VARIABLE SPEED ELECTRIC DRIVES - CHARACTERISTICS AND APPLICATIONS

D S Henderson

Napier University, UK.

INTRODUCTION

In all of the industrialised nations, the majority of non-domestic electricity consumption is by electric motors. In the UK for example, 65% of the electricity used by industry powers motors, whilst 23% of the electricity used by commerce is for motors. Any industry which wishes to improve its profitability by reducing electricity consumption must achieve efficient use of motors.

A second force behind the increasing attention being paid to efficient use of motors is that of the environmental effects from the emissions from generating powerstations. In a typical fossil-fuel powered power station the generating efficiency is around 35%. Coupled with transmission, distribution and then the electrical and mechanical losses in a drive system, the net effect is that 100 kWh of fuel input can result in only 11 kWh of useful output energy.

The agreements made at the Earth Summit in Rio have resulted in major international commitments to reduce CO_2 emissions. This has resulted in proposals to legislate for minimum efficiency standards for motors and motor driven plant in some countries, e.g. Canada, the US and Denmark.

The majority of installed motors are a.c. induction motors, for many years the first choice due to its low cost, low maintenance and reliability. The most common applications are in the movement of fluids, (liquid or gas). Also, over 50% of the motor capacity drives either fans or pumps and so the costs of fluid movement are very high. In the UK alone, these costs are estimated at over £2,000 Million per annum.

In many cases, the energy used to move fluids is wasted due to poor design and operation of the system. Most systems are designed to deliver a higher volume of fluid than is actually required. Flow control is used to match the actual demand, traditionally by introducing a mechanical restriction. Examples are outlet damper fans or throttle valves on pumps.

The energy efficient alternative is speed control. Replacing mechanical methods of flow control with speed control offers an energy and cost effective means of controlling flow. Secondary benefits, including quality and reliability, often arise as a consequence of the use of a speed control system.

SPEED CONTROL

Speed control can save energy in flow control applications as a consequence of the laws which govern centrifugal fans and pumps. These laws determine that the flow is proportional to the speed and that the power absorbed by a centrifugal fan or pump is proportional to the cube of the speed. Hence a 20% reduction in flow gives rise to (nearly) a 50% reduction in power.

Speed control can be achieved by a number of means. Coupling control, variable speed motors and electronic speed control are the three main categories. The former of these methods uses a fixed speed motor which drives a coupling which can alter the speed of the load. These are described in detail in a separate paper of this colloquium. The synchronous speed equation provides two variables, number of poles and frequency, which give rise to the other two categories.

Variable speed motors are usually induction motors in which the number of motor poles can be altered by external switchgear, and hence change the speed of the motor. Common pole configurations are 2:4 or 4:6 giving rise to two discrete operating speeds. This is useful for applications where the flow is to be either one value or another, e.g. day and night flows. This is a simple and low cost solution to the energy efficiency problem where sophisticated control is unnecessary.

Electronic speed control, performed by plant referred to as Variable Speed Drives rely on the control of the motor supply frequency for their operation. The basic concept of these drives, Figure 1, is that a rectifier converts the fixed frequency grid supply to d.c. A d.c. link stage smoothes the rectified output to a stable d.c. voltage (or current). This d.c. is then inverted to provide a synthesised a.c. waveform at the motor terminals. The frequency and power of the a.c. supply delivered to the motor is controlled by a microprocessor built in to the inverter.

This paper introduces the most common types of variable speed drive systems presently available; and for each type reviews the method of operation, lists the principle characteristics and highlights the principle applications.

INVERTER DRIVES

The term “inverter” nearly always implies a static switching system which synthesises a varying frequency and controlled amplitude three phase system from a direct current or voltage supply. The simplest from of such a system is shown in Figure 2 where six switches are arranged in a bridge pattern across a d.c. supply. In theory it is possible to adopt any switching sequence of these devices, but in practice there are constraints necessary to avoid a short-circuit on the d.c. side. In addition, as the inverter load is usually an inductive (motor) one, freewheel diodes are required in parallel with each device to protect against overvoltages.

A common switching sequence results in the so-called “quasi-square” waveform shown in Figure 3. Any desired three-phase output frequency can be obtained within the switching rate capabilities of the devices used, however control of the output amplitude requires further control action.

