CHAPTER EIGHT

Inverter-fed Induction Motor Drives

1. INTRODUCTION

We have seen in Chapter 6 why the relatively simple and low-cost induction motor is the preferred choice for many fixed speed applications, and in Chapter 7 we saw that by using field orientation/vector or direct torque control, it is possible to achieve not only steady-state speed control but also dynamic performance superior to that of a thyristor d.c. drive. We have also seen that achieving such performance is dependent on the ability to perform very fast/real-time modeling of the motor and very rapid control of the motor voltage magnitude and phase.

In this chapter we look at some of the practical aspects of inverter-fed induction motor drives and consider the impressive performance of commercially available drives. We will also briefly revisit the subject of control and, for the sake of balance, look at an application where field orientation struggles and direct torque control simply doesn't work.

While it comes as no surprise that the inverter-fed induction motor is now the best-selling industrial drive, the adoption of the standard induction motor in a variable-speed drive is not without potential problems, so it is important to be aware of their existence and learn something of the methods of mitigation. We will therefore consider some of the important practical issues which result from operating standard (utility supply) motors from a variable frequency inverter.

Finally, we will look at the most popular inverter circuits and highlight their most important characteristics.

2. PULSE-WIDTH MODULATED (PWM) VOLTAGE SOURCE INVERTER (VSI)

Several alternative drive topologies are applied to induction motors and the most relevant of these are discussed later in this chapter. By far the most important for most industrial applications has a diode bridge rectifier (which only allows energy flow from the supply to the d.c. link) and a PWM VSI, as shown in Figure 8.1, and this arrangement will now be the focus of our attention.

Most low-power inverters use MOSFET switching devices in the inverter bridge, and may switch at ultrasonic frequencies, which naturally results in quiet

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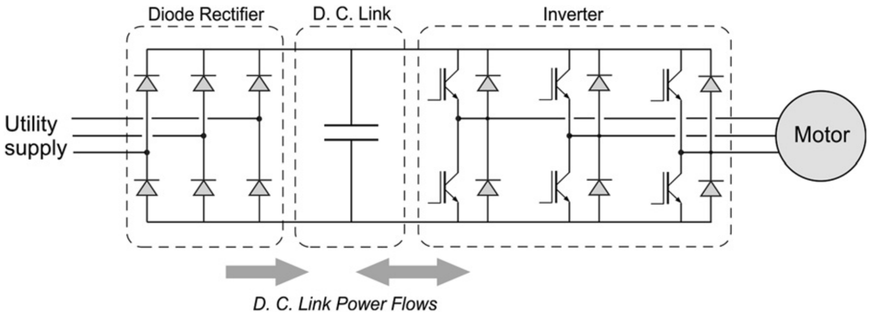

Figure 8.1 Pulse-width modulated (PWM) voltage source inverter (VSI).

operation. Medium- and larger-power inverters use insulated-gate bipolar transistors (IGBTs) which can be switched at high enough frequencies to be ultrasonic for most of the population. It should be remembered, however, that the higher the switching frequency the higher the inverter losses, and hence the lower the efficiency, and so a compromise must be reached.

Variable-frequency inverter-fed induction motor drives are used in ratings up to many megawatts. Standard 50 or 60 Hz motors are often used, though the use of a variable-frequency inverter means that motors of almost any rated frequency can be employed. By 'rated' frequency we mean the frequency at which the maximum possible output voltage of the power converter is achieved. We saw in Chapter 7 that operation above rated frequency limits performance and so this needs to be carefully considered when specifying a drive system. Commercially available inverters operate with output frequencies typically from 0 Hz up to perhaps several hundred Hz, and, in some cases, much higher frequencies. The low-frequency limit is generally determined by the form of control, while the higher frequency depends on the control and the physical dimensioning of the power electronic circuits (where stray inductance can be a problem if interconnections become too long).

The majority of inverters are 3-phase input and 3-phase output, but single-phase input versions are available up to about 7.5 kW. Some inverters (usually less than 3 kW) are specifically designed for use with single-phase motors, but these are unusual and will not be considered further. The upper operating frequency is generally limited by the mechanical stresses in the rotor. Very-high-speed motors for applications such as centrifuges and wood working machines can be designed, with special rotor construction and bearings for speeds up to 40,000 rev/min, or even higher.

A fundamental aspect of any converter which is often overlooked is the instantaneous energy balance. In principle, for any balanced 3-phase load, the total load power remains constant from instant to instant, so if it were possible to build an ideal 3-phase input, 3-phase output converter, there would be no need for the converter to include any energy storage elements. In practice, all converters require some energy storage (in capacitors or inductors), but these are relatively small when the input is 3-phase because the energy balance is good. However, as mentioned above, many low-power (and some high-power, rail traction) converters are supplied from a single-phase source. In this case, the instantaneous input power is zero at least twice per cycle of the mains (because the voltage and current go through zero every half-cycle). If the motor is 3-phase and draws power at a constant rate from the d.c. link, it is obviously necessary to store sufficient energy in the converter to supply the motor during the brief intervals when the load power is greater than the input power. This explains why the most bulky components in many power inverters are electrolytic capacitors in the d.c. link. (Some drive manufacturers are now designing products, for connection to a 3-phase supply, with low values of d.c. capacitance for undemanding applications where the subsequent reduction in control/performance is acceptable, and this is discussed in section 7.)

The output waveform produced by the PWM inverter in an a.c. drive also brings with it challenges for the motor, which we will consider later. When we looked at the converter-fed d.c. motor we saw that the behavior was governed primarily by the mean d.c. voltage, and that for most purposes we could safely ignore the ripple components. A similar approximation is useful when looking at how the inverter-fed induction motor performs. We make use of the fact that although the actual voltage waveform supplied by the inverter will not be sinusoidal, the motor behavior depends principally on the fundamental (sinusoidal) component of the applied voltage. This is a somewhat surprising but extremely welcome simplification, because it allows us to make use of our knowledge of how the induction motor behaves with a sinusoidal supply to anticipate how it will behave when fed from an inverter.

In essence, the reason why the harmonic components of the applied voltage are much less significant than the fundamental is that the impedance of the motor at the harmonic frequencies is much higher than at the fundamental frequency. This causes the current to be much more sinusoidal than the voltage (as previously shown in principle in Figure 7.1), and this means that we can expect a sinusoidal traveling field to be set up in much the same way as discussed in Chapter 5.

In commercial inverters the switching frequency is high and the measurement and interpretation of the actual waveforms is not straightforward. For example, the voltage and current waveforms in Figure 8.2 relate to an industrial drive with a 3 kHz switching frequency. Note the blurring of the individual voltage pulses (a result of sampling limitations of the oscilloscope), and the near-sinusoidal fundamental component of current. We might be concerned at what appear to be spikes of current, but consideration of the motor leakage inductance and the limited forcing voltage will confirm that such rapid rates of change of current are impossible: the spikes are in fact the result of noise on the signal from the current transducer.

