connected to an ac motor. This system does not control speed directly, but adjusts the output torque until the desired speed is reached. By adjusting the excitation (and slip) of the clutch the output shaft torque could be varied. The system speed would change until the required torque matched the output torque. This system is still widely used. However it is not easily used in retrofit applications because adding the clutch requires modifying the motor mounting hardware.

Both the MG set and eddy-current drives provide isolation from power system disturbances through the inertia of the devices and the ridethrough of the control circuit. Inertia also reduces the shock seen by the process to speed changes. These two systems do not reduce in-rush current on startup and do not have the response time of electronic drives that directly control motor speed.

Solid-State Power Components

The increased current-carrying capacity of semiconductor devices, combined with reduced costs, has led to the development of accurate, reliable, and inexpensive solid-state drives in both ac and dc applications. Incorporating microprocessors in drive systems makes precise control combined with protective features. These features were not even available 20 years ago. Fig. 14.7 outlines dc and ac drive systems.

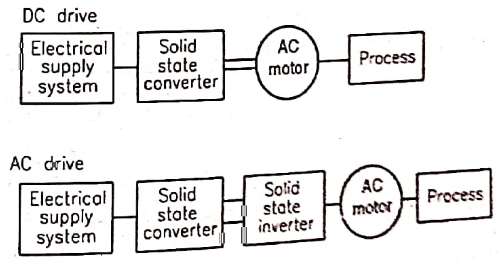

Fig. 14.7. Solid state adjustable speed controls.

Most industrial solid-state drives convert incoming fixed voltage-fixed frequency from ac to dc voltage. This dc voltage can be either a constant value (using diodes) or a variable voltage (using SCR's). The ac-to-dc conversion section is the converter ; the dc-to-ac conversion section is the inverter. Fig. 14.8 shows the power semiconductor devices that the converter and inverters use. They include (1) diode (2) SCR—silicon-controlled rectifier (3) transistor (4) GTO—gate turn-off thyristor.

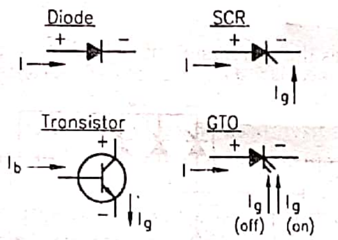

Fig. 14.8. Power electronic components.

These devices allow current to flow in only one direction, but differ in how they block the conduction of this current. The GTO and transistor are used exclusively in the inverter section, while the diode is used in the converter section. The SCR is used in both the converter and inverter sections. When SCR's are used in the inverter, they require a commutation circuit for each SCR to turn it off. Each of these devices can be demaged by excessive voltage of temperature.

(1) *Diode.* The diode will conduct when it is correctly biased, as Fig. 14.8 shows. Commutation (changing from the conduction to the blocking state) occurs when the current through the diode is zero and the voltage bias is reversed. Diodes give a fixed output voltage because they cannot be controlled. This lack of control means they will feed a fault if the bias is correct.

(2) *SCR.* The SCR will conduct if it is forward biased and has one of the following :

(*a*) gate pulse
(*b*) high forward voltage
(*c*) high *dv/dt*—transient voltage spikes can trigger sympathetic turn on
(*d*) high temperature.

SCR's commutate when the current through them tries to reverse. SCR's can limit fault current if they are controlled by a microprocessor that monitors the current through each SCR and does not turn on the next scheduled SCR if the *di/dt* through the previous SCR is too high. SCR's can handle large currents and high voltages (4 kA and 6 kV).

(3) *Transistor.* The transistor will conduct if it is biased correctly and has an appropriate base current. Removing the base current causes commutation. The transistor will block any current flow if there is no base current. Power transistors are normally used as switches—the base current will cause full conduction or full blocking. Transistors are used in drives up to 100 hp.

(4) *GTO.* The GTO is used in large hp drives, and is finding applications in smaller drives as well. The GTO offers the current-carrying capacity of the SCR, combined with the controlled turn off of the transistor. The main drawback of the GTO is the gate current required to control conduction or blocking. The current is large compared to an SCR, and the gate driver board should be matched to the individual GTO. The customization required has kept the GTO from becoming a commodity component. GTO's are capable of handling high voltages (up to 6.9 kV) and are frequently used in medium voltage drives.

