Guidance Notes for Reducing Energy Consumption Costs of Electric Motor and Drive Systems
GUIDANCE NOTES FOR REDUCING ENERGY CONSUMPTION COSTS OF ELECTRIC MOTOR AND DRIVE SYSTEMS

This booklet is No. 2 in the Good Practice Guide Series and is aimed at those who are seriously considering how they can reduce the operating costs of electric motors and drive systems.

Much of the content draws on the work of the University of Surrey and the experience of some of the more adventurous companies who were willing to invest in the technology in the early days.

Accordingly the writers would like to thank all those who have provided information used in the preparation of this Guide.

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FOREWORD

This Guide is part of a series produced by the Department of the Environment under the Energy Efficiency Best Practice programme. The aim of the programme is to advance and spread good practice in energy efficiency by providing independent, authoritative advice and information on good energy efficiency practices. Best Practice is a collaborative programme targeted towards energy users and decision makers in industry, the commercial and public sectors, and building sectors including housing. It comprises four inter-related elements identified by colour-coded strips for easy reference:

— Energy Consumption Guides: (blue) energy consumption data to enable users to establish their relative energy efficiency performance;

— Good Practice Guides and Case Studies: (red) independent information on proven energy saving measures and techniques and what they are achieving;

— New Practice Projects: (green) independent monitoring of new energy efficiency measures which do not yet enjoy a wide market;

— Future Practice R&D support: (purple) help to develop tomorrow’s energy efficiency good practice measures.

If you would like any further information on this document, or on the Best Practice programme, please get in touch with your regional Government Office. The addresses are given below:

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GUIDANCE NOTES FOR REDUCING ENERGY CONSUMPTION COSTS OF ELECTRIC MOTORS AND DRIVES

1. INTRODUCTION

Electric motor and drive systems account for 64% of industrial electrical demand. A large proportion of this is used to drive fans, pumps and compressors. The electricity used costs some £2,000 million/year at present prices. A further £1,000 million/year is consumed in commercial applications, mainly by refrigeration, air conditioning and ventilation equipment.

The UK industrial motor population is estimated to be in excess of 10 million units. Furthermore, 3,000 new motors, predominantly standard ac induction motors rated below 150 kW, are purchased every working day.

In typical applications, levels of utilisation are approximately 50% with power losses estimated to be between 40% and 80% of the motor full load rating.

The latest developments in microcomputer based technology present financially attractive opportunities to reduce these losses by investment in higher efficiency motor and drive systems*. These systems reduce the incidence of the inherent losses of standard ac motors and offer improved motor control opportunities.

Many technologies and techniques are now proven and it is estimated that cost-effective investment by industry and commerce could save in excess of £300 million/year, i.e. approximately 10% of the total expenditure in these sectors.

Unfortunately, many opportunities for obtaining substantial savings are missed even though advice is available from numerous sources, including Government, professional bodies, consultants and equipment suppliers. The reasons for this include:

- lack of awareness and/or scepticism about the latest technologies;
- overall financial and operational benefits are often not fully appreciated;
- energy saving projects too often take second place to other production related expenditure;
- lowest ‘first cost’ takes precedence over ‘life cycle’ cost (i.e. initial cost plus running and maintenance costs).

The purpose of this ‘Good Practice Guide’ is to bring to the attention of potential users the opportunities for achieving substantial cost-effective savings on electric motors and drives up to 150 kW.

Part A of the Guide provides an introduction to the subject of electric motors and drives and explains the interaction of such systems with the electricity supply network. It also suggests where energy saving opportunities might be realised.

Those readers familiar with the principles of motors and drives need not concern themselves with this first part.

Part B examines the methods by which such opportunities can be identified and exploited. Typical applications, case studies and examples of cost/benefit analyses are also provided.

The results of tests on selected high efficiency motors, and motor controllers with standard motors, are presented. These are compared against the standard motors alone and show levels of performance, energy consumption and savings.

