14

Variable Speed Electrical Drivers

14.1 INTRODUCTION

Due to an increasing concern about conserving energy there has become a requirement for variable speed drivers in the oil industry. The most common requirement is for compressors where the gas composition may not be well known or it may vary in composition and desire throughout, which is often the case in the production industry. Occasionally, benefits may be obtained by driving pumps with variable speed motors, especially large oil loading and pipeline pumps.

An important area where variable speed is used is in the drilling of wells where accurate control of speed and torque is essential. In recent years some attention has been focused on the application of variable speed motors in the down-hole pumping of oil, as discussed in sub-section 14.4.2.

Speed variation can be obtained by using two alternative types of electric motors.

- AC motors
- DC motors

AC methods include standard squirrel-cage induction motors, wound rotor induction motors, synchronous motors and commutator motors. Speed variation is obtained by the control of applied voltage to the stator or the control of current and voltage in the rotor by external circuit connections.

Before thyristors and power transistors were introduced for AC to DC and AC to DC to AC converter systems, there were a number of special designs of AC motors that gave better performance than standard squirrel-cage motors. These motors required connections to the rotor windings. They had better speed control, superior torque versus speed characteristics and some methods were energy efficient. However, they were more complicated and hence more expensive.

Much depends upon the performance required, e.g. accuracy, energy efficiency, standstill and low speed torque control. External equipment such as extra switchgear, controllers, instrumentation and protection is required and this increases the overall cost of the system. Also required will be extra maintenance and stocking of spare parts.

DC methods mostly use shunt or compound wound motors. Occasionally series wound motors are used when high torque at low speeds is required. These machines are fed with DC voltage derived from a three-phase AC source using a thyristor converter. The thyristor converter rectifies the AC into DC but with control over the magnitude of the average DC voltage. Thyristors are also called ‘silicon controlled rectifiers’.

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DC motors have a widely variable drooping torque versus speed characteristic and so, for any given torque and speed within its rating, the motor can be controlled to give a chosen speed and torque. Hence a DC motor can be controlled to accurately match and operate the characteristics of its driven machine from zero to beyond rated speed.

References 1, 2 and 3 give a good description of the operation and the characteristics of the motors used in traditional variable speed systems. When considering using variable speed motors the environment, the power supply and the economics should be carefully investigated.

14.1.1 Environment

The application of variable speed motors in the oil and gas industries tends to be for the larger pumps and compressors in the several thousands of kilowatt range. In such cases the motor and driven machine unit would often be located in a hazardous area or zone.

This greatly restricts the options available because it may not be permissible to have a motor which has slip-rings or a commutator. The only option in such cases is the squirrel-cage induction motor which would be fed from a variable frequency supply remote from the motor. There are notable exceptions, however, and one in particular is a drilling rig. Under most operating conditions on a drilling rig, the environment is actually non-hazardous, even though the area is classified Zone 2 or Zone 1. Hence for most of the time there will be no gas or vapour present in uncontrolled or unknown amounts and so the possibility of fire or explosion is negligibly small.

Drilling rigs require DC motors in the range of 500 to 800 kilowatts to drive the rotary table, draw-works, mud-pumps, winches and the propulsion system in the case of semi-submersibles. To reduce the danger of fire or explosion to even smaller levels, special ‘safe air’ purging systems are used. Safe air is continuously passed into the commutator end of the motor and vented from the drive end via appropriate fans and ducts. Even large induction motors above about 750 kilowatts will present problems for use in hazardous areas. In such cases an air purging system will be needed and the motor will be specified as a type Ex (p), see Chapter 10. Whether the motor is AC or DC it will also need to withstand, and be specified for, the full range of weather and climatic variations envisaged, e.g. hot and dry, cold and wet, high humidity, corrosive atmosphere, high winds and storms. These aspects are also addressed in Chapter 10 under the subject of types of protection against the ingress of water and solid particles.

14.1.2 Power Supply

Most power systems in the oil industry do not have variable speed drives and so the AC supply is a highly dependable and simple source of sinusoidal voltage and current. Little or no harmonics are present. If a large variable speed drive is required, and an inverter or thyristor controller of some form is used, then the combination of these equipments will cause harmonic currents to be drawn from the supply.

These harmonics will cause two secondary problems. Firstly, the harmonic currents will flow in cables, transformers and generator windings and in so doing will immediately produce harmonic volt-drops in these series circuits. This in turn will cause the voltages at various points in the system to contain harmonic components, e.g. either side of a transformer, at motor control centres and switchboards, other driving motors. Hence the voltages throughout the system will be contaminated by harmonics, a condition which is sometimes called ‘noise’. This can be troublesome and difficult to accommodate or remove. In some situations, the current drawn from the supply by the inverter or controller can be filtered and smoothed to an almost pure sine wave but this requires extra equipment which can be large, bulky and expensive.

The second effect of the harmonic currents is to induce harmonic emfs by mutual coupling, and consequently additional harmonic currents, into cables that are run close to the power cables feeding the driving motor or its controller. This is particularly troublesome for low power cabling e.g. computer cables, instrument cables, telemetry systems, telephones and communications cables, electronic circuit cables.