Solid-State Devices

Fig. 14.9 illustrates the conversion of ac to dc using solid-state devices.

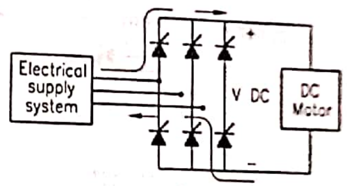

Fig. 14.9. Converter fed dc motor.

When the proper conduction conditions are met, the current flows through the upper conducting device (diode or SCR) through the load, and back through the lower conducting device. Both diodes and SCR's allow current flow only in one direction (Fig. 14.8). Controlling of firing instant with respect to the incoming voltage waveform determines the voltage on the dc bus. Diodes provide a constant dc bus voltage.

Control of DC Drives

Controlling the dc voltage output allows control of a dc motor. Fig. 14.10 shows the basic model for dc motor control.

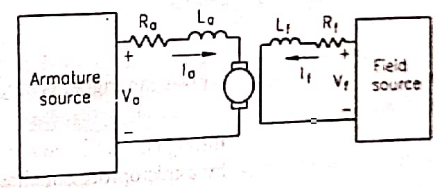

Fig. 14.10. DC motor model.

The speed of a dc motor is proportional to the armature voltage, up to base speed (the speed at rated voltage and rated field current). Higher speeds can be obtained by reducing the field current (field weakening), which reduces the torque output. Operation above base speed is the constant horsepower range of operation and should not be used in applications requiring constant torque loads.

The analysis of ac induction motors is more complex, but can be condensed to the illustration in Fig. 14.11.

The speed of an induction motor is dependent on the frequency of the supply voltage. The torque is proportional to the air gap flux, which can be controlled by maintaining a constant volts/hertz ratio throughout the frequency range. Maintaining this ratio results in constant torque available at all speeds. The next section of this paper covers the methods for adjusting the frequency.

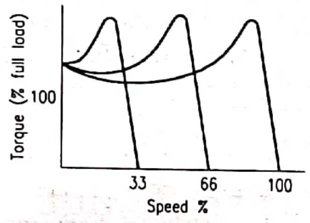

Fig. 14.11. Speed torque curves (Induction motor).

AC Drives

Three types of ac drives are generally used today :

(*i*) voltage source inverter (VSI)

(*ii*) current source inverter (CSI)

(*iii*) pulse-width modulated inverter (PWM).

(*i*) ***Voltage Source Inverter.*** Fig. 14.12 shows the voltage source inverter.

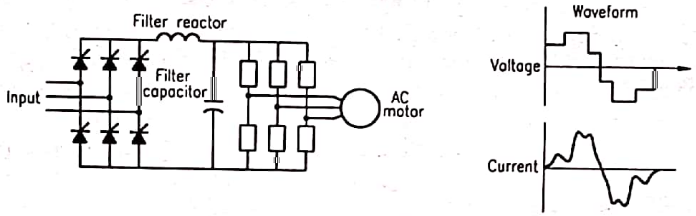

Fig. 14.12. VSI inverter.

This type of drive uses an SCR converter to control the dc bus voltage and SCR's, or transistors in the inverter section. The output voltage is controlled and the current is delivered as required. The output voltage waveform is commonly called a six-step output.

This type of drive is fairly simple, rugged, and can handle multimotor situations. The drive can be tested and set up without a motor connected because it is regulated by voltage. The drive does not use high-frequency switching, so the switching devices and controls are not complex or expensive.

The disadvantages include poor input power factor at low speeds (due to the delayed firing angle) and low-speed pulsations. Low-speed operation means that the voltage pulses are very wide and the motor can experience "cogging" (turning, stopping, etc). As a result, this drive design is being replaced in the under

100 hp range by the PWM drive. Regeneration (feeding power from the inverter to the line) is possible only with an additional converter section. Regeneration is used to rapidly decelerate the load. An alternate method is to put a large resistor across the dc bus. With an SCR switch, the dissipates the motor energy.