* Words and phrases in italics are explained in the glossary (Appendix 1).
Part C contains useful information, lists of suppliers and details of further reading.

A number of graphs showing performance are included in this Guide. These are generally illustrative and should not be scaled for particular situations.

Throughout this Guide, emphasis is placed on the financial benefits resulting from the implementation of technologies to save energy and improve performance. Energy managers should find sufficient information in the Guide to enable them to identify particular opportunities and develop cases for implementation that will provide attractive financial rewards for their organisations.
PART A: INTRODUCTION TO ELECTRIC MOTORS AND DRIVE SYSTEMS

2. ELECTRICITY

To understand the operation of electric motors and drives it is necessary to explain some aspects of electricity. Electricity is generally purchased from the local supply authority although it may be provided by on-site generation facilities.

2.1 Characteristics

Electricity is produced by the action of a moving magnetic field and, depending on the configuration of the generator, may take whatever form is required.

For engineering and economic reasons the three-phase system has been universally adopted for the generation and transmission of public electricity supplies. The main characteristics of electricity are voltage, current and, in the case of alternating current (ac) systems, frequency. Voltage (volts) and current (amperes) combine to provide power (watts). In the UK a 415 volts, 50 Hz three-phase supply is the accepted norm at the point of use. This corresponds to 240 volts, single-phase.

In ac systems the current (and hence the power) is made up of a number of components. These are the currents taken by the resistive, inductive and capacitive elements of the power consuming load. The inductive (lagging) and capacitive (leading) components are added vectorially to produce the nett reactive lagging or leading current. The resistive current, which is in phase with the voltage, combines with the voltage to provide the ‘true’ or ‘useful’ power. The reactive current combines with the voltage to provide the ‘wattless’ or reactive power. The true power (watts) when added vectorially to the reactive power (volt-amperes reactive) gives the apparent or total power (volt-amperes).

From this relationship the power factor can also be derived (Fig 1). Power factor is defined as the cosine of the angle by which the total power lags or leads the useful power.

Charges for supplying electricity take account of true power in kilowatts (kW), apparent or total power in kilovolt-amps (kVA) and power factor which is the ratio of kW to kVA.

\[
\begin{align*}
\text{kVA} & \quad \text{(Apparent power)} \\
\text{kVAR} & \quad \text{(Reactive power)} \\
\text{kW} & \quad \text{(True power)} \\
\cos \phi & = \text{Power factor}
\end{align*}
\]

Fig 1 kW, kVA & kVAR Relationship

2.2 Tariffs

The system supply capacity to a site is usually based on the total power requirement in kVA. Where system capacity is charged for in kW the power factor is taken into account. If it is below a predetermined level, typically between 0.9 and 0.94, a penalty charge is incurred.

Running costs are related to the true power in kilowatts consumed in a given period, usually one hour. Hence a unit of electricity is known as a kilowatt-hour (kWh).
The peak rate of consumption, known as Maximum Demand (MD), is usually monitored and charged for. These charges can be quite large particularly from November to February. It can therefore be financially worthwhile to limit the peak demand by reducing load at specific times.

Average costs of electricity can vary between about 3p and 7p/kWh, depending upon the:

- type of supply, i.e. High or Low Voltage;
- level of peak consumption and time of occurrence;
- ratio of on-peak to off-peak consumption;
- ratio of total consumption to peak consumption, known as load factor;
- tariff employed;
- power factor of site load.

In some instances the power factor is derived by metering the reactive power in $k\text{VARh}$ in a similar way to the true power. This method is preferable as the power factor is then based on the average over the period of registration rather than the peak level obtained by dividing the kW by the kVA.

The inductive and capacitive power components add vectorially to produce the nett reactive power. Therefore, to correct a system power factor that has a value of, say, 0.9 lagging, additional capacitive leading current has to be taken by the system. This is usually achieved by connecting power capacitors, either at the motor terminals or the incoming point of supply for the site.