These induced harmonic currents and emfs can be damaging to electronic equipment in particular and troublesome to computer systems. Often the induced emfs and currents contain very ‘spikey’ components that have large peak values, and these can be difficult to remove or suppress.

14.1.3 Economics

A clear operational advantage must be obtained to justify the use of a large, variable speed motor when compared to the conventional methods of operation and design. The problems of environment and technical complexity introduced by the variable speed approach will add significantly to the unit capital costs and to the on-going maintenance costs. Since the system is bound to be more complicated and will have additional rather sophisticated equipments, the possibility of longer system down-time exists. The extra down-time will have two associated costs, one for loss of production and one for increased maintenance. The cost associated with obtaining high reliability should not be overlooked. A manufacturer that has a good ‘track record’ should eventually be chosen. Well-established technology should be used unless there is a very good reason to try out some new technology.

AC methods can be broadly divided into two groups:

a) Group 1.

A conventional AC power system is used in which the motors consume sinusoidal currents and do not produce harmonics.

Various standard types AC motors are used e.g. squirrel-cage and wound rotor induction motors, variable speed commutator AC motors.

b) Group 2.

A special AC power system is required that will contain thyristor controllers, inverters or the like, that will produce harmonics.

The system must be designed to ‘absorb’ the harmonics and the problems they could cause. The motors could be AC or DC, however, the degree of control and the scope of performance of these systems tends to be better than the more conventional approach of Group 1 above. Some very sophisticated control systems are now available. Some of the methods used in Group 1, although interesting and have been successful in the past, are now obsolete.

14.2 GROUP 1 METHODS

In this group there are three alternative possibilities that are practical. The first possibility uses an intermediate device between the sinusoidal supply and the motor to vary the magnitude of the voltage applied to the motor. Secondly, simple switching methods are available when two or three discrete speeds are required. These are usually obtained by special stator winding arrangements for squirrel-cage induction motors.

Examples in this sub-group are:-

- Star-delta stator winding.
- Pole-changing motors, e.g. PAM and NS motors.
- Special motors that have connections made to their rotor windings.

References 4 and 5 give descriptions of the PAM and other switched winding methods.

These methods find little application in the oil industry.

The third possibility includes systems that allow the speed to be continuously varied over part or all of the torque-speed characteristic of the motor. This is achieved by making special connections to the rotor or secondary circuit of the motor. Examples in this sub-group are:

- Wound rotor induction motors.
- AC commutator motors, e.g.
  - Schrage motor
  - Double-fed motor
  - Three-phase series motor
- Special combinations of machines that use the slip frequency energy of the rotor circuit e.g.
  - Kramer combination
  - Scherbius machine

All of these possibilities have become obsolete due to the availability of highly reliable electronic controllers.

14.2.1 Simple Variable Voltage Supplies

These methods provide continuously variable control of the speed over part or all of the torque-speed characteristic of the motor. One of the simplest ways of causing an induction motor speed to change is by altering the magnitude of the applied voltage to its stator. This will cause the motor torque to change in proportion to the square of the voltage, i.e. $T \alpha V^2$.

Thus, at the new voltage a new torque will be produced and this will match the load requirements at some new value of speed. The shape of the torque-slip (speed) curve of the motor will be

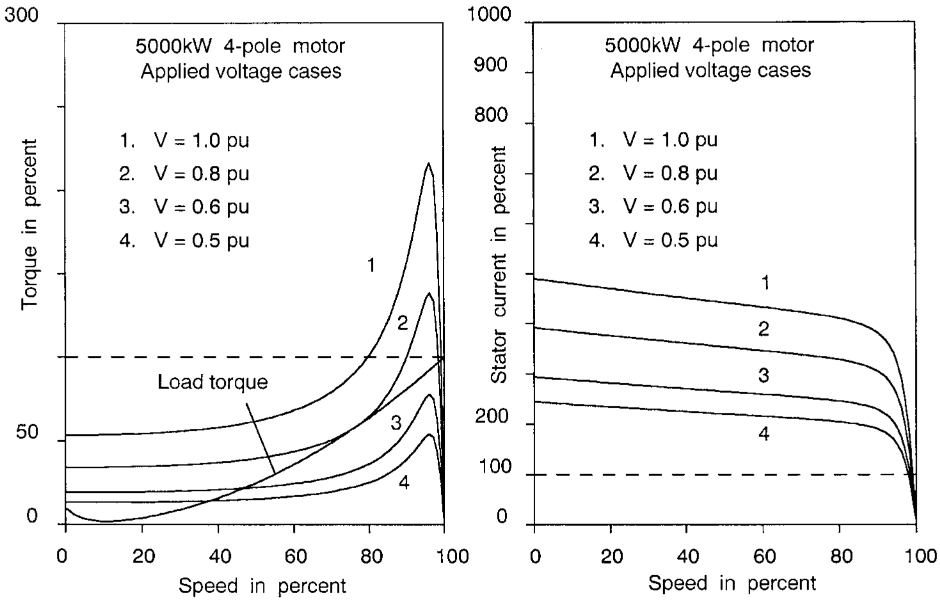

Figure 14.1 Variable applied voltage with a normal design of an induction motor.

the same as that for full voltage operation, but scaled up or down by the ratio $(V/V_r)^2$ where V is the applied voltage for the new speed and V_r is the rated voltage, see Figure 14.1.