(*ii*) ***Current Source Inverter.*** Fig. 14.13 illustrates the current source inverter type of ac drive.

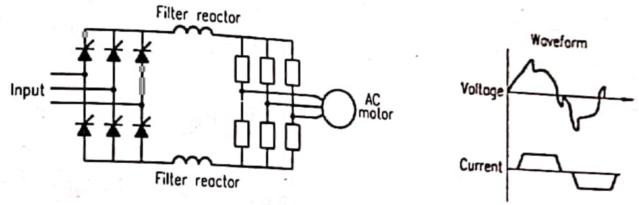

Fig. 14.13. CSI inverter.

The current source inverter controls the current to the motor to maintain required voltage and frequency. This drive is very rugged, but is more complex than the VSI.

CSI drives are dependent on the motor inductance for proper commutation and are generally sold as motor-drive units. The motor inductance factor allows these drives to run motors larger than their horsepower rating provided the current rating of the drive is not exceeded. These drives are easily regenerative and is a good application on equipment with high inertial loads.

The drives cannot be set up or tested without a motor or equivalent inductance because the current regulator will not operate properly and will try to increase the current to obtain the required voltage—an infinite current in the case of an open circuit.

(*iii*) ***Pulse-Width Modulated Inverter.*** Fig. 14.14 shows the pulse-width modulated inverter. The PWM drive is rapidly becoming the drive of choice on application of 100 hp or less.

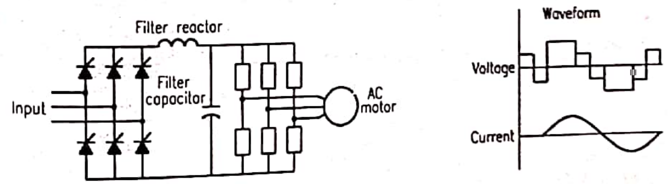

Fig. 14.14. PWM inverter.

The PWM drive uses a diode bridge for the converter, thus minimizing the harmonics generated by the drive. The harmonics are reduced because of the small-constant time delay in the turn on of the diodes.

The PWM inverter requires higher frequency devices than either the VSI or CSI. The regulator is also quite complex because it must control both the output voltage and frequency at the same time. The PWM waveform generates more motor heating, and motor derating factors of up to 10% and are commonly used when motors are driven by this type of drive. These drives are less efficient at reduced speeds, due to commutation and load voltage loss.

14.4 ADJUSTABLE SPEED DRIVE APPLICATIONS

The use of electric motors can be divided into three basic categories:

1. Constant torque applications where the same amount of torque is required at low speed as at high speed. The horsepower is directly proportional to speed.

   Typical applications are conveyors, mixers, screw feeders, extruders, and positive displacement pumps.

2. Constant horsepower applications that require high torque at low speeds and low torque at high speeds.

   Typical applications are found in the machine tool industry on cutters and lathes. These applications generally use dc motors.

3. Variable torque applications which require lower torque at lower speeds and higher torque at higher speeds.

   These applications are generally centrifugal loads such as fans, pumps, and blowers—good targets for energy savings by retrofitting with solid-state drives.

Fig. 14.15 and 14.16 are charts showing the distribution of constant torque and variable torque loads and their usage.

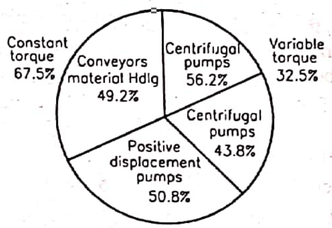

Fig. 14.15. Motor population total applicationsabove 1 hp.

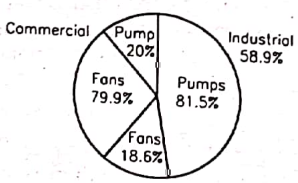

Fig. 14.16. Variable torque applications above1hp.

Fig. 14.15 compares the percentage of constant torque loads to variable torque loads.

The variable torque loads are about 1/3 of the total load ; however, they offer the best opportunities for energy savings through retrofitting with ac drives.