These capacitors consume minimal true power and can, when connected at the point of supply, be controlled either manually or automatically via a power factor relay. In large installations the capacitors can be automatically introduced or removed from the circuit in a series of stages. This has the advantage of not over-correcting the power factor as the load varies.

More information on tariffs and their structure is given in the EEO's booklet 'Fuel Efficiency - No. 9' available from any of the regional offices of the EEO.

When calculating savings from efficiency improvements, it is important that the incremental cost of electricity is used, i.e. a cost derived from only those elements of the average price which vary with consumption.
3. **ELECTRIC MOTORS**

3.1 **Types**

The main types of electric motor encountered in industry and commerce are generally; standard *squirrel cage* ac induction motors, *wound rotor* ac induction motors and *shunt* and *series* or *compound wound* direct current (dc) motors. The ac motors are usually *asynchronous*, (sometimes known as non-synchronous) or, *synchronous* mainly at higher power ratings, i.e. >150 kW. Synchronous motors, although generally more efficient than asynchronous machines, are also more expensive. Consequently they can only be economically justified at larger ratings. There are also the three-phase commutator ac motor and the variable reluctance motor and drive. Although small ac motors are sometimes single-phase 240 volt 50 Hz machines, most ac motors operate on the standard 3-phase 415 volt 50 Hz mains supply. This is because of the superior motive power performance which is possible using three phases. Electricity for DC motors is usually supplied from *static rectifiers* but occasionally, in larger applications, from *rotary motor generator sets*.

3.2 **Principal Components**

The main components of electric motors are the stator, the rotor, the mechanical casing and a self cooling fan mounted on the rotor shaft (Fig 2).

The stator and rotor are the heart of the electric motor: the former carries the load current and the latter, in the case of ac induction machines, the *induced current*. Both are constructed from laminations of high quality steel with the copper current-carrying conductors wound on to the stator. Generally, in ac machines, solid aluminium conductors are mounted on the rotor. In the case of a squirrel cage induction motor, the most common type, the rotor conductors are permanently short-circuited.

Torque is produced by the reaction of current-carrying conductors on one member of the motor, usually the stator, with the magnetic field produced by the other member. AC commutator motors and dc motors have *commutators* and *brushgear* to feed the electricity to the rotor.
3.3 Losses
Total losses in electric motors comprise four main components. These are:

- **iron losses** (sometimes referred to as the magnetising losses) which are voltage related and therefore constant for any particular motor irrespective of the load;
- **copper losses**, known as $I^2R$ losses, which are proportional to the square of the load current;
- friction (or mechanical) and windage losses, which are constant for a given speed irrespective of load;
- stray load-related losses.

Fig 3 shows a typical induction motor load/loss graph.

Iron losses comprise *hysteresis losses* determined by the physical characteristics of the steel used and *eddy current losses* determined by the construction and assembly of the steel laminations. Iron losses, because they result from the consumption of reactive current, affect the power factor of the motor. At low load the iron losses predominate and produce correspondingly low power factors. Even at full load the induction motor has a relatively poor power factor, typically between 0.8 and 0.9 lagging. It is therefore good economic practice to match the motor as closely as possible to the load so that low efficiencies and poor power factors are minimised. Small motors tend to have worse power factor characteristics than their larger counterparts and accordingly, in installations with many small motors the overall power factor is likely to be low.

Fig 3  Power Losses in Electric Motors

3.4 Control
Electric motor starting, and protection when in use, is usually provided by an electromechanical device incorporating a main *contactor* with overload coils and a control coil with associated contacts. These provide manual and/or automatic ON-OFF operation. More sophisticated electromechanical motor starters can provide automatic reversing of the motor or limit starting currents by initially connecting the motor windings in 'star' and then, after a pre-set time period, changing over to the more usual 'delta' connection. This is shown diagrammatically in Fig 4.
3.5 Application

Electric motors are used to satisfy a number of basic application requirements. These are determined by the characteristics of the equipment to be driven, such as:

- constant speed/constant load;
- variable speed/variable load;
- 'on/off' or 'load/no-load';
- constant speed/variable load i.e. duty cycling.