It may be seen that if this method is used to control the speed of a standard, almost constant-speed type of induction motor, then the actual range of speed control obtained will, in fact, be small before stalling occurs. The situation could be improved by using a motor with a high rotor resistance as shown in Figure 14.2. The rotor resistance at full-load has been increased by a factor of 10 in order to demonstrate the effect on the torque-speed characteristic.

However, this method is not used for medium and large industrial drives, because of the practical difficulty in designing a high resistance rotor. If a slip-ring wound rotor design is used then an external high resistance can be added, but this method is seldom acceptable in the oil industry because of restrictions imposed by hazardous area classification.

The voltage applied to the stator can be varied in two ways:

- In steps using a transformer that has various taps on its secondary winding. This gives a course control and is used for 'open loop' control, i.e. no feedback regulation is used.
- Continuously by using some form of thyristor controller which will allow feedback action in the form of 'closed loop' control to be used to accurately regulate the speed. However, if such a scheme is used then it is the customary practice to adjust the applied frequency so as to maintain a constant air-gap flux, see 14.3.2 and 14.6.

14.2.2 Pole-changing of the Stator Winding

If an induction motor has more than two poles, e.g. four or eight, then it can be arranged to operate at two different synchronous speeds, one being half of the other. This technique is one of several which

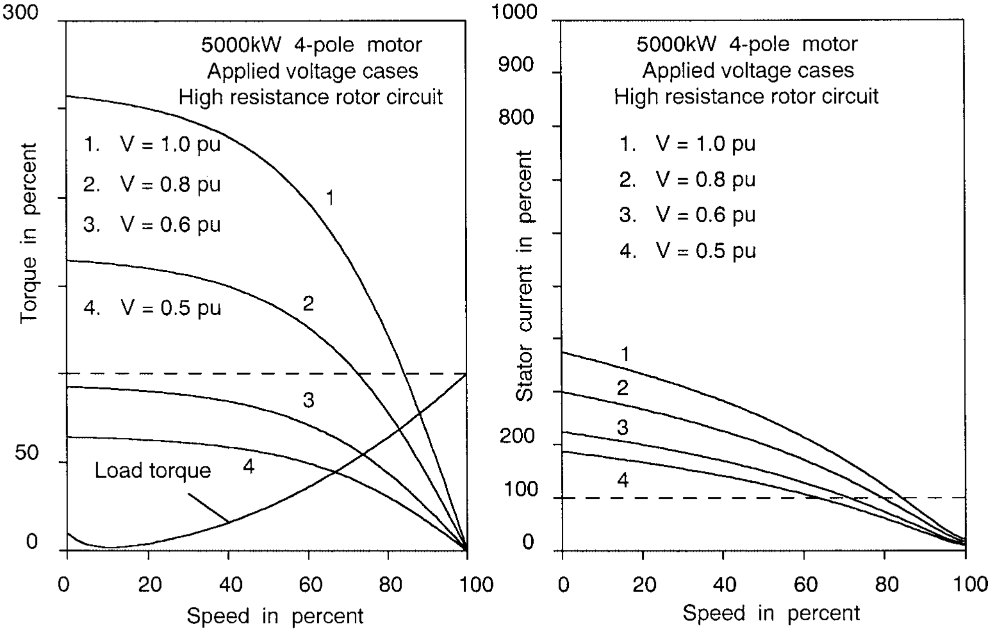

Figure 14.2 Variable applied voltage with a high resistance rotor design for an induction motor.

come under the general heading of ‘pole-changing’ motors. The method just outlined is applied to squirrel-cage motors but not to wound rotor motors.

In a multi-pole motor for eight-pole operation, the adjacent poles change in polarity from North to South around the air gap.

If half of the pole windings have their connections reversed so that the current flows in the opposite direction around the windings, then those windings will produce poles of opposite polarity. Hence each pair of adjacent poles will have the same polarity.

Therefore the resulting number of effective North and South poles will be halved and so the synchronous speed will be doubled.

Care should be taken when specifying the duty of multi-speed motors to ensure that the windings are appropriately rated for continuous or short-term duty since this may affect the amount of heat and temperature rise produced in the windings and also the effectiveness of any shaft-mounted cooling fans that may be employed.

14.2.3 Pole Amplitude Modulated Motors

A variation on the theme of pole changing is a particular type of squirrel-cage induction motor, called the Pole Amplitude Modulated (PAM) motor. PAM motors should be used for low speed applications thereby requiring many poles e.g. 10, 12, 16. In addition, the various speeds required should not be widely different. This means that the number of effective poles will not be too dissimilar, e.g. 8-pole and 10-pole operation. Commonly used two-speed pole ratios are 4/6, 6/8, 6/10, 6/12, 8/10, 10/12, 12/14, 12/16, 16/20 and 16/40. Low speed motors have many poles e.g. 16 and 24, and so complicated winding reconnections can be devised to produce more than just two speeds from the motor, as described in Reference 4. However, this is mainly of academic interest since the demand in the oil industry for such motors is rare. Three-speed ratios are 4/6/8, 6/8/10 and 8/10/12. Fractional ratios of speeds can be obtained by reversing and reconnecting only a small number of the poles or leaving some poles unexcited. Hence, an irregular distribution of poles around the stator is produced and this tends to produce harmonic torques throughout torque-slip characteristics.