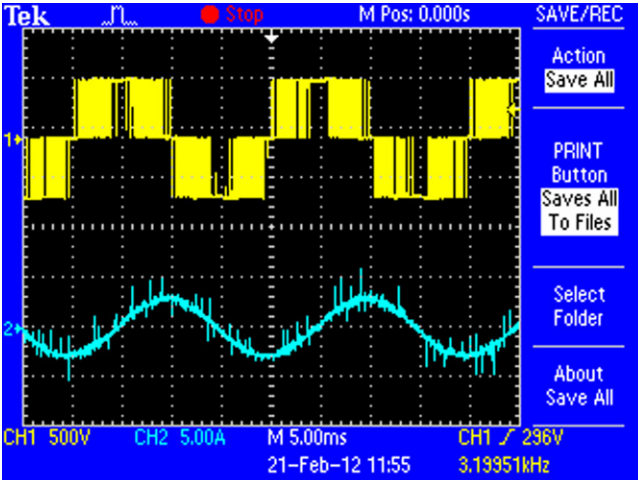

Figure 8.2 Actual voltage and current waveforms for a star-connected, PWM-fed induction motor. Upper trace – voltage across U and V terminals; lower trace – U phase motor current. (See Plate 8.2)

Measurement of almost all quantities associated with power electronic converters is difficult, and great care must be taken in the selection of instrumentation and interpretation of the results. A clear understanding of grounding is also important when reviewing inverter d.c. link and output waveforms since unlike a utility supply there is no clear, or at least simple, ground reference.

3. PERFORMANCE OF INVERTER-FED INDUCTION MOTOR DRIVES

It has often been said that the steady-state performance of the inverter-fed induction motor is broadly comparable with that of an industrial d.c. drive, but in fact the performance of the inverter-fed induction motor is better in almost all respects.

To illustrate this, we can consider how quickly an induction motor drive, with field-oriented control, can change the motor shaft torque. Remarkably, the torque can be stepped from zero to rated value and held there in less than 1 ms, and this can now be achieved by a motor even without a speed/position sensor. For comparison, a thyristor-fed d.c. motor could take up to one-sixth of a 50/60 Hz mains cycle, i.e. around 3 ms before the next firing pulse can even initiate the process of increasing the torque, and clearly considerably longer to complete the task.

The induction motor is also clearly more robust and better suited to hazardous environments, and can run at higher speeds than the d.c. motor, which is limited by the performance of its commutator.

The field-oriented control strategy, coupled with the ability, through a PWM inverter, to change the stator voltage phasor in magnitude, phase and frequency very rapidly, is at the heart of this exceptional motor shaft performance. The majority of commercial inverter systems embody such control strategies, but the quantification of shaft performance is subject to a large number of variables and manufacturers' data in this respect needs to be interpreted with care. Users are interested in how quickly the speed of the motor shaft can be changed, and often manufacturers quote the speed loop response, but many other factors contribute significantly to the overall performance. Some of the most important, considering a spectrum of applications, are:

- Torque response: The time needed for the system to respond to a step change in torque demand and settle to the new demanded level.
- Speed recovery time: The time needed for the system to respond to a step change in the load torque and recover to the demanded speed.
- Minimum supply frequency at which 100% torque can be achieved.
- Maximum torque at 1 Hz.
- Speed loop response: This is defined in a number of different ways but a useful measure is determined by running the drive at a non-zero speed and applying a square wave speed reference and looking at the overshoot of speed on the leading edge of the square wave: an overshoot of 15% is – for most applications – considered practically acceptable. For the user, it is always a good idea to seek clarification from the manufacturer whenever figures are quoted for the speed (or current/torque) loop bandwidth of a digital drive, because this can be defined in a number of ways (often to the advantage of the supplier and not to the benefit of the application).

Note that the above measures of system performance should be obtained under conditions which avoid the drive hitting current limits, as this obviously limits the performance. Tests should typically be undertaken on a representative motor with load inertia approximately equal to the motor inertia.

Indications of the performance of open-loop and closed-loop field-oriented induction motor control schemes are shown in Table 8.1.

The performance of a closed-loop inverter-fed induction motor is comparable to that of a closed-loop permanent magnet motor, which we discuss in Chapter 9. This comes as a great surprise to many people (including some who have spent a lifetime in drives). It is particularly noteworthy given that the majority of induction motor drives use standard motors which were designed for fixed speed operation and broad application. Permanent magnet motors, however, tend to be customized and many have been designed with relatively low inertias (long length and small diameter rotor), which facilitate rapid speed changes, or high inertias (short shaft and large diameter rotor), which promote smooth rotation in the presence of load changes. Special induction motor designs are available, however, and are sometimes the preferred solution.

Table 8.1 Performance of open-loop and closed-loop field-oriented induction motor control schemes.

	Open-loop (without position feedback)	**Closed loop (with position feedback)**
Torque response (ms)	<0.5	<0.5
Speed recovery time (ms)	<20	<10
Min. speed with 100% torque (Hz)	0.8	Standstill
Max. torque at 1 Hz (%)	>175	>175
Speed loop response (Hz)	75	125

In the remainder of this section we give broad indications of the applicability of the various drive configurations that should prove helpful when looking at specific applications.

3.1 Open-loop (without speed/position feedback) induction motor drives

Open-loop induction motor drives are used in applications that require moderate performance (fans and pumps, conveyors, centrifuges, etc.). The performance characteristics of these drives are summarized below:

- There is moderate transient performance with full torque production down to approximately 2% of rated speed.
- Although a good estimate of stator resistance improves torque production at low speeds, the control system will work with an inaccurate estimate, albeit with reduced torque.
- A good estimate of motor slip improves the ability of the drive to hold the reference speed, but the control system will work with an inaccurate estimate, albeit with poorer speed holding.

The performance of open-loop induction motor drives continues to improve. Techniques for sensing the rotational speed of an induction motor without the need for a shaft-mounted speed or position sensor pervade the technical literature, and will in time find their way into some commercial drives.

3.2 Closed-loop (with speed/position feedback) induction motor drives

Induction motor drives with closed-loop control are used in similar applications to d.c. motor drives (cranes and hoists, winders and unwinders, paper and pulp processing, metal rolling, etc.). These drives are also particularly suited to applications that must operate at very high speeds with a high level of field weakening, for example spindle motors. The performance characteristics of these drives are summarized below.

- There is good dynamic performance at speeds down to standstill when position feedback is used.
- Only incremental position feedback is required. This can be provided with a position sensor or alternatively a sensorless scheme can be used. The transient performance of a sensorless scheme will be lower than when a position sensor is used and lower torque is produced at very low speeds.
- The robustness of the rotor makes induction motors particularly well suited to high-speed applications that require field weakening. The motor current reduces as the speed is increased and the flux is reduced.
- Induction motors are generally less efficient than permanent magnet motors because of their additional rotor losses.

3.3 When field orientation and direct torque control cannot be used

Field orientation and direct torque control both rely upon modeling the flux in the motor. If a single inverter is being used to feed more than one motor as in Figure 8.3, neither control strategy can be used.