3.6 Maintenance

Maintenance of electric motors is generally straightforward. However, because of its relative simplicity it can sometimes receive inadequate attention.

The main points to be considered when developing a maintenance plan for electric motors are:

- lubrication of bearings;
- overall cleanliness of motor;
- mechanical alignment;
- electrical integrity of insulation;
- condition of commutator, slip rings and brushes.

3.7 Rewinding

When the windings of electric motors fail it is usually cost-effective to undertake a *rewind* of the motor. However, great care should be taken to ensure that the rewind is carried out to the highest standards and results in a motor with at least the same quality of performance as the original.

Particular points for consideration when rewinding motors are:

- conductors should be formed from wire of adequate cross-sectional area to maintain as low a resistance as possible, thus minimising $I^2R$ losses;
- the necessary heating, before and after the rewinding process, should be carefully monitored and controlled to limit potential damage to the steel laminations. Failure to do so may have an adverse effect on the magnetic characteristics, and hence the losses, of the motor.
4. DRIVE SYSTEMS

Modern starting and control systems, usually referred to as drive systems, utilise microcomputer technology to facilitate the continuous close monitoring and operation of a wide range of motors and their applications. When the terms drive and/or drive system are used in this Guide they do not refer to the mechanical aspects of driving equipment or machinery, but solely to the method of controlling the output and performance of the motor and any associated power couplings. Essentially there are three methods of improving energy efficiency by changing motor and drive systems.

1. High Efficiency Motor; this is the generic name for electric motors which have been designed to minimise the inherent losses of the motor.

2. Motor Controllers; sometimes known as voltage controllers or soft start with energy saver. These constantly adjust the voltage to the motor terminals to that which is just sufficient to meet the load. Hence the voltage related iron losses are minimised. Motor controllers usually incorporate a 'soft start' facility. This reduces the peak current during the starting cycle of the motor.

3. Variable Speed Systems; these fall broadly into three categories, the objective being to adjust the speed of the driven load in accordance with some measured parameter. The systems comprise:
   - Electronic Variable Speed Drives; known as VSD's, of which there is a wide variety. They operate by electronically matching the speed of the motor, and the power input to it, to the requirements of the load. Hence the iron and other losses are reduced to a minimum.
   - Variable Speed Motors; these include established conventional variable and two-speed motors and the recently introduced 'Latest Technology' Motors. These utilise modern electronic control capability to widen and extend the use of motors previously restricted by conventional electromechanical controls.
   - Electro/Mechanical Drives; these use constant speed motors with mechanical or electromechanical control to vary the speed of the driven system.

Motor controllers and VSD's are electronic 'black-boxes' which substitute for the conventional electromechanical motor starters. Generally located adjacent to the motors they can be physically larger than the starters they replace but are usually easy to retrofit.

5. SAVINGS OPPORTUNITIES

There is scope for achieving cost savings from most electric motors. This is because:
   - motors are manufactured in fixed sizes and prudence dictates 'too large' when choosing a motor, even for constant load use;
   - until recently it has not been possible, on any but the larger motors, to cost-effectively adjust the speed and/or voltage to follow a changing load;
   - energy costs have not always been regarded as a significant part of overall operating costs;
   - high efficiency motors are a relatively new addition to the range of motors available.
The application of electric motors is so varied that an exhaustive list of the opportunities for potential savings would be unrealistic. However, typical applications where savings could be confidently expected would include:

- pumps;
- compressors;
- fans;
- conveyors;
- mixers;
- machine tools;
- refrigerators;
- wood working machinery;
- paper pulpers.

Some of the more common applications are discussed in Part B of this Guide. However, not all of these will be cost-effective. Worked examples showing the benefits that can be achieved are given. Decision trees are also included to identify suitable application areas for the technologies available.
6. SITE MEASUREMENTS

To establish what potential benefits may accrue from investment in high efficiency motors or improved drives, it is first necessary to establish the actual operating parameters for existing systems. This is achieved by undertaking site measurements.