The source of the d.c. input to the inverter is the starting point for describing the different inverter types. If an uncontrolled diode bridge rectifier is used, the d.c. output is a substantially constant voltage. This has the advantage that a battery can be used as a standby power source. The disadvantage is that if control of the inverter output voltage is required, then this has to be done separately. If a controlled rectifier is used, then the d.c. voltage can be varied by firing angle control of the input bridge, and reverse power flow is also possible (if *fully* controlled).

There are two approaches to the control of the d.c. link; either voltage control or current control. These approaches give rise to the two fundamental inverter types; current-source inverters and voltage-source inverters.

Current source inverters (CSI’s)

Method of operation

In the current source inverter, a controlled d.c. link current is switched between the motor windings in a sequential pattern, and the load voltages establish themselves depending on the particular speed, torque and rotational direction of the motor. The “hard” d.c. link current is maintained by the presence of a large inductor in the d.c. link, Figure 4c.

Characteristics and applications

Natural commutation of current from one switch to another is relatively slow and so simple forced commutation circuits are often used. Regenerative braking is possible through firing angle control of the devices in the inverter and the rectifier, without any additional circuits.

Until recently, the fact that line-frequency thyristors with simple commutation circuits were suitable for the inverter switches was an important asset of CSI drives. With the availability of higher power rated controllable switches, nowadays CSI drives are used mostly in very large power applications only. Drives are available with converter voltages of up to 10 kV, rated currents up to 2000 A and rated powers of up to 60 MW.

Voltage source inverters (VSI’s)

Method of operation

In the voltage source inverter, a firm d.c. link *voltage* is switched between the motor windings, and the load currents establish themselves depending on the load impedance of the motor. The d.c. link voltage is maintained by the presence of a capacitor in the d.c. link, Figure 4b.

Characteristics and applications

The polarity of the d.c. link voltage can not be reversed, and so regeneration requires the reversal of the link current. In order to recover such regenerative power, it is thus necessary to deploy a four quadrant converter (switch-mode or back-to-back) at the input bridge stage.

The majority of inverter drives used nowadays are fundamentally of the VSI type. Different methods of control of the output voltage and different speed control techniques give rise to a multitude of overall drive topologies.

The simplest of these is the quasi-square wave or six-step inverter. Each inverter switch is on for half a cycle and a total of three switches are on at any one time. Control of the output voltage is achieved by varying the d.c. link voltage. This can be done either with a d.c chopper circuit in the link itself, or through controlled rectification at the input bridge. Low-order harmonics are a feature of this drive which gives rise to operational problems such as torque pulsations and noise at low speeds. This type of drive has been superseded in performance several times over and is rarely applied nowadays.

PWM inverters

Method of operation
A better approach to the control of the output voltage is the PWM (Pulse Width Modulation) technique. In this system, the output voltage is controlled within the inverter, resulting in the deployment of a cheaper and simpler uncontrolled diode rectifier at the front end, Figure 4a. The inverter switches are controlled in such a way as to produce a series of short positive pulses of constant amplitude followed by a series of short negative pulses. The mark-space ratio of these pulses is arranged to produce an average which approaches a sine wave of variable peak amplitude, Figure 5. The duration of the positive and negative sequences can be controlled and hence the output frequency and voltage can thus be varied independently.

Characteristics and applications
The pulse width and spacing are designed so as to eliminate the low order harmonics. Consequently operation at low speeds is much improved when compared with the quasi-square wave inverter. This method does not use feedback in respect of speed or rotor position and is effectively open-loop control. Speed holding accuracy is typically in the order of 1 - 3 %.

The PWM inverter drive is available for three phase drives from 5 kW ratings up to several thousand kW. Converter voltage and output current are available at the 660 V, 2000 A or at the 6600 V, 1200 A levels. As such, this drive offers a low cost and simple solution to control of a.c. motors. By implication it is best suited to applications which do not require high levels of accuracy or precision, such as fans or pumps.

VECTOR CONTROL DRIVES

Inevitably there must be comparison with the performance of the d.c. drive. Initially d.c. drives were used for variable speed control because they could easily achieve good torque and speed response with high accuracy. These parameters are controlled directly through control of the armature current. In addition, the d.c. motor generates maximum torque through field orientation whereby the field is always maintained (by the commutator) at right angles to the field created by the armature winding.

The a.c. drive suffers from the fact that the controlling parameters are voltage and frequency. Consequently it has relatively poor transient performance, especially in applications where rapid response to changes in speed or load are required, e.g. in rolling mills.