Occasionally in refineries there is a need for large gas compressors to operate at two different speeds for long periods of time. If these two speeds can be matched to the pole arrangements of a multi-pole motor, then pole changing can be used satisfactorily.

These motors have been used successfully on large multi-speed air fans for power plant steam boilers. Most of the research on PAM motors took place between about 1958 and 1975 and is well documented in the proceedings of the IEE of the UK during this period.

14.2.4 Wound Rotor Induction Motors

A more versatile and satisfactory method of speed control of an induction motor is to make use of the rotor impedance. There are two basic approaches, firstly by simply adding resistance into the circuit by means of rotor slip-rings and an external static resistance bank or, secondly, by injecting a slip frequency AC voltage into the rotor circuit in such a way that the rotor current can be changed in magnitude or phase angle for any particular speed. The second method can be achieved by using rotor slip-rings or a rotor commutator, which looks and functions rather like those used on DC machines. In both approaches the essential effect is that the time phase of the flux produced by the rotor current, relative to the main flux produced by the applied voltage to the stator, is reduced to a minimum. Maximum torque is produced when this effect is achieved. If the rotor circuit is made predominantly resistive at any particular slip then the desired effect is achieved.

The simplest method of achieving the effect is to insert extra resistance into the rotor circuit. The rotor of the induction motor has to be specially wound so the winding can be split into three sections. Each section is connected to shaft-mounted slip-rings. The conductors of the rotor winding are carefully insulated from the iron core and from each other. The extra resistance is an external static unit mounted near to the motor.

If, for example, a water pump needs to be run at reduced flow rate for much of its operating time then a reasonably accurate method is to use a wound rotor motor with an external resistance. The resistance can be in the form of wire elements with various fixed tappings (for coarse control and starting) or an electrolytic tank using a water and caustic soda solution (for fine control and starting). In practice, the tendency is for this electrolytic tank to be preferred for large motors. A wide range of speed control with good torque performance is obtained by this method.

Until the introduction of thyristor and power transistor controllers a wound rotor motor with added resistance was one of the most common and simplest methods of speed control and is used for motors up to 10 MW. The main disadvantage is that the resistance bank is wasteful of energy, and the removal of the heat produced can prove difficult. The stability of the resistance of the electrolyte is also a problem since the resistance varies considerably with temperature and chemical composition of the electrolyte. Reasonably good speed regulation can be obtained by closed loop control, even though the stability of the electrolyte can introduce complications. Precise regulation is obtainable by other, more sophisticated, methods as will be described in following pages. However, now that power electronic controllers are available for even the largest motors, the use of wound rotor motors has been largely superseded and no longer used in the oil industry.

14.3 GROUP 2 METHODS

In this group there are several systems that use power electronics to provide a variable magnitude voltage at a variable frequency. Most of the systems use rectifiers and thyristors in the form of converters and inverters.

Examples are:-

- Thyristor rectifier for variable voltage but constant frequency.
- Thyristor rectifier-inverter for variable voltage and variable frequency.

These systems can be used to supply either induction or synchronous motors, although the first method is mainly used for small induction motors up to about 20 kW. The second method is suitable for motors up to about 30,000 kW. In all cases standard motor designs are used but some attention to the effects of harmonic currents and voltages is necessary on the part of the motor manufacturer.

14.3.1 Variable Voltage Constant Frequency Supply

A thyristor circuit is placed in series with the stator windings of the motor.

In each phase winding circuit there are two thyristors which are connected in parallel but with opposite polarities. This allows controlled conduction in the windings and allows the current to flow in both directions through the winding. The phase voltage is varied by delaying the firing of the thyristors and so only part of the sinusoidal waveform is applied to the motor. The average and rms values of the applied voltage are therefore reduced.

The torque produced by the motor is therefore reduced in proportion to the square of the rms value of the applied voltage. Circuits are available for both star and delta connected motors. Closed loop feedback control may be used to adjust the firing of the thyristors, thereby making accurate speed regulation possible. These systems are only used for small machines, e.g. up to 20 kW because they tend to produce many harmonic currents and voltages in the supply.

14.3.2 Variable Frequency Variable Voltage Supply

A typical basic circuit is shown in Figure 14.3 which consists of two main parts, a three-phase bridge-connected thyristor rectifier and a three-phase bridge-connected thyristor inverter.