These applications normally can justify changing the present flow control method to one utilizing variable speed by giving a payback of less than three years. The constant torque loads can profit from increased process control flexibility.

The chart in Fig. 14.16 shows the division of variable torque applications. The commercial section is predominantly fans (HVAC), while the industrial sector variable torque applications are mostly pumps.

The majority of motors are in the 1-5 hp range, however, the chart also illustrates in variable torque the energy consumption versus hp rating. Even though motors above 125 hp make up less than 2% of the population, they use 46% of the electrical power consumed by centrifugal loads.

The next section of this paper shows the energy savings that can result from retrofitting these motors with variable speed drives.

Variable Torque Applications

The variable torque load is one whose torque is directly proportional to some power of speed (usually speed squared). These loads are normally centrifugal equipment-fans, blowers, and pumps. Typical constant speed systems will use dampers or vales to reduce the flow by increasing the pressure. This method introduces valve losses that increase the motor load. The motor input power will reduce linearly or less, depending on the type of valve. Realizable savings are the difference in energy used at a reduced flow with valve control, compared to energy usage with a variable speed drive.

Constant Torque Applications

The constant torque load accounts for over 2/3 of the motor applications. These loads generally involve friction that the torque is required to overcome. Typical loads are conveyors, extruders, and positive displacement pumps. The application of variable speed drives will normally be to improve the response and accuracy of the process.

When applying drives to this load, make sure the drive you specify is rated for constant torque operation. Drives are rated for the specific applications variable or constant torque. Motor cooling must be considered in a constant torque application. The torque output of a motor is proportional to the current through the motor.

dc Motor. Torque = Kt *armature current * field current.

ac Motor. Torque = K *rotor current * sin

(angle between rotor MMF and the stator flux).

This angle is normally close to 90° for small values of slip, and the rotor current is proportional to the stator current, so the torque is also proportional to the stator current.

The heat generated by the motor is largely due to the I^2R losses in the windings. If motors are supplying constant torque at a reduced speed, auxiliary cooling may be necessary. Most self-cooled motors use centrifugal fans for cooling, and the air flow reduction is proportional to speed. The motor could be supplying rated torque, generating rated heat, and suffering from reduced cooling if the application is not carefully analysed.

Medium Voltage Drives

Medium voltage drives (above 480 V) are available in two basic configurations—direct conversion and transformer conversions, as Fig. 14.17 shows.

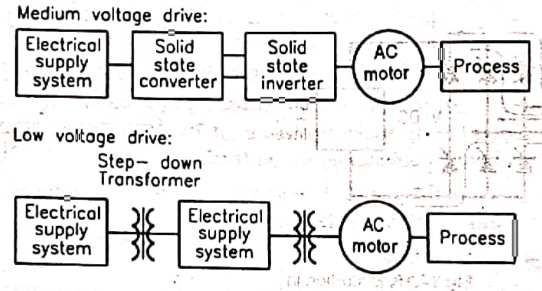

Fig. 14.17. Medium voltage drive control schemes.

The direct conversion drives utilize higher voltage components for operation directly from bus voltages up to 6900 V. These drives use GTO's or SCR's and are PWM or voltage source inverters. There are only a few manufacturers that make this size of drive.

Many manufacturers match their large horsepower low voltage drives with two transformers to control a medium-voltage motor. The step-down transformer helps reduce the magnitude of the voltage notching that appears on the medium voltage system. The step-up transformer is usually of special design to allow operation at lower frequencies. Large horsepower motors can require several drives paralleled to meet the current requirement.

Medium-voltage installations should be carefully coordinated with the drive supplier.

Drive Control Power Supply

When problems occur after installing new equipment, the new equipment generally gets the blame. Solid-state drives can cause problems with their power system. However, by recognizing these problems before installation, one can minimize them.

Line Notching

The most serious problem is a distortion of the system voltage from the commutation of the solid-state devices in the converter section of drive. Fig. 14.18 shows why these distortions occur.