In such systems individual motor control is not possible and the only practical form of control is to feed the motor group with an appropriate voltage source, of which the magnitude and frequency can be controlled. In fact, this is exactly the traditional form of *V/f* control which predominated in early inverters. The output frequency, and hence the no-load speed of the motor, is set by the speed reference signal, which was traditionally applied in the form of an analogue voltage (0–10 V) or current (4–20 mA), but is now a digital signal. In most automated applications the speed demand comes from a remote controller such as a PLC (programmable logic controller), while in simpler applications there will be a digital user interface on a control panel, or on the drive itself. The drive would

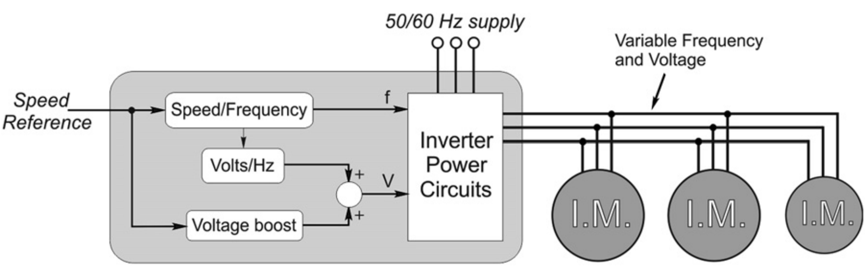

Figure 8.3 Simple *V/f* induction motor control strategy applied to a multi-motor system.

have the facility to adjust the V/f ratio. It would also have the facility to boost the voltage at low frequencies to compensate for the dominating influence of the stator winding resistance.

The fact that field orientation schemes use a vector modulator/PWM controller (see Figure 7.22) indicates that to adapt the field-oriented scheme for multi-motor drives is relatively simple: all that is required is to provide a sawtooth waveform of the appropriate frequency as input to the vector modulator (see Figure 7.21). Unfortunately, for direct torque control there is no such controller available and in order to provide multi-motor operation manufacturers employing this control strategy must also provide a PWM controller specifically to cater for such a load.

4. EFFECT OF INVERTER WAVEFORM AND VARIABLE SPEED ON THE INDUCTION MOTOR

It is often stated that standard 'off-the-shelf' a.c. motors can be used without problem on modern PWM inverters. While such claims may be largely justified, inverters do have some impact and limitations are inevitable. In particular, the harmonic components of the voltages and currents create acoustic noise; they always give rise to additional iron and copper losses; and they have other effects which are perhaps less obvious. In addition, the operation of a standard motor – with its cooling system designed to suit fixed-speed operation – can be a significant limitation, and this will also be considered here.

4.1 Acoustic noise

Acoustic noise can usually be reduced by selecting a higher switching frequency (at the cost of higher inverter losses). It is interesting to note that not all motors exhibit the same motor characteristic when connected to identical inverters. The differences are usually small, and relate primarily to the clamping of the iron in the stator of the motor. Certain switching frequencies may excite resonances in some motors often related to the tie bars between the end frames: these can be alarming but easily remedied by changing the switching frequency, or, if the tie bar is external to the motor frame, by adding a wedge to change the natural frequency of the bar.

4.2 Motor insulation and the impact of long inverter-motor cables

The PWM waveform has another very significant, but perhaps less obvious, effect, related to the very high rates of change of voltage (dV/dt), which results in transiently uneven voltage distribution across the motor winding, as well as short duration voltage overshoots because of reflection effects in the motor cable. This might damage the motor insulation.

In a modern 400 V power converter the d.c. link voltage is around 540 V, the voltage switches in a time of the order of 100 ns, and so *at the terminal of the drive* there is a dV/dt of over 5000 V/μs. The motor insulation will usually cope with this high dV/dt, but in practical installations the motor may be some distance, perhaps hundreds of meters, away from the drive, and in this case we also have to recognize that at these very high rates of change of voltage the cable behaves as a transmission line. Hence when the voltage edge reaches the motor terminals, a reflection occurs because the motor impedance is higher than that of the cable. Consequently, the motor terminal voltage sees an overshoot of theoretically up to twice the step voltage. Fortunately the inductance and the high-frequency resistance of the cable mitigate these effects somewhat, causing the actual rise time to increase so that in practice the voltage overshoot usually has little detrimental effect on the main motor insulation systems between phases and from phase to earth, which are traditionally designed to withstand overvoltage pulses. However, some low-cost (or very old) motors may have relatively poor inter-phase insulation, which can lead to premature insulation failure. Further, at each pulse edge the drive has to provide a pulse of current to charge the capacitance of the converter-motor cable, and in small drives, with very long motor cables, this charging current may, in extreme cases, exceed the rated current of the motor, and determine the rating of the required drive!

In case all this sounds alarming, the fact is that such problems are extremely unusual and usually associated with systems employing very old or very-low-cost motors with poor insulation systems, and/or with drive systems with rated voltages over 690 V. Naturally enough, the problem is more pronounced on medium voltage drives where it is not uncommon for dV/dt filters to be fitted between the inverter and the motor.

This phenomenon is now very well understood by reputable motor manufacturers. International standards on appropriate insulation systems have also been published, notably IEC 34-17 and NEMA MG1pt31.

4.3 Losses and impact on motor rating

Operation of induction motors on an inverter supply inevitably results in additional losses in the machine as compared with a sinusoidal utility supply. These losses fall into three main categories:

- Stator copper loss: This is proportional to the square of the r.m.s. current although additional losses due to skin effect associated with the high-frequency components also contribute. We have seen in Figure 8.2 that the motor current is reasonably sinusoidal and hence, as we would expect, the increase in copper loss is seldom significant.
- Rotor copper loss: The rotor resistance is different for each harmonic current present in the rotor due to skin effect (and is particularly pronounced in deep bar

rotors). Since the rotor resistance is a function of frequency, the rotor copper loss must be calculated independently for each harmonic. While these additional losses used to be significant in the early days of PWM inverters with low switching frequencies, in modern drives with switching frequencies above 3 kHz the additional losses are minimal.

- Iron loss: This is increased by the harmonic components in the motor voltage.

For PWM voltage source inverters using sinusoidal modulation and switching frequencies of 3 kHz or higher, the additional losses are therefore primarily iron losses and are generally small, resulting in a loss of motor efficiency by 1–2%. Motors designed for enhanced efficiency, e.g. to meet the IEC IE2/IE3 requirements or NEMA EPACT and premium efficiency requirements, also experience a proportionately lower increase in losses with inverter supplies because of the use of reduced-loss magnetic steels.

However, the increase in losses does not directly relate to a derating factor for standard machines since the harmonic losses are not evenly distributed through the machine. The harmonic losses mostly occur in the rotor and have the effect of raising the rotor temperature. Whether or not the machine was designed to be stator critical (stator temperature defining the thermal limit) or rotor critical clearly has a significant impact of the need for, or magnitude of, any derating. The cooling system (see below) is at least as important, however, and in practice it emerges that a standard motor may have to be derated by 5 or even 10% for use on an inverter supply.

Whereas a d.c. motor was invariably supplied with through ventilation provided by an auxiliary blower, to allow it to operate continuously at low speeds without overheating, the standard induction motor has no such provision. Having been designed primarily for fixed-frequency/full-speed operation, most induction motors tend to be totally enclosed (IP44 or IP54) with a shaft-mounted fan at the non-drive end running within a cowl to duct the cooling air over a finned motor body as shown in Figure 8.4. Note also the cast ‘paddles’ on the rotor endrings which provide internal air circulation and turbulence to assist with transmitting the heat from the rotor to the stator housing and from there to the atmosphere.

Thus although the inverter is capable of driving the induction motor with full torque at low speeds, continuous operation *at rated torque* is unlikely to be possible because the standard shaft-mounted cooling fan will be less effective at reduced speed and the motor will overheat. We should say, however, that for applications such as fans and pumps where the load torque is proportional to the cube of the speed, no such problems exist, but for many applications it is a significant consideration.