The rectifier produces a variable magnitude DC voltage by applying control signals to the thyristor gates. The output current from the rectifier is specially filtered by a series inductance so that it is almost a pure DC current which passes through the three branches of the bridge-connected inverter in such a way that the three currents are caused to flow into the motor. This is achieved by cyclically firing the gates of the inverter and the frequency of the cyclic firing determines the AC fundamental frequency at the motor. A variable frequency oscillator is used to generate the firing pulses for the inverter thyristors. It is possible to arrange for the oscillator to accept feedback signals

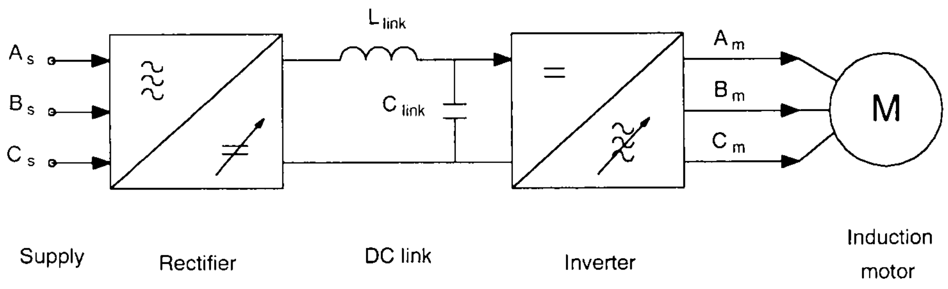

Figure 14.3 Schematic diagram of a variable voltage and variable frequency rectifier inverter system for an induction motor.

for accurate speed control and other signals for protection purposes, e.g. short circuit, and stalling, current limiting.

If an induction motor is run at a frequency below its normal operating frequency, the air-gap flux will rise if the supply voltage magnitude is kept constant. The rise in flux will cause magnetic saturation in the iron circuit of the motor and this in turn will cause a very large increase in magnetising current in the X_m branch shown in Figures 5.1 or 15.11.

The applied voltage must be reduced almost in proportion to the frequency so that the flux remains almost constant. The control of the flux is achieved by using a frequency sensing circuit to fire the rectifier thyristors. As the frequency is reduced the X-to-R ratio of the complete circuit is reduced and therefore the shape of the torque-speed curve becomes less peaked. Figure 14.4 shows the

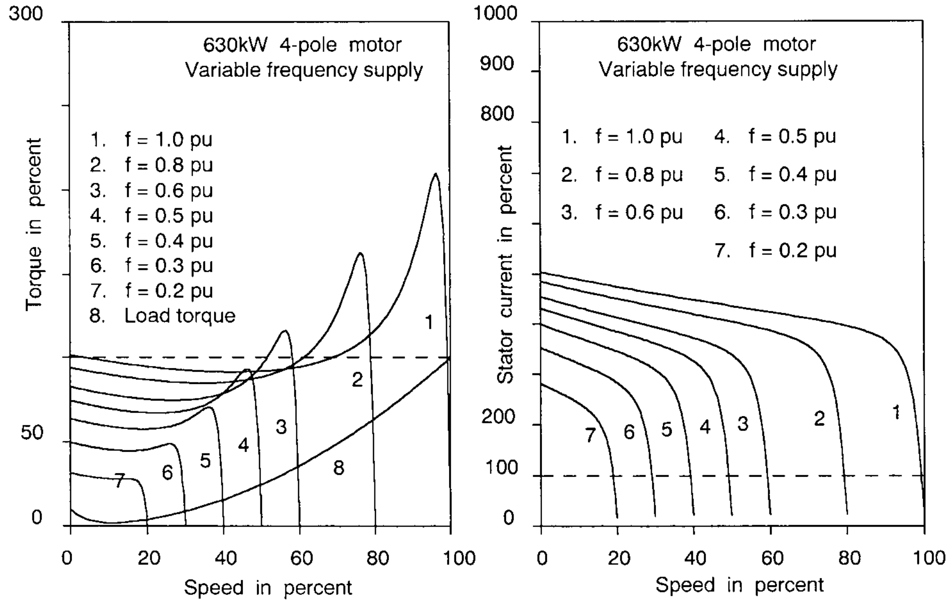

Figure 14.4 Torque and current versus speed curves of a 630 kW four-pole motor that is fed from a variable voltage and variable frequency supply. Also shown is a typical torque versus speed curve for a centrifugal pump or compressor.

torque-slip characteristic for operation at various supply frequencies. This method, and its variants, is applied to the largest induction motors used in the oil industry. The method is also applied to submersible motors for ‘down-hole’ pumping in oil and water wells.

14.4 VARIABLE SPEED DC MOTORS

In the oil industries, DC motors are used for driving drilling rig systems, e.g. rotary table, draw-works, mud pumps and winches. Modern drilling rigs use thyristor rectifiers to supply DC power to the motors which are in the range of 700 to 800 kW. Drilling rigs do not normally require very fast reversal of speed and so reversal by means of field control is usually adequate, or if a series motor is used than a reversing switch will need to be used at zero speed and zero current.

Often the driven machine requires to be braked e.g. draw-works, anchor winches. It is possible, although not yet common practice, to use the motor as a brake for the mechanical load. This is achieved by using the load to drive the motor as a generator and to pass its current through the thyristors in their inversion mode. This requires the thyristor bridge circuit to have six thyristors and some additional electronic control circuits. Thus the motor ‘supplies the supply’ with energy during the braking period. The transition from motoring to braking, and from braking to motoring can be arranged to be fully automatic, without any kind of surge or disturbance at the point of changeover. The electronic circuit makes this possible.