To emulate the field orientation process of the d.c. motor, the flux vector drive needs to know the spatial angular position of the rotor flux inside the a.c. induction motor. This sophisticated control is available in the form of the *vector* or *field orientated* control and has effectively become the present day “industry standard” in respect of inverter drives.

Method of operation
The underlying principle of vector control, Figure 6, is to separate out the component of the motor current responsible for producing the torque and the component responsible for producing the flux in such a way that they are magnetically decoupled, and then control each independently. Information about the rotor status is obtained by feeding back rotor speed and angular position relative to the stator field by means of a pulse encoder, a closed-loop speed control system. In addition, the motor’s electrical characteristics are mathematically modelled within the microprocessor control system of the drive. The outputs from this control system are the controlling variables of voltage, current and frequency which are fed via a modulator to the motor. It is noted that the *torque* is therefore controlled *indirectly*.

Characteristics and applications
Vector control offers good torque response, achieving full torque at zero speed and a performance approaching that of a d.c. drive. Speed holding accuracy can be in the order of 0.02% depending on the encoder selection. This high-level performance is achieved at the expense and the complexity of a feedback device and the modulator circuitry.

Power outputs from 5 kW up to 890 kW are typically available at converter voltages of up to 480 V and rated currents of up to 1130 A. Paper mills, steel mills, cranes/hoists etc. represent the type of applications to which this sophisticated drive is best suited.

DIRECT TORQUE CONTROL DRIVES

Method of operation
Torque vector controlled drives are capable of controlling the stator flux and torque more accurately than vector controlled drives, while the controller complexity is reduced considerably. Field orientation is achieved without rotor speed or position feedback using advanced motor theory to calculate the motor torque directly without using modulation. The controlling variables are motor magnetising flux and motor torque.

The measured motor current and voltage are inputs to an adaptive motor model which produces torque and flux values which are used as feedback signals for the controller, Figure 7. The states of the power switches are determined directly by the measured and the reference torque and flux signals. Motor torque and flux comparitors compare the actual values to the reference values. The outputs from these comparitors are fed to an optimum pulse selector which determines the inverter switch positions. In so far as the voltage and current are subsequently effected by the new switch positions, closed loop control is operative, however in terms of *speed control*, the basic system is an open-loop one.

Characteristics and applications

Open loop speed control matches that of closed loop flux vector control. Through the use of a feedback encoder, closed loop speed control can be provided with improved accuracy, a value of 0.01% being quoted by the manufacturers.

Drives with rated output powers in the range 2.2 kW to 315 kW are presently available. Again this type of drive is best suited to high performance applications such as mixers, conveyors, lifts, cranes and winders, as well as fans and pumps.

SYNCHRONOUS DRIVES

All of the drives previously described have been designed for operation with a standard cage induction motor. The drive described in this section is designed specifically for operation with a synchronous motor.

Method of operation

The basic drive, Figure 8, is similar to the CSI drive. The input bridge is a fully controlled rectifier, the d.c. link has a smoothing inductor and the output bridge is a standard thyristor inverter. There are however, two major differences. Firstly the switching points of the inverter devices are set by a shaft encoder on the motor. Secondly, commutation of the inverter devices is achieved by the use of the back EMF generated by the motor field. Natural commutation allows the use of standard converter grade devices.

Characteristics and applications

The d.c. link voltage is reversible, and so regeneration is possible without the use of any additional converters. High speeds up to 10000 rev/min are possible and high power ratings are also possible, theoretically unlimited. Converter voltages of up to 18 kV and rated currents of up to 2000 A are available.

The use of the synchronous motor tends to determine that this drive combination is not economically viable below ratings of approximately 250 kW. This is partly as a result of the fact that synchronous motors are not as readily available at low power ratings. This drive has an advantage over the induction motor drive because the running speed is a direct function of the applied frequency, and does not suffer from slip. Hence accurate speed control is achieved without speed feedback. These drives compete well with large d.c. drives in applications calling for high speeds and in hazardous area applications (no brushes).

CYCLOCONVERTERS

This drive is suitable for use with both induction and synchronous type a.c. motors. The cycloconverter employs a line commutation phase control method first developed for producing 16.66 Hertz for traction purposes. Within its operational limits, it is an infinitely variable frequency drive with regenerative capabilities.