Fig. 14.18 shows that to turn off the first device (diode or SCR), current must flow back in the reverse direction. Reverse current flow happens when the second device beings conduction, creating a short circuit between the two phases for a small period of time. The depth of the voltage notch is dependent on the line

inductance (*Lt*) and the drive inductance (*Ld*). The voltage notch can create many problems for other equipment on the power system, that depend on a stable sinusoidal voltage supply. Drives using SCR's will cause the notch to move up and down the voltage wave as the firing angle of the SCR changes.

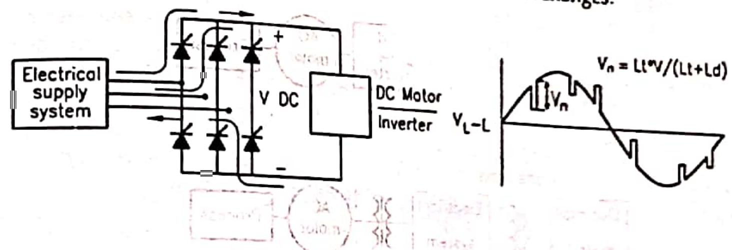

Fig 14.18. Distortion in converter fed motor.

Drive "Crosstalk"

Fig. 14.19 illustrates one "crosstalk" problem that was encountered due to line notching.

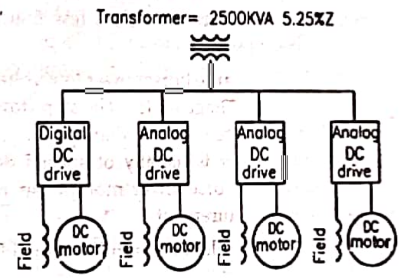

Fig 14.19.

Researches in drive control reports that when digital dc drive replaces an analog drive it was observed erratic speed changes in the adjacent analog drive when the digital drive was running at base speed.

No problems are encountered when the digital drive was above or below base speed. Both drives used SCR's to control both the armature voltage and the field current. The reduction in field current is obtained by increasing the firing angle (delaying the time of turn on) of the field SCR.

A report on drive control research suggests the case where the oscillations is resulted from the positive spike (high dv/dt) from the digital drive, causing a sympathetic turn on of the field SCR on the analog drive. When this SCR turned on early, the motor went from top speed (weak field) to base speed (full field). This misfiring was not constant, so the motor speed oscillated widely.

The voltage spikes are measured at 1100 V peak. The first solution is to place a surge suppressor across the field circuit to reduce the spikes to 850 V. The MOV suppressor did clip the spikes and reduced the oscillations, but the operation was still not satisfactory. The combination of the MOV and higher rates SCR solved the problem. The voltage spikes from the digital drive were larger than form the analog drives because of improvements in SCR technology. The newer solid-state devices have reduced turn-off time. The notch width is dependent on commutation time, while the area of the notch is proportional to the energy that must be dissipated during the commutation. The new technology has reduced the commutation time, but the energy was the same as with the previous analog drive ; therefore, the voltage spike was greater. The remaining analog drives were retrofitted with MOV's and the higher peak inverter voltage SMV : SCR's.

Power Factor Correction Capacitors

IEEE Standard 519-1981 lists the allowable notch depth for different applications. These notches can cause both transient and steady-state problems. The distorted waveform can be analysed using Fourier analysis to see that harmonics are generated by the switching of solid-state devices. These harmonics can interact with power factor correction capacitors and cause capacitor damage or unexplained blowing of capacitor fuses.

The diode converter maintains a constant power factor of 0.95, while the power factor of SCR converters is proportional to speed. To properly size capacitors for an SCR drive, use the kVAR required at the minimum operating speed. These capacitors should be placed as far from the drive as possible. Capacitors should never be placed at the output of the drive.

The harmonics generated by solid-state devices can cause severe problems with capacitors if the system is resonant at the harmonic frequency. The system can be analysed to determine if a potential exists for resonance. The system will notify of an incorrect analysis (or lack of analysis) by having frequent blowing of capacitor fuses and incorrect operation of protective devices. The harmonics that cause problems are the 5th, 7th, 11th, and the 13th. The resonant harmonic for the capacitors and system can be calculated with this equation ;

$$h = \text{square root } (kVAsc/CkVAR)$$

where h is the harmonic, kVAsc is the short-circuit kVA duty at the capacitor connection, and CkVAR is the capacitor rating. The harmonic should not be 5, 7, 11, or 13. If the system is resonant at one of these frequencies, the capacitance value can be changed or harmonic filters can be added. Adding capacitors on the primary system (with the largest kVAsc) provides a situation where the harmonic is most likely to be above 13.