The very flexible nature of the thyristor controller allows the motor to have accurate control plus excellent overload protection. Most thyristor controllers are furnished with maximum current limits for motor armature current and for short-circuit current protection. During conditions of rapid acceleration or heavy load the armature current will rapidly become high and so the maximum current limiter will automatically hold the armature current until the duty is reduced. Thyristor controllers also make it possible to gain accurate control of the torque or load at zero speed. This is very desirable when handling anchors and the drill string.

14.5 ELECTRICAL SUBMERSIBLE PUMPS

14.5.1 Introduction

There are many methods by which well-bore fluids can be raised to the platform or land level. In situations where high flow rates are required, the main options are:-

i) Gas lift, assuming adequate gas supply.
ii) Water flood.
iii) Electric submersible pumping (ESP).

Gas lift and water flood systems give higher reliability over ESP systems (by virtue of their operating environment at ground level or on a platform deck) but are disadvantaged by equipment weight and space requirements plus the large power demands involved. Moreover, gas lift cannot easily be installed gradually across a field on a well-to-well basis.

Electrical submersible pumps, albeit less reliable than gas and water flood systems, are utilised worldwide due to the major advantages of minimum topside weight and space requirements. The units, when properly selected, operated and maintained, provide an acceptably economic means of lifting well-bore fluids.

This sub-section deals briefly with the basic mechanical and electrical components that form the pump unit. The mechanical and electrical aspects are reviewed in this section with attention being paid to methods of speed control.

14.5.2 Electrical Submersible Pump Construction

The basic components involved are:

- Motor.
- Seal or protector.
- Pump.
- Gas separator.
- Feeder cable.
- Controller.

The pump unit must be designed to operate at very onerous levels of pressure, temperature and in the presence of contaminates such as sand, acids etc. Moreover, the unit must be suitable for lowering into a well-bore which can vary from only 150 to 300 mm in diameter. Due to diametral limitations and the necessary power requirements the motor pump unit itself becomes extensive in length, e.g. up to 10 metres. See Reference 6 for an overview of the subject of submersible pumps.

14.5.2.1 Pump motor parameters are varied

The following list provides some basic data that are applicable to ESP motors:

- Power range 20 to 700 kW.
- Applied voltage 415 to 3000 volts.
- Squirrel-cage induction motor in cascaded sections.
- Number of poles is usually two.
- The insulation needs to be superior to Class H (epoxy impregnation system).
- High grade insulating oil is used.
- Variable frequency speed control is used.

The motor can be expected to operate at a depth of 5 km or more in an hostile and acidic environment with temperatures of up to 150°C.

The oil insulant provides the means of heat transfer from motor internal components to the motor casing.

To provide the necessary power requirements within severe diametrical limits, the motor length can be up to 10 metres.

14.5.2.2 The seal or protector

The seal (or protector) operates, as its name implies, to provide a barrier between the well-base fluids and the motor. The seal is normally multi-chamber and is additionally designed to equalise the internal motor pressure and to enable the motor insulant to either expand or contract.

14.5.2.3 The separator

Depending upon the gas to oil ratio (GOR) of the well fluid and possibly pump damage, a need may arise to separate out the gas prior to pumping the well fluid to the surface.

14.5.2.4 The pump

The pump is of the centrifugal type, consisting of a multi-stage impeller and fixed diffuser. The lift and volume requirements of the pump determine the number of stages, the length of the pump and the power rating of the motor.

14.5.2.5 The cable

Cables for supplying power to the pump motor are of a specialised design and must conform to stringent requirements due to the severe operating conditions. Typically, the cable must:

- Possess ‘breath ability’ to allow trapped gases to escape during decompression when the pump is raised for maintenance.
- Use materials suitable for use in temperatures up to 200°C.
- Have smooth and flexible wire armouring.

14.5.2.6 The controller

The controller is of the variable voltage, variable frequency type, thereby providing a complete speed range for the motor at constant torque. The system inherently provides soft start which is necessary to alleviate high torsional stresses within the motor-pump unit, that may otherwise damage the shaft and couplings.

The controller, being typically designed for 2 to 3 kV, is usually supplied via a unit transformer. Because of the multi-stage nature of the motor the terminal voltage required for the motor may be non-standard and so a transformer must be used to match the motor to the power system.

The major advantages of variable frequency controllers for submersible motors are:-

- Soft start.
- Variable torque.
- Variable pumping capability to suit change in fluid pressure and flow parameters.
- System frequency up to 75 Hz, giving 25% extra motor power output.

14.6 CONTROL SYSTEMS FOR AC MOTORS

In the oil industry the use of variable speed AC motors has become a requirement for several reasons:

- Availability of economical high power inverter systems.
- Improved reliability of power electronic control systems.
- Availability of micro-computers for intelligent control and protection of the rectifier-inverter motor system.
- The modern emphasis on the conservation of energy.
- Control performance that is superior to non-electrical fluid controllers such as throttle value control and fluid couplings.
- Standard or 'near standard' motors can be used.

The application of speed control to a large AC motor is generally for one of two reasons, or less frequently a combination of both:

- Steady state speed control over a significant range e.g. 10% to 100%, 50% to 100%, 75% to 110%.
- To restrict the starting and reacceleration currents that the motor requires.