4.4 Bearing currents

Scare stories periodically appear in the trade press and journals relating to motor failures in inverter-fed a.c. motors. It should be said immediately that such failures are rare, and mainly associated with medium voltage systems.

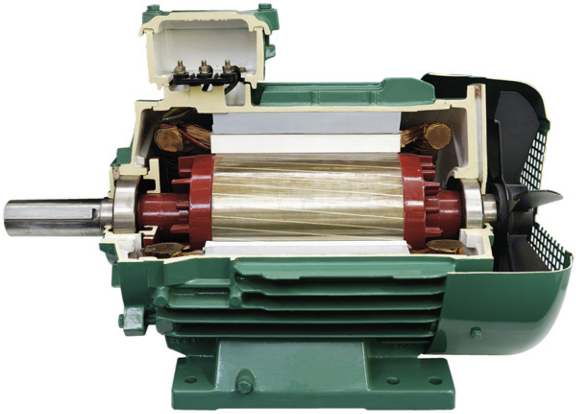

Figure 8.4 Typical shaft-mounted external cooling fan on an a.c. induction motor. *(Courtesy of Emerson – Leroy Somer.)* (See Plate 8.4)

With a balanced 3-phase sinusoidal supply the sum of the three stator currents in an a.c. motor is zero and there is no further current flow outside the motor. In practice, however, there are conditions which may result in currents flowing through the bearings of a.c. motors even when fed with a sinusoidal 50 or 60 Hz supply, and the risk is further increased when using an inverter supply. Any asymmetric flux distribution within an electrical machine can result in an induced voltage from one end of the rotor shaft to the other. If the bearing 'breakover voltage' is exceeded (the electrical strength of the lubricant film being of the order of 50 V) or if electrical contact is made between the moving and fixed parts of the bearing this will result in a current flowing through both bearings. The current is of low (often slip) frequency and its amplitude is limited only by the resistance of the shaft and bearings, so it can be destructive. In some large machines it is common and good practice to fit an insulated bearing, usually on the non-drive end, to stop such currents flowing.

Any motor may also be subject to bearing currents if its shaft is connected to machinery at a different ground potential from the motor frame. It is therefore important to ensure that the motor frame is connected through a low-inductance route to the structure of the driven machinery. This issue is well understood and with modern motors such problems are rare.

4.5 'Inverter grade' induction motors

Addressing the above potential hazards, induction motors bearing the name 'inverter grade' or similar are readily available. They would typically have reinforced insulation systems and have a thermal capacity for a constant torque operating range, often down to 30% of base speed, without the need for additional external cooling.

Further they would have options to fit thermocouples, a separate cooling fan (for very-low-speed operation) and a speed/position feedback device.

International standards exist to help users and suppliers in this complex area. NEMA MG1-2006, Part 31 gives guidance on operation of squirrel cage induction motors with adjustable-voltage and adjustable-frequency controls. IEC 60034-17 and IEC 60034-25 give guidance on the operation of induction motors with converter supplies, and design of motors specifically intended for converter supplies, respectively.

5. EFFECT OF THE INVERTER-FED INDUCTION MOTOR ON THE UTILITY SUPPLY

It is a common misconception to believe that the harmonic content of the motor current waveform and the motor power-factor are directly reflected on the utility supply, but this is not the case. The presence of the inverter, with its energy-buffering d.c. link capacitor, results in near unity power-factor as seen by the utility regardless of load or speed of operation, which is of course highly desirable. It is not all good news, however, so we now look at the impact of an inverter-fed drive on the utility.

5.1 Harmonic currents

Harmonic current is generated by the input rectifier of an a.c. drive. The essential circuit for a typical a.c. variable-speed drive is shown in Figure 8.1. The utility supply is rectified by the diode bridge, and the resulting d.c. voltage is smoothed by the d.c. link capacitor and, for drives rated typically at over 2.2 kW, the d.c. current is smoothed by an inductor in the d.c. circuit. The d.c. voltage is then chopped up in the inverter stage, which uses PWM to create a sinusoidal output voltage of adjustable voltage and frequency.

While small drive ratings may have a single-phase supply, we will consider a 3-phase supply. We see from Figure 8.5 that current flows into the rectifier as a series of pulses that occur whenever the supply voltage exceeds that of the d.c. link, which is when the diodes start to conduct. The amplitude of these pulses is much larger than the fundamental component, which is shown by the dashed line.

Figure 8.6 shows the spectral analysis of the current waveform in Figure 8.5.

Note that all currents shown in spectra comprise lines at multiples of the 50 Hz utility frequency. Because the waveform is symmetrical in the positive and negative half-cycles, apart from imperfections, even-order harmonics are present only at a very low level. The odd-order harmonics are quite high, but they diminish with increasing harmonic number. For the 3-phase input bridge there are no triplen harmonics, and by the 25th harmonic the level is negligible. The frequency of this harmonic for a 50 Hz supply is 1250 Hz, which is in the audio frequency part of the

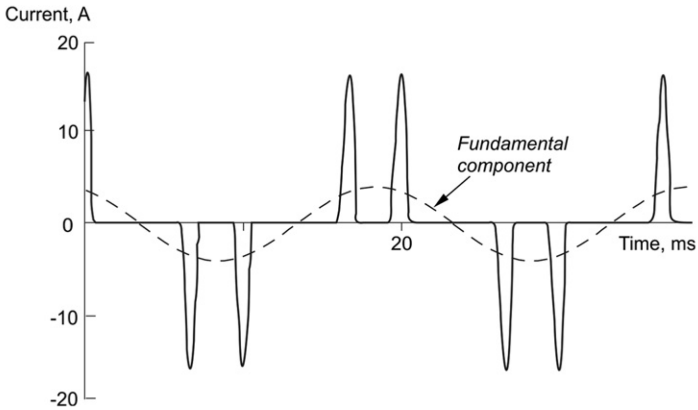

Figure 8.5 Typical current from utility supply for a 1.5 kW 3-phase drive.

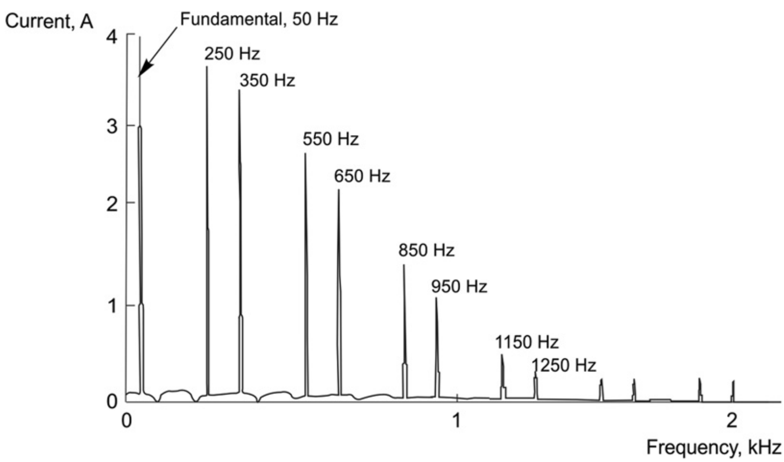

Figure 8.6 Harmonic spectrum of the current waveform shown in Figure 8.5.

electromagnetic spectrum and well below the radio-frequency part, which is generally considered to begin at 150 kHz. This is important, because it shows that supply harmonics are low-frequency effects, which are quite different from radio-frequency EMC effects. They are not sensitive to fine details of layout and screening of circuits, and any remedial measures which are required use conventional electrical power techniques such as tuned power-factor capacitors and phase-shifting transformers. This should not be confused with the various techniques used to control electrical interference from fast switching devices, sparking electrical contacts, etc.