Manufacturers of electric motors carry out standard tests to accurately determine motor efficiency. However, it is not possible, in the majority of cases, for the user to make such measurements. The following can be checked using basic instrumentation:

- electrical power input (kW);
- power factor;
- mechanical output and efficiency.

Electrical power measuring instruments are not normally fitted to individual motors in the power range under consideration (<150 kW). However, measuring equipment is available which can be temporarily connected to the motor to record power input.

6.1 Safety

Safety when taking measurements is of prime importance as both electrical and mechanical accidents can be fatal if stringent precautions are not taken.

The appropriate Health and Safety Executive regulations should be applied; it is recommended that a qualified and competent person should always carry out the tests and measurements. All requisite ‘permits to work’ should be obtained prior to carrying out the measurements and any regulations should be fully understood and implemented.

6.2 Obtaining the Information

Several instruments are available for recording the necessary electrical parameters. The information most usually sought is kW or kVA of demand, and kWh and kVARh consumption details.

To obtain this information it is necessary to monitor both voltage and current.

Voltage measurements are usually taken by connecting the instrument to the motor terminals. Current readings can be obtained by using clip-on ammeters or current transformers (CT’s) fitted around each of the phases of the motor supply cables. Some monitoring systems use a standard 240 volt single-phase power supply with the user inputting the voltage of the system being measured. In these cases only the current readings need to be taken. Even if the waveform of the supply is distorted by a motor controller it is still possible to get ‘accurate’ readings using clip-on CT’s although this is not recommended if the power factor is low. Fig 5 shows the basic connections.
Self-contained electrical power measuring and recording instruments can be purchased for between £700 and £2,000, depending on the degree of sophistication, or hired on a week-by-week basis for between £50 and £100. (See Appendix 2 for details of suppliers/manufacturers.) However, not all instruments measure kW and kWh and care should be taken when choosing such equipment.

To measure the power factor of a motor, or the site electricity system in general, it is necessary to obtain both the value of the power taken, using a wattmeter, and the r.m.s. volts and amperes, using a voltmeter and ammeter. The voltmeter should be connected across the load (in parallel with it) and the ammeter connected in series.

The power factor (p.f.) is then given by:

\[
p.f. = \frac{\text{Power input (Watts)}}{\text{r.m.s. volts} \times \text{r.m.s. amps (Volt. Amps)}} \quad \text{i.e.} \quad \frac{W}{VA} \quad \text{or} \quad \frac{kW}{kVA}
\]

Motors and drives do not exist in isolation but are part of an integrated process or environmental system. Therefore, before any tests or modifications are carried out, it is essential that the role of the motor in the complete system is understood.
Incorrect or inefficient practices should be identified and if possible eradicated. Only then can a fair assessment of the true situation be made. For example, if the driven equipment is in need of substantial maintenance or overhaul, the load on the motor could be much higher than actually required. Consequently the results of any tests may not reflect the best possible case for improvements to the motor and/or drive system.

The measured data should be used, in conjunction with the motor nameplate details, to determine the mechanical output and efficiency. It can also be used to calculate running costs and provide an estimate of the potential savings if changes are implemented.

6.3 Obtaining Assistance

Specialist assistance can be obtained from consultants, motor manufacturers/suppliers or electrical/mechanical contractors. The potential benefits from improving motor efficiencies and drive systems are usually sufficient to warrant the use of outside help even though there may be a cost associated with engaging specialists.

6.4 Where Load and/or Speed Varies

Where significant load or speed variations occur, it is also necessary to determine the duty cycle (See Fig 6). With a pump, for example, this is done by monitoring the hydraulic system pressure and flow over a representative time period.

In Fig 6 the cycle has been divided into eight segments, each segment showing the proportion of the total operating time spent by the pump delivering that particular flow.

The pump operates for significant periods at less than its rated capacity. In fact for almost 50% of the time the flow is 60% or less of the rated capacity and the application of a variable speed drive would be cost-effective.