Isolation Transformers

On use of isolation transformers is somewhat controversial. Drive manufacturers recommended them in the past. However, the price of the system including transformers was higher than one without, so additional protection was built into the drives, and isolation transformers are not normally recommended.

Isolation transformers help protect drives from high over-voltages which some switching and fault conditions on an unbounded power system can cause, and from large fault currents from a solidly grounded system. Most drives today use current-limiting fuses to minimize damage from fault currents. If the isolation transformer secondary is resistance grounded, the first grounded drive will not shut down the rest of the equipment on the system. This is an advantage in coordinated systems using several drives.

The main benefit from isolation transformers is the reduction of the line notch depth and its interference with other equipment on the system. The main disadvantages are their cost and size.

Process Control Integrity

The process controller is critical in maintaining the process according to specifications when using solid-state drives. The drives handle large amounts of power and create voltage spikes throughout the system, while the drives themselves are controlled by a small voltage (0-10 V dc) or current (4-20 mA).

The control system must be designed and installed to provide an accurate and stable signal. This will mean using a signal running in shielded cable separate from any power circuits. If this signal is not stable, the drive will not be stable. Thus, the drive may operate properly, but not give the desired result. The feedback signal from the process to the controller and the control signal to the drive are an integral part of the system and must be considered.

14.3 SUMMARY OF MAJOR CONSIDERATIONS

This discussion has covered some of the basic principles of solid-state drive applications and system considerations. The successful implementation of solid-state drives to improve quality or reduce process cost requires considering the following :

(1) *Environment.* What atmosphere will the drive and motor will be subject to (gas, moisture, dust) ? What is the ambient temperature ?

(2) *Speed Range.* What speed range will the process require ? What is the normal operating speed ? What is the allowable speed error ?

(3) *Multimotor.* Will the drive be controlling one motor or several ? If several, will they start simultaneously or sequentially ?

(4) *Required Acceleration Time.* What is the maximum and minimum time for acceleration of the total drive inertia ?

(5) *Process Duty Cycle and Load Cycle.* What percent of the operating time will the equipment be at each speed ?

(6) *Potential Overheating.* Will overheating be a problem ? This is especially critical for constant torque-reduced speed applications.

(7) *Protection Features.* What drive and equipment protection is required and still maintain process continuity ? Some drives tip instantly on an overcurrent condition (electronic shear pin), while other drives will maintain a constant torque

to the motor (120-150%) and reduce the speed of the motor to maintain the current required to give this torque for 30-60 s. This feature will maintain process continuity in spite of temporary overloads.

(8) *Torque Requirements.* What are the torque requirements for this application ? The application of an adjustable speed drive is primarily a mechanical problem. The engineer must try to best match the speed-horsepower-torque characteristics at the motor shaft to the driven machine requirements. The four torques involved are as follows :

(*i*) Breakaway Torque : The torque required to start the machine.

(*ii*) Process Torque : The torque required to process the material used in the machine or transported by the machine.

(*iii*) Accelerating Torque : The torque required to bring the machine to the required operating speed within a given period of time. If controlled deceleration is required, dynamic braking or regeneration can be used.

(*iv*) Running torque : The torque required to maintain the drive process or machine after it has reached the operating speed.

Running torque will be one of the following :

Constant Torque (*e.g.*, conveyors, extruders).

Constant Horsepower (*e.g.*, machine tools).

Squared Exponential Horsepower (*e.g.*, mixers).

Cubed Exponential Horsepower (*e.g.*, centrifugal fans and pumps).

(9) *Extent of Diagnostics.* How critical is the down time of the load ? If extensive fault analysis is desired, a digital drive provides the most accurate and precise fault indications. Analog drives normally provide the following fault annunciation.

(*i*) bus overvoltage

(*ii*) input undervoltage

(*iii*) drive overtemperature