The actual magnitudes of the current harmonics depend on the detailed design of the drive, specifically the values of d.c. link capacitance and, where used, d.c. link inductance, as well as the impedance of the utility system to which it is connected, and the other non-linear loads on the system.

We should make clear that industrial problems due to harmonics are unusual, although with the steady increase in the use of electronic equipment, they may be more common in the future. Problems have occurred most frequently in office buildings with a very high density of personal computers, and in cases where most of the supply capacity is used by electronic equipment such as drives, converters and uninterruptible power supplies (UPS).

As a general rule, if the total rectifier loading (drives, UPS, PCs, etc.) on a power system comprises less than 20% of its current capacity then harmonics are unlikely to be a limiting factor. In many industrial installations the capacity of the supply considerably exceeds the installed load, and a large proportion of the load is not a significant generator of harmonics – uncontrolled (direct-on-line) induction motors and resistive heating elements generate minimal harmonics.

If rectifier loading exceeds 20% then a harmonic control plan should be in place. This requires some experience and guidance can often be sought from equipment suppliers. The good news is that if it is considered that a problem will exist with the estimated level of harmonics then there are a number of options available to reduce the distortion to acceptable levels.

A.C. drives rated over 2.2 kW tend to be designed with inductance built into the d.c. link and/or the a.c. input circuit. This gives the better supply current waveform and dramatically improved spectrum as shown in Figures 8.7 and 8.8, respectively, which are again for a 1.5 kW drive for ease of comparison with the previous illustrations. (In this case the inductance in each line is specified as '2%', which means that when rated fundamental current flows in the line, the volt-drop across the inductor is equal to 2% of the supply voltage.) Note the change of vertical

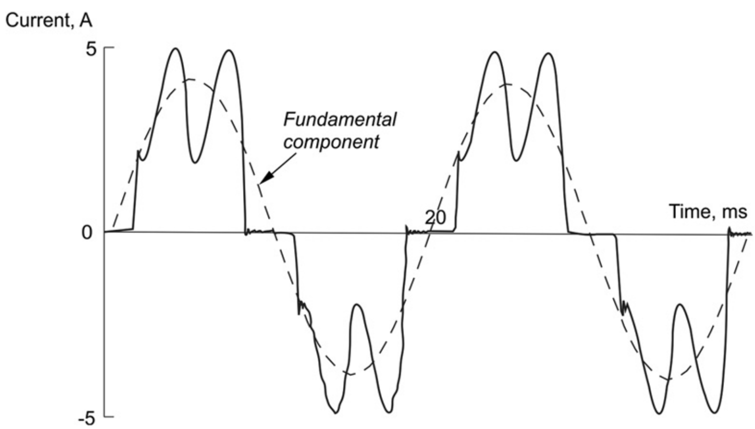

Figure 8.7 Input current waveform for the 3-phase 1.5 kW drive with d.c. and 2% a.c. inductors.

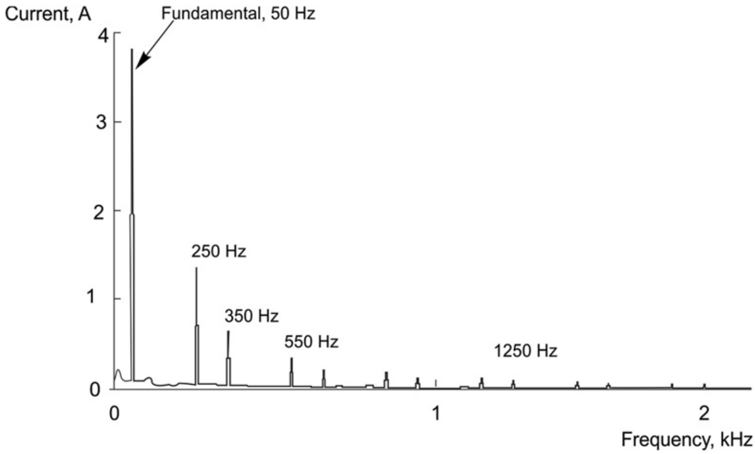

Figure 8.8 Harmonic spectrum of the improved current waveform shown in Figure 8.7.

scale between Figures 8.5 and 8.7, which may tend to obscure the fact that the pulses of current now reach about 5 A, rather than the 17 A or so previously, but the fundamental component remains at 4 A because the load is the same. (Remember that while we have just demonstrated the tremendous improvement in supply harmonics achieved by adding d.c. link inductance to a 1.5 kW drive, standard drives would rarely be manufactured with any inductance because while the harmonic spectrum looks worrying, the currents are at such a low level that they would rarely cause practical problems.)

Standard 3-phase drives rated up to about 200 kW tend to use conventional 6-pulse rectifiers. At higher powers, it may be necessary to increase the pulse number to improve the supply-side waveform, and this involves a special transformer with two separate secondary windings, as shown for a 12-pulse rectifier in Figure 8.9.

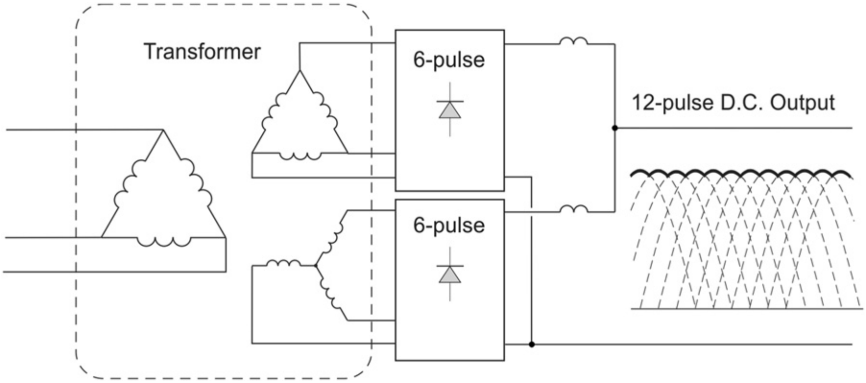

Figure 8.9 Basic 12-pulse rectifier arrangement.

The voltages in the transformer secondary star and delta windings have the same magnitude but a relative phase shift of 30°. Each winding has its own set of six diodes, and each produces a 6-pulse output voltage. The two outputs are generally connected in parallel, and, because of the phase shift, the resultant voltage consists of 12 pulses of 30° per cycle, rather than the six pulses of 60° shown, for example, in Figure 2.13.

The phase shift of 30° is equivalent to 180° at the fifth and seventh harmonics (as well as 17, 19, 29, 31, etc.), so that flux and hence primary current at these harmonics cancels in the transformer, and the resultant primary waveform therefore approximates well to a sinusoid, as shown for the 150 kW drive in Figure 8.10.

The use of drive systems with an input rectifier/converter using PWM which generates negligible harmonic current in the utility supply is becoming increasingly common. This also permits the return of power from the load to the supply, and is discussed later in section 7.