![Fig 6 Typical Centrifugal Pump Duty Cycle](image)
6.5 Determination of Present Operating Costs

Where a device is being driven by a motor providing a steady and continuous load, the operating costs can be readily predicted. However, there are many applications where the load fluctuates, is intermittent or is cyclic in nature. In such cases, the load pattern, over a suitably representative period, has to be determined by monitoring the varying times and levels of load that are imposed. The running costs can be calculated using the assessed loads, motor efficiencies and associated running times.

Two examples of running costs are given below. Motor efficiencies are taken from manufacturers' data sheets.

Calculation 1.

<table>
<thead>
<tr>
<th>Basis</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Full load efficiency</td>
<td>30 kW</td>
</tr>
<tr>
<td>Part load motor output</td>
<td>20 kW</td>
</tr>
<tr>
<td>Calculated motor efficiency</td>
<td>20 kW</td>
</tr>
<tr>
<td>Annual hours run</td>
<td>2,000h</td>
</tr>
<tr>
<td>Energy cost</td>
<td>5p/kWh</td>
</tr>
</tbody>
</table>

Annual cost of energy for continuous running under actual load:

\[
\text{Cost (£)} = \frac{(20 \times 2000)}{0.85} \times 0.05
\]

\[
= £2,353
\]

Calculation 2.

Basis: As for Calculation 1 but with the 2,000 hours split into 500 hours at full load, 1,000 hours at 20 kW and 500 hours at an idling load of 5 kW. Under this last condition the calculated efficiency has fallen to 75%.

\[
\text{Cost (£)} = \left[ \frac{(30 \times 500)}{0.87} + \frac{(20 \times 1000)}{0.85} + \frac{(5 \times 500)}{0.75} \right] \times 0.05
\]

\[
= [17,241 + 23,529 + 3,333] \times 0.05
\]

\[
= £2,205
\]

If the motor can be switched off during the idling periods then a cost saving can usually be made. An unknown factor is the amount of additional energy consumed during the restart. However it would not be expected, other than for motors with extended run-up times or abnormal starting currents, for the additional power taken to exceed 1% of the motor rating, on the basis of one start per hour. Normally the effect on maximum demand due to additional transients would also be minimal.

These calculations have been simplified in that they do not allow for the actual electricity tariff structure which is more complicated and usually involves maximum demand charges etc.
6.6 Storing the Data

It is important that all data are tabulated in an organised manner so that performances can be reviewed systematically at any time. Results should be presented with the most financially attractive options for improvement at the top of the list.

To facilitate updating and re-calculation, the use of a computer-based spreadsheet can provide a systematic and speedy review of schemes previously investigated but yet to be implemented. This can be extremely useful when limited capital resources preclude full implementation of all schemes.

In addition, it is useful for future reference if motors are allocated a unique code number. This can simply be painted on to the motor or, if appropriate, a transfer or plaque can be affixed.
7. LOW-COST SAVINGS OPPORTUNITIES

Before embarking on a plan of motor and/or drive renewal it is advisable to review the existing situation to establish whether savings can be achieved without incurring significant costs.

7.1 Stop/Start Operation

The simplest way of achieving savings is to 'switch off' the motor if it is not required. In many cases motors are switched on at the beginning of the working day but are only required on an intermittent basis. The accumulated energy loss during idling conditions can be considerable. There are also applications where under normal running conditions the unit may not be required. For example, air handling units can be switched off for significant periods of time without any noticeable impact on air quality in the ventilated space.

A number of devices are available which facilitate automatic stopping of the motor. The majority of these employ load sensors which automatically stop the motor when it runs in an unloaded state for a pre-set time. Typical applications include:

- weaving machine motors left running whilst production and/or machine problems are resolved;
- pumps and compressors left running against closed valves;
- machine tools left running during meal breaks or between different cutting operations.

An alternative approach involves stopping the motor for a set period in every hour. This is usually more effective where there is a group of motors and each one can be stopped in rotation for a relatively short time. To ensure the electrical integrity of the motors and their control equipment, excessive stopping and starting should be avoided. Applications include air conditioning plant, extract fans and circulating pumps.