Method of operation

The basic operation of the cycloconverter is illustrated by the fact that 9 controllable switches enable any portion of a 3-phase supply to be connected to any phase of a 3-phase load. Consequently a 3-phase variable voltage and frequency output can by synthesised directly, i.e. without the intermediate d.c. link. In practice, each phase requires a “positive” bridge for operation when the supply voltage is positive and a “negative” bridge for operation when the supply voltage is negative, Figure 9. Hence each phase of the motor requires its own double bridge converter, consisting of 12 thyristors, and so the three phase drive requires a total of 36 devices. Although this represents a high device count, the advantage is that natural commutation means that standard converter grade devices can be used and there are no forced commutation circuits.

Characteristics and applications

Cycloconverters are only capable of producing acceptable output waveforms at frequencies well below the 50 Hz supply system value, typically one third of mains frequency. Again, power ratings are theoretically unlimited. Drives with converter voltages of up to 18 kV and rated currents of up to 2500 A are available.

Typical applications are in traction and haulage. The combination of multi-pole, slow speed motors and the infinitely variable low frequency drive makes this a good option as a very low speed, direct drive for mine-winding, kiln and crusher applications.

SLIP-ENERGY RECOVERY DRIVES

Through the use of a variable rotor resistance, it has always been possible to effect speed control of the wound-rotor induction motor. The disadvantage of this method has been the dissipation of the rotor power in the external rotor resistance. The slip energy recovery drive (or Kramer Drive) achieves the same controlling function whilst recovering the rotor power and feeding it back into the supply system.

Method of operation

The slip-frequency a.c. rotor power is rectified into d.c. and a smoothed d.c. link voltage established, Figure 10. A three phase inverter bridge converts the rotor power to a.c. and then the power is returned to the a.c. source, usually via a transformer. The firing angle of the inverter devices is used to control the d.c. link voltage. In turn, this controls the slip, and hence the speed of the motor. This method is very efficient as the rotor power is returned to the supply.

Characteristics and applications

This method of speed control is economical when compared with a standard inverter drive because the converters only carry the slip power of the rotor, not the fully rated stator power. Consequently the converters are much smaller than if they were placed in the stator circuit. The proviso here is that the speed range of the application is limited to half speed to full speed (or less, often 80 -100% speed) otherwise the rotor power will begin to approach the rated stator power. Such drives are available in the 1 - 20 MW power range with converter voltages and currents to suit the application.

By far the most common application for this drive is in the field of moving fluids, where the cube law relating power to speed applies. Hence typical applications are large centrifugal fans and pumps.

CONCLUSION

The use of a Variable Speed Drive for a speed control application usually offers an energy efficient and environmentally friendly solution. The best opportunities for energy savings, with subsequent economic savings, arise through the laws which govern the operation of centrifugal fans and pumps. Simple and straightforward VSD's, such as the PWM inverter drives, are available for applications where the speed control accuracy is not critical.

More onerous speed control applications may require the deployment of the, now standard, vector control drive. Such drives compare favourably with their d.c. counterpart in respect of their dynamic and speed holding accuracy. Largely these are closed-loop speed control systems relying on a shaft position and speed feedback signal, in addition to a motor model, to generate a modulated output. The latest development to emerge is the so called Direct Torque Control Drive which is an open-loop speed control system which uses advanced motor theory to calculate the torque directly, without using modulation. This type of drive offers even better dynamic speed performance than the vector control drive.

Application specific drives are also available, such as the current source inverter, the synchronous motor drive, the cycloconverter and the slip energy recovery scheme. Each of these has a fairly limited range of, usually high power, applications to which they are best suited.

This paper has reviewed the principal types of VSD available today. It has sought to explain the principles of operation of each and to identify their key characteristics. The principal applications of each drive have also been given. It is acknowledged that this is not an exhaustive summary of all of the available drives. New control schemes are emerging all of the time which offer a plethora of variations on the main themes. Future developments will undoubtedly raise the standards of performance ever upwards in a constantly changing industry.

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Figure 1 - Variable Speed Drive block diagram

Figure 2 - Inverter bridge circuit

Figure 3 - Quasi-square wave

Figure 4 - Inverter arrangements; a) PWM, b) VSI, c) CSI.

Figure 5 - PWM voltage waveform

Figure 6 - Vector Control block diagram

Figure 7 - Direct Torque Control block diagram

Figure 8 - Synchronous motor drive

Figure 9 - Cycloconverter motor drive

Figure 10 - Slip Energy Recovery drive