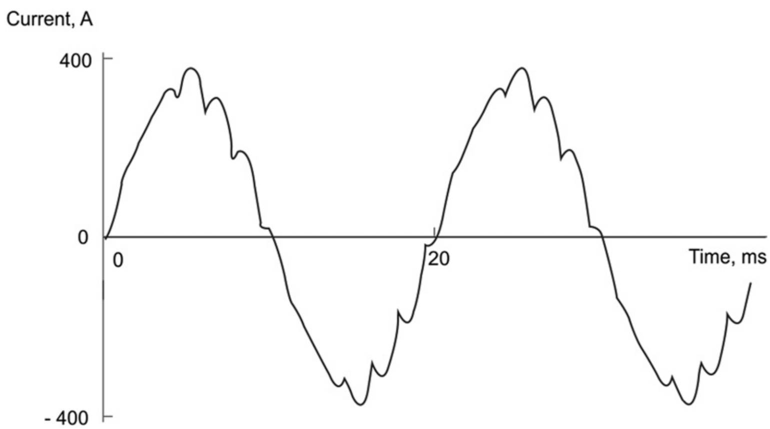

Figure 8.10 Input current waveform for 150 kW drive with 12-pulse rectifier.

5.2 Power-factor

The power-factor of an a.c. load is a measure of the ratio of the average power to the product of r.m.s. current and voltage, and is given by:

$$\text{Power-factor} = \frac{\text{Average power (W)}}{\text{r.m.s. volts} \times \text{r.m.s. amps}}$$

With a sinusoidal supply voltage and a linear load the current will also be sinusoidal, with a phase-shift of ϕ with respect to the voltage. The power is then given by the simple expression

$$W = VI \cos\phi,$$

where V and I are r.m.s. values (which are equal to the peak of the sinusoid divided by $\sqrt{2}$), and so in this case the power-factor is equal to cos ϕ. Clearly the maximum possible power-factor is 1.

Unfortunately, in power electronic circuits either the voltage or the current or both are non-sinusoidal, so there is no simple formula for the r.m.s. values or the mean power, all of which have to be found by integration of the waveforms. There is therefore no simple formula for the power-factor, but frequent use is made of a related quantity known as the fundamental power-factor, given by

$$\text{Fundamental power-factor} = \frac{\text{Average power}}{\text{Fundamental r.m.s. volts} \times \text{Fundamental r.m.s. amps}}$$

The influence of the harmonics in the non-sinusoidal waveforms causes the actual power-factor to be lower than the fundamental power-factor, so users should be aware that when suppliers quote the power-factor of a drive they are usually ignoring the harmonic currents, and quoting cos ϕ, the fundamental power-factor.

It may be worth reminding readers who are not familiar with industrial energy tariffs why maximizing the power-factor is important. All industrial users pay primarily for the energy used, which depends on the integrated total of the product of power and time, but most are also penalized for drawing the power at a low power-factor (because the currents are higher and therefore switchgear and cables have to be larger than would otherwise be necessary). In addition, there may be a penalty related to the maximum volt-ampere product in a specified period, so again a high power-factor is desirable.

Fortunately, for the diode bridge, which is the most common form of rectifier in a commercial a.c. drive, cos ϕ is close to unity for all speed and load conditions. To illustrate this, we can consider a typical 11 kW induction motor operating at full-load, connected either directly to the mains supply or through an a.c. variable-speed drive. Comparative figures are given in Table 8.2.

Table 8.2 Comparative figures for a typical 11 kW induction motor operating at full-load.

At supply terminals	DOL motor	Motor via a.c. drive	Notes on drive parameters
Voltage (V)	400	400	
R.m.s. current (A)	21.1	21.4	No significant change
Fundamental current (A)	21.1	18.8	Reduced because magnetizing current is not drawn directly from the utility supply
Fundamental power factor (cos ϕ)	0.85	0.99	Improved because input rectifier current is in phase with supply voltage
Power (W)	12,440	12,700	Slight increase at full-load due to drive losses

A typical PWM induction motor drive improves the power-factor as compared with a direct-on-line motor because it reduces the requirement of the supply to provide the magnetizing current for the motor, but in return generates harmonics. Power consumption at full-load is slightly increased due to losses of the drive.

6. INVERTER AND MOTOR PROTECTION

We have stressed before that power semiconductors are notoriously intolerant of excess current, and so even in the earliest drives of this type, current was measured in order to trip the drive when a simple current threshold was exceeded and before damage to the inverter could be done. Some protection schemes would also sense high currents and reduce the applied frequency to reduce the current.

The stored energy in the drive and motor inductances and capacitances also needs to be handled without inducing voltages or currents which can damage the system components. As previously mentioned, the basic power circuit is not inherently capable of regenerating energy back into the supply, and, when a braking duty results in energy flow into the d.c link, a 'dump resistor' (see section 7) of the right thermal rating needs to be provided in order to limit the circuit voltages.

Motor protection also requires current measurement, but here it is thermal protection of the motor that is of concern. A very approximate indication of the losses or heating effect in the motor is obtained by monitoring the product of the square of the motor current times time. This so-called i^2t protection is still referred to as motor thermal protection in drives, though many of the thermal algorithms now employed are very much more complex and accurate than their primitive predecessors.

Modern commercial drives include extensive internal protection systems as well as thermal motor modeling systems, but such drives are designed for a multiplicity of applications and motor designs and so must be configured during installation. Where multiple motors are fed from a single inverter (as described in section 3) each motor must have individual thermal trips, because the fault current of an individual motor may not be significant when a large number of motors are connected to the same inverter.

7. ALTERNATIVE CONVERTER TOPOLOGIES

7.1 Braking

The inverter (motor converter) that forms the output stage of the popular voltage source a.c. motor drives described above inherently allows the motor to be controlled in either direction of rotation and also allows power to flow in either direction between the d.c link and the motor, as shown in Figure 8.1.

The simple diode rectifier that is often used between the utility supply and the d.c. terminals of the inverter does not allow power to flow back into the supply. Therefore an a.c. motor drive based on this configuration cannot be used where power is required to flow from the motor to the utility supply. On the face of it, this limitation might be expected to cause a problem in almost all applications when shutdown of a process is involved and the machine being driven by the motor has to be braked by the motor. The kinetic energy has to be dissipated, and during active deceleration power flows from the motor to the d.c. link, thereby causing the voltage across the d.c. link capacitor to rise to reflect the extra stored energy.

To prevent the power circuit from being damaged, d.c. link overvoltage protection is included in most industrial drive control systems. This shuts down the inverter if the d.c. link voltage exceeds a trip threshold, but this is at best a last resort. It may be possible to limit the voltage across the d.c. link capacitor by restricting the energy flow from the motor to the d.c. link by controlling the slowdown ramp, but again this is not always acceptable to the user.

To overcome the limited deceleration possible with the scheme described above, the diode rectifier can be supplemented with a d.c. link braking resistor circuit as shown in Figure 8.11.

In this arrangement, when the d.c. link voltage exceeds the braking threshold voltage, the switching device is turned on. Provided the braking resistor has a low enough resistance to absorb more power than the power flowing from the inverter, the d.c. link voltage will begin to fall and the switching device will be turned off again. In this way the on and off times are automatically set depending on the power from the inverter, and the d.c. link voltage is limited to the braking threshold. To limit the switching frequency of the braking circuit, appropriate hysteresis is included in its control.