It is comparatively easy to make an assessment of the savings which automatic stopping equipment can achieve. In Calculation 2 (Section 6), the cost of idling a motor at 5 kW for 500 hours was £167/year. This calculation neglects the effect of low power factor, which is common to lightly loaded motors, because its impact on savings/costs would be negligible unless the majority of motors on the site were similarly loaded. Also ignored are the marginal costs associated with starting currents.

In conjunction with adjustments to motor switching procedures, it is advisable to review the tariff structure. Most electricity tariffs penalise users whose consumption tends to exhibit peaks. Cost savings may be possible by the re-scheduling of plant operations to reduce peak demands. Similarly, the transfer of operations to a lower priced electricity tariff period may be practical.
7.2 Star/Delta Connection

Star and delta motor winding connections were briefly mentioned in Section 3. In many cases all six ends of the three phase windings of a motor are brought out to the terminal box to facilitate star or delta connection (Fig 7).

By reconnecting the windings of a three-phase motor in star when their normal connection at rated voltage is delta, the voltage across each winding is reduced by the square root of 3 (i.e. 58% of its rated value). However, for any given load the current in the windings will increase by root 3 to compensate for the reduction in voltage, thereby limiting the amount of power available. Consequently, continuous running in this mode should only be contemplated where the motor is permanently underloaded, i.e. running at less than 58% of full load. Such a system should be cheaper than buying a smaller replacement motor and if full load power is subsequently required, it is a straightforward procedure to revert to the delta connection.

Fig 8  Effect on Losses of Reconnection from Delta to Star of a 7.5 kW Standard Motor
These low load power savings were demonstrated by work carried out at Surrey University. In the case of a 7.5 kW standard motor, the reconnection from delta to star limited the available output power to 4.3 kW. However, reasonable power savings were achieved at light loads. At 1 kW load a reduction of 50% in the losses, to 0.25 kW, was achieved. When the load exceeds approximately half of the rated value, the savings disappear and losses become higher than those of the delta-connected configuration. These trends are illustrated in Fig 8.

The effect of reconnecting the motor windings in star is to reduce the voltage-related iron losses. At low loads the iron losses are more significant than the current-related copper losses and therefore, although the copper losses increase due to the increased current, they are more than offset by the reduction in iron losses.

Similarly, reactive power consumption was also shown to be lower with a star connection, particularly at very light loads. The saving in kVAR as a function of output power for the standard 7.5 kW motor is shown in Fig 9.

The financial benefits of reduced reactive power consumption can only be evaluated in conjunction with the supply tariff and with a knowledge of the load pattern for the complete installation. A lower reactive power consumption will also give better voltage stability at the motor terminals, opportunities for smaller cable sizes, and require less extensive power factor correction.

High efficiency motors are discussed later, but it is appropriate to note that data from Surrey showed the difference in performance of the star-connected standard and star-connected high efficiency motor to be minimal.

---

**Fig 9**  Effect of Reconnection from Delta to Star on Reactive Power Consumption of 7.5 kW Standard Motor
7.3 Decision Tree

The decision tree in Fig 10 can assist in determining whether a low cost option exists.

The option of switching to running in star should only be considered if a star-delta starter is already attached to the motor. If it is not attached a more cost-effective option would be a motor controller. These are discussed further in Section 8.2.
8. THE TECHNOLOGY

A basic understanding of the technologies involved is useful in selecting the most cost-effective option for minimising losses. High efficiency motors (discussed in Section 8.1) and motor controllers (Section 8.2) are options for constant speed motors. A decision tree detailing appropriate application areas for these technologies is given at the end of Section 8.2. Section 8.3 discusses options for varying the speed of a motor.

As discussed in Section 3, motor losses are:

- copper losses \( (I^2R) \), proportional to load;
- iron losses, constant regardless of load;
- mechanical losses, related to