The steady state speed control can be easily achieved by modern control systems and the regulation about a set speed can be as low as 1% or less. In addition rapid and adequately damped responses to changes in set points or to process disturbances are standard features of most systems. The high performance of modern electronic control systems enables the sharing of loads and process duties between parallel pumps or compressors to be accurately achieved without much difficulty. These systems also allow scheduling and the admission into or the removal from service of motors to be achieved in a smooth manner. Modern protective systems for the power electronics and the motor are very comprehensive, and fast to react if required to do so.

Most oil industry power systems permit, and indeed encourage, direct-on-line starting of motors. This becomes difficult as the motor ratings are large in relation to the capacity of the main power source e.g. several gas-turbine driven generators. In large installations such as LNG plants and refineries, and along bulk oil or gas pipe lines, it is common to find motors with ratings up to 10 MW. In order to start such large motors it has become the practice to use a variable speed rectifier-inverter system as a starting device, which is sometimes referred to as a 'soft start' system. Whilst the starting problem has been solved by such a system, it is then a simple matter to take advantage of the variable speed controls to adjust the motor speed during its normal running operations.

The basic elements of variable speed control systems for an AC motor are shown in Figure 14.5. In practice there are several variations to the basic system, see Reference 7, Chapters 4 and 6, and Reference 8, Chapter 9. Some of the devices and signal lines, e.g. A or B, may not be used in all practical systems.

The following comments apply to the various blocks ( ) in the diagram.

The system receives its main power from a circuit breaker (6) or contactor in the upstream switchboard or motor control centre. This switchgear will contain the main power protective relays

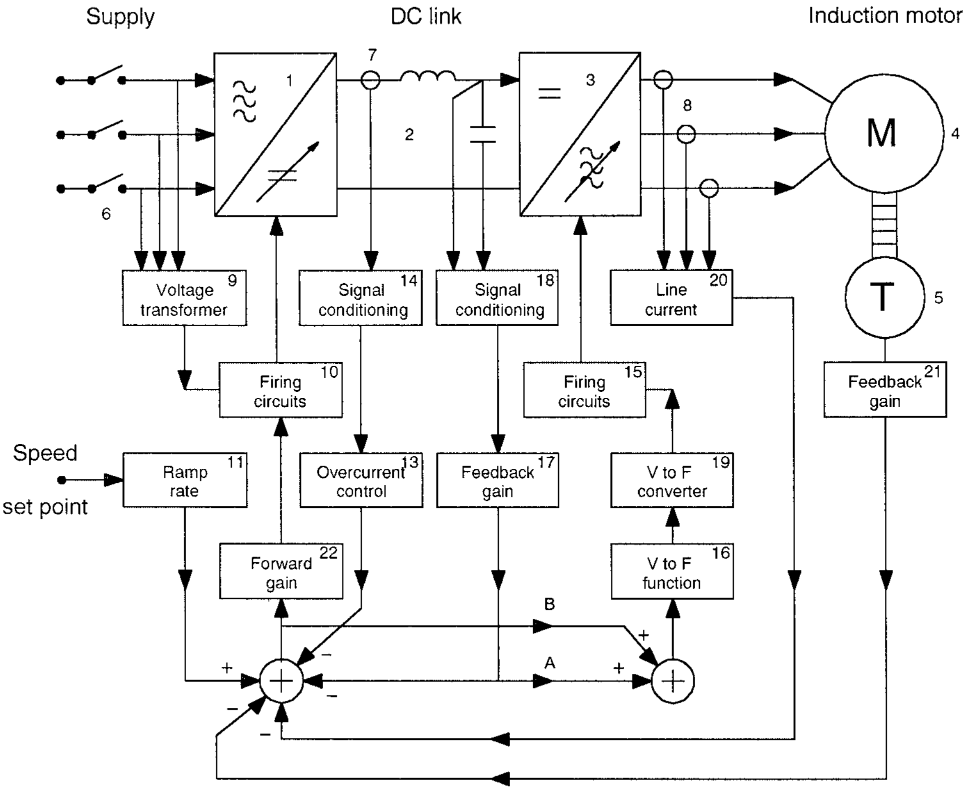

Figure 14.5 Block diagram of the control system for an induction motor fed from a variable voltage and variable frequency.

such as overcurrent, undervoltage, earth fault, and fuses if appropriate. These will protect the power circuit up to rectifier input terminals including its transformer. The transformer may be fitted with additional devices such as winding temperature detectors and a Buchholz relay which will send their alarm and tripping signals back to the switchgear. The switchgear will also receive alarm and tripping signals derived from the rectifier-DC link-inverter motor system. For example a major fault may develop in the motor which should be de-energised as quickly as possible. Failure of power diodes, thyristors and power transistors is usually taken care of by high speed fuses, whereupon fuse failure can be detected and a signal sent back to the switchgear.

Modern switchgear and variable speed controllers are available with micro-computer based control, protective and indication facilities. These can communicate between each other and to external networks by such links as fibre optics and digital hardwire networks.

The rectifier (1) may be of the 6 or 12-pulse type. The choice mainly depends upon the tolerance that is available for the harmonics, which will be injected into the upstream power system. The rectifier will be designed to provide a source of variable voltage to the DC link. The 12-pulse type will usually be necessary for the highly rated motors within their voltage level. Inside the rectifier compartment will be a set of voltage transformers (9) which will be used to derive a set of firing pulses (10) for the rectifier elements. These pulses will be in synchronism with the power supply.