A braking resistor circuit is used in many applications where it is practical and acceptable to dissipate stored kinetic energy in a resistor, and hence there is no longer a limit on the dynamic performance of the system.

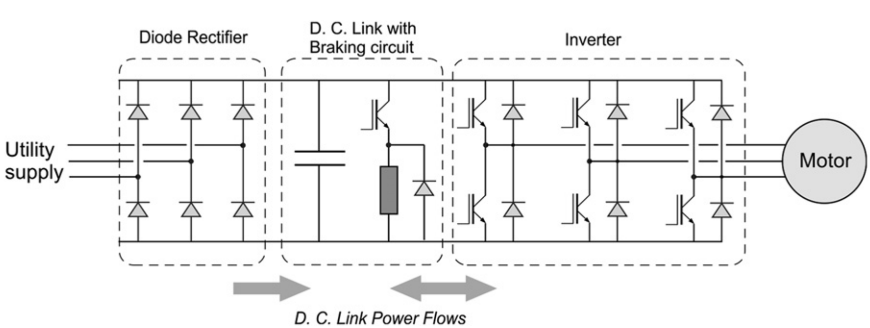

Figure 8.11 Induction motor drive with a braking resistor circuit.

7.2 Active front end

The diode rectifier does not allow power flow from the d.c. link to the supply. There are various circuits that can be used to recover the load energy and return it to the supply, one of which is the active rectifier shown in Figure 8.12, in which the diode rectifier is replaced with an IGBT inverter.

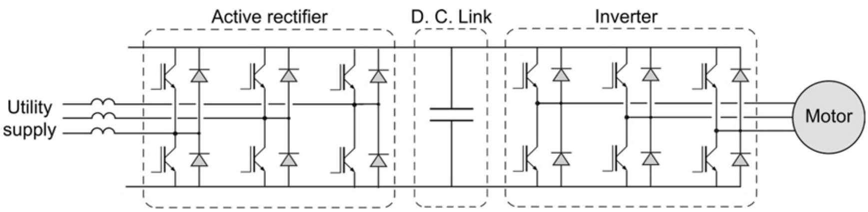

Figure 8.12 Induction motor drive with active front-end rectifier.

The labeling of the two converters shown in Figure 8.12 reflects their functions when the drive is operating in its normal 'motoring' sense, but during active braking (or even continuous generation) the converter on the left will be inverting power from the d.c. link to the utility supply, while that on the right will be rectifying the output from the induction generator.

This arrangement if often referred to as an 'active front end'. Additional input inductors are usually required to limit the unwanted currents generated by the switching action of the inverter, but by using PWM control the front-end converter can be controlled to give near sinusoidal current waveforms with a power-factor close to unity, so that the complete system presents a near perfect load to the utility supply.

An active rectifier is used where full four-quadrant operation and good quality input waveforms are required. Cranes and elevators, engine test rigs and cable laying ships are some applications where an active rectifier may be appropriate. The performance characteristics of this configuration are summarized below:

- Power flow between the motor and the mains supply is possible in both directions, and so this makes the drive more efficient than when a braking resistor is used.
- Good quality input current waveforms, i.e. low harmonic distortion of the utility supply.
- Supply power-factor can be controlled to near unity.

Clearly, however, an active rectifier is more expensive than a simple diode rectifier and a brake resistor.

7.3 Multi-level inverter

The inverter drive circuit described above is widely used in drive systems rated to around 2 MW at voltages from 400 V but is more usually seen at higher voltages including in medium voltage inverters (2–11 kV). At higher powers, switching the current in the devices proves more problematic in terms of the losses, and so switching frequencies have to be reduced. At higher voltages the impact of the rate of change of voltage on the motor insulation causes switching times to be extended and hence losses increase. In addition, while higher voltage power semiconductors are available, they tend to be relatively expensive and so commercial consideration is given to the series connection of devices, but here voltage sharing between devices is a problem due to the disproportionate impact of any small difference between switching characteristics.

Multi-level converters have been developed which address these issues. One example from among many different topologies is shown in Figure 8.13.

In this example four capacitors act as potential dividers to provide four discrete voltage levels, and each arm of the bridge has four series-connected IGBTs with anti-parallel diodes. The four intermediate voltage levels are connected by means of clamping diodes to the link between the series IGBTs. To obtain full voltage between the outgoing lines all four devices in one of the upper arms are switched on, together with all four in a different lower arm, while for say half voltage only the bottom two in an upper arm are switched on. The quarter and three-quarter levels can be selected in a similar fashion, and in this way a good 'stepped' approximation to a sinewave can be achieved.

Clearly there are more devices turned on simultaneously than in a basic inverter, and this gives rise to an unwelcome increase in the total conduction loss. But this is offset by the fact that because the VA rating of each device is smaller than that of the equivalent single device, the switching loss is much reduced.

For the inverter in Figure 8.13 the stepped waveform will have four positive, four negative and a zero level(s). The oscilloscope trace in Figure 8.14 is from a six-level

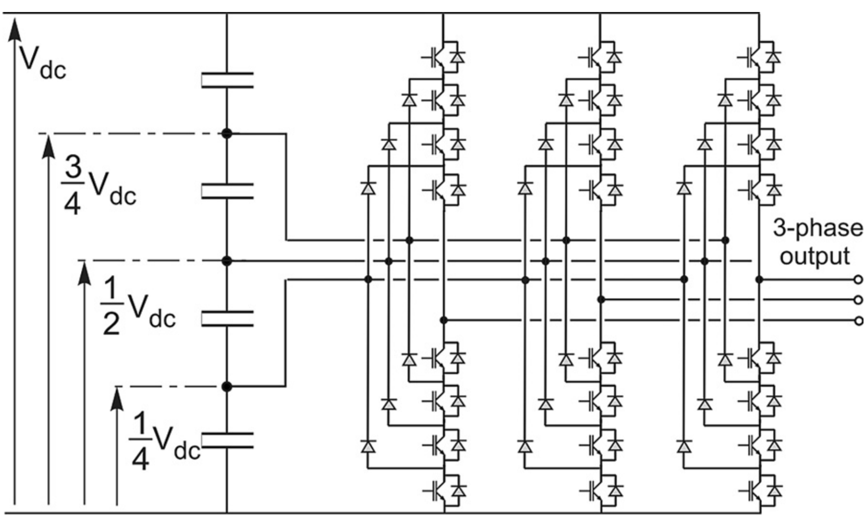

Figure 8.13 Multi-level inverter (motor converter only shown).

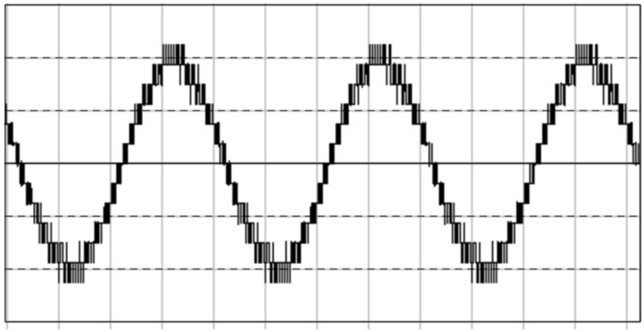

Figure 8.14 Six-level inverter output voltage waveform.

inverter, and clearly displays the six discrete levels. A sophisticated modulation strategy is required in order not only to achieve a close approximation to a sinewave, but also to ensure that the reduction of charge (and voltage) across a capacitor during its periods of discharge period is compensated by a subsequent charging current.

Multi-level inverters have advantages over the conventional PWM inverter:

- Higher effective output switching frequency for a given PWM frequency. Smaller filter components are required.
- Improved EMC due to lower dV/dt at output terminals – less stress on the motor insulation.
- Higher d.c. link voltages achievable for medium voltage applications due to voltage sharing of power devices within each inverter leg.

However, there are drawbacks:

- The number of power devices is increased by at least a factor of two; each IGBT requires a floating gate drive and power supply; and additional voltage clamping diodes are required.
- The number of d.c. bus capacitors may increase, but this is unlikely to be a practical problem as lower voltage capacitors in series are likely to be the most cost-effective solution.
- The balancing of the d.c. link capacitor voltages requires careful management/control.
- Control/modulation schemes are more complicated.

For low-voltage drives (690 V and below) the disadvantages of using a multi-level inverter tend to outweigh the advantages, with even three-level converters being significantly more expensive than conventional topologies. However, multi-level converters are entering this market, so the situation may change.

7.4 Cycloconverter

The operation of the cycloconverter was discussed in Chapter 2, so here – for completeness – we need only to recap the main features and areas of application.

The drive is inherently four quadrant; its maximum output frequency is limited to approximately half the supply frequency by considerations related to harmonics in the motor currents and torque, stability, and dimensions of the drive components. It is thus suited to large low-speed drives, where motors can be made with high pole-number and thus low synchronous speed. The complexity of the drive means that only high power systems (>>1 MW), or specialized applications (e.g. conveyor drives for use in hazardous environments) are economic. They are used on large ball mills, mine winders, etc.

Due to the modulation of the converter firing angles, the harmonic content of the utility supply is complex and designs for appropriate harmonic filters become somewhat involved.

7.5 Matrix converter

Recently, much attention has been focused in technical journals on the matrix converter, the principle of which is shown in Figure 8.15.

The matrix converter operates in much the same way as a cycloconverter. For example, if we assume that we wish to synthesize a 3-phase sinusoidal output of a known voltage and frequency, we know at every instant what voltage we want, say between the lines A and B, and we know what the voltages are between the three incoming lines. So we switch on whichever pair of the A and B switches connects us to the two incoming lines whose voltage at the time is closest to the desired output line-to-line voltage, and we stay with it whenever it offers the best approximation to what we want. As soon as a different combination of switches would allow us to hook onto a more appropriate pair of input lines, the switching pattern changes.

Because there are only three different incoming line-to-line voltages to choose from, we cannot expect to synthesize a decent sinusoidal waveform with simple switching, so in order to obtain a better approximation to a sinusoidal waveform we must use chopping. This means that the switches have to be capable of operating at much higher frequencies than fundamental output frequency, so that switching loss becomes an important consideration.

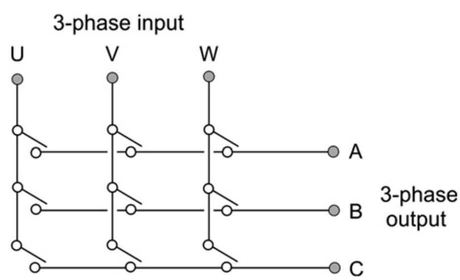

Figure 8.15 Matrix converter.

While the basic circuit is not new, recent advances in power devices offer the potential to overcome many of the drawbacks inherent in the early implementations that used discrete IGBTs due to the lack of suitable packaged modules. On the other hand, the fact that the output voltage is limited to a maximum of 86% of the utility supply voltage means that applications in the commercial industrial market, where standard motors predominate, remain largely problematic. However, there appear to be good prospects in some aerospace applications and possibly in some specific areas of the industrial drives market, notably integrated motors (where the drive is built into the motor, the windings of which can therefore be designed to suit the voltage available).

7.6 PWM voltage source inverter with small d.c. smoothing capacitance

For a 3-phase rectifier, the d.c. link capacitance value can be much reduced provided that the modulation strategy in the inverter is adapted to compensate for the resulting voltage ripple. The input current waveform is then improved, as compared with the very peaky waveform seen in Figure 8.5. This is a useful technique for cost-sensitive applications where harmonic current is a critical factor. However, there are disadvantages resulting from the reduced capacitance, in that the d.c. link voltage becomes more sensitive to transient conditions, both from rapid variations in load and from supply disturbances. This approach is therefore most attractive in applications where the load does not exhibit highly dynamic behavior.

Another practical factor is that the capacitor now has a disproportionately high ripple current, so that a conventional aluminum electrolytic capacitor cannot be used and a more expensive capacitor with a plastic dielectric is required.

Converter circuits with zero d.c. link capacitance exist in the literature. They have no energy storage, so it is evident that this topology is another form of matrix converter, with the output voltage being made up of 'chunks' of the utility supply waveform.

7.7 Current source induction motor drives

The majority of inverters used in motor drives are voltage source inverters (VSIs), in which the output voltage to the motor is controlled to suit the operating conditions of the motor. Current source inverters (CSIs) are still sometimes used, particularly for high-power applications, and warrant a brief mention.

The forced-commutated current-fed induction motor drive, shown in Figure 8.16, was strongly favored for single motor applications for a long period, and was available at power levels in the range 50–3500 kW at voltages normally up to 690 V. High-voltage versions at 3.3/6.6 kV were also developed but they have not proved to be economically attractive. Today it is not seen as having merit and

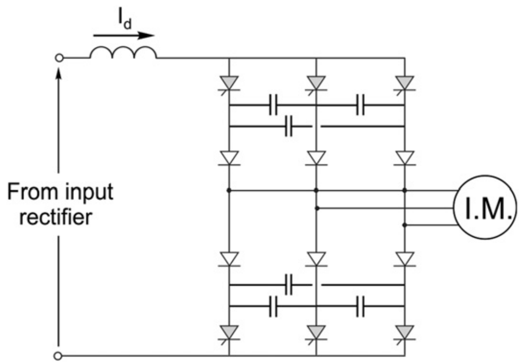

Figure 8.16 Forced-commutated current-fed induction motor drive (motor converter only shown).

has virtually disappeared from the portfolios of most companies. A brief description is included here for interest only.

The d.c. link current I_d, taken from a 'stiff' current source (usually in the form of a thyristor bridge and a series inductor in the d.c. link), is sequentially switched at the required frequency into the stator windings of the induction motor. The capacitors and extra series diodes provide the mechanism for commutating the thyristors by cleverly exploiting the reversal of voltage resulting from resonance between the capacitor and the motor leakage reactance. The resultant motor voltage waveform is, perhaps somewhat surprisingly, approximately sinusoidal apart from the superposition of voltage spikes caused by the rise and fall of machine current at each commutation.

The operating frequency range is typically 5–60 Hz, the upper limit being set by the relatively slow commutation process. Below 5 Hz, torque pulsations can be problematic but PWM control of the current can be used at low frequencies to ease the problem.

This system was most commonly used for single motor applications such as fans, pumps, extruders, and compressors, where very good dynamic performance is not necessary and a supply power-factor which decreases with speed is acceptable.