The control of motor speed essentially requires two components, one for varying the terminal voltage of the motor and one for varying the frequency of this voltage. Part of the control system will contain a function generator that will convert a voltage signal into a frequency signal. As the voltage is changed so will the frequency be changed in sympathy. Above about 10% of rated voltage the characteristic of this sympathetic control will be linear dependency. Below 10% the voltage-to-frequency ratio will need to be slightly increased so as to avoid over-fluxing the iron core of the motor. Block (16) contains the appropriate characteristic. However, controlling the speed in such a low range is seldom required. During the starting sequence the motor will initially receive at least 10% of its rated voltage and frequency, thereafter it will be ramped upwards to the required steady state conditions. The ramp rate (11) will depend upon the response characteristics of the mechanical load, e.g. static torque versus speed curve, low or high moment of inertia. The ramp rate should be slower than the speed response of the driven load otherwise the operating point on the torque versus speed curve of the motor will more towards the peak value, and in the extreme situation move to the left of the peak value. During these undesirable situations the current drawn by the motor may exceed its full load value. If an overcurrent limiter (13) is incorporated then the motor will be forced to operate in the stable right-hand side of its torque-speed curve. In practice the setting of the current limiter should be a reasonable margin above the full-load current of the motor e.g. +20%, but not too high as to require an unnecessarily high current rating for the rectifier and inverter power semiconductors. The manufacture of the rectifier-inverter will often be able to advise what the upper limit should be to suit a particular driven load. The current signal taken in the DC link at (7) could alternatively be taken from current transformer in the AC supply circuit, i.e. in the switchgear or the rectifier cubicle. The voltage control of the rectifier should be of a closed-loop type which should have a reasonably high degree of regulation. The control loop can be closed by feedback (A) from the DC link voltage (17) or the inverter output (20). Signal (B) which is used to control the rectifier firing circuits (10) can also be used as an alternative to (A) for controlling the frequency of the inverter. If the cables are long then some compensation for volt-drop could be incorporated into the voltage controller. If a very small speed regulation is required e.g. less than 1% then a tacho-generator (5) will be needed, which will to some extent override the voltage feedback provided by the DC link voltage measurement blocks (17) and (18). The regulation can be adjusted by the feedback gain (21), the more the feedback the lower the regulation. However, the system has time constants in most of the blocks and so the overall transfer function is likely to become unstable if the feedback gain (21) or the forward path gain (22) is too high. Without the tacho-generator the inverter-motor system is open-loop unless a frequency signal is derived from the measurement of current or voltage in block (20).

Block (19) is an oscillator in which its frequency is controlled to be directly proportional to its input DC signal from the characteristic block (16).

Some manufacturers recommend using a filter at the output of the inverter to smooth the waveform applied to the motor and to reduce the sharp rise and fall in the notches that may be present, as in the case of current-fed motors. Steep sided notches cause a high dV/dt across the insulation of the motor, which can reduce the life expectation of the insulation. The filter may also be required to reduce electromagnetic interference (EMI).

Modern fast-acting micro-computers are capable of storing and manipulating a reasonably detailed mathematical model of the motor. It is therefore possible to compute the model in ‘parallel’ with the actual motor and compare the computed variables with those measured at the output of the inverter. An algorithm can be developed that will adjust the rectifier and inverter set-points so that the actual motor responds more like the mathematical model. An advantage of such a scheme is the ability of the model to store the non-linear parameters of the motor e.g. stator and rotor resistances as functions of slip, saturation of the magnetising reactance, stator and rotor reactances also as functions of slip. Hence the 'deep-bar' effects in the rotor can be taken into account. In such a scheme the use of a tacho-generator may not be needed to improve the speed regulation. The necessary parameters, with their non-linearities, can be obtained from factory tests near to the time when the motor is to be delivered to site.

REFERENCES

1. H. Cotton, *Advanced electrical technology*. Sir Isaac Pitman and Sons Ltd (1967).
2. E. Openshaw-Taylor, *The performance and design of AC commutator motors*. Pitman, London (1958).
3. A. E. Fitzgerald and C. Kingsley, *Electric machinery. The dynamics and statics of electromechanical conversion*. McGraw-Hill Book Company, Inc. (1961).
4. A. B. Goldhammer and L. P. Waring, *Multi-speed induction motors*. Publication No. 3506-71 EdB 500 0269. AEI Large Electrical Machines Ltd. Manchester, M17 1PT, UK.
5. J. C. H. Bone and K. K. Schwarz, *Large AC motors*. *Proc IEE*, Paper No. 6976P, Vol. 120, No. 10R, Oct 1973.
6. Douglas Hale, *Pump control 5 km down an oil well*. *Electrical Review*, Vol. 213, No. 19, Nov 1983.
7. David Finney, *Variable frequency AC motor drive systems*. Peter Peregrinus Ltd (1991). ISBN 0 863-41114-2
8. S. B. Dewan, G. R. Slemon and A. Straughen, *Power semiconductor drives*. John Wiley & Sons (1984). ISBN 0 471-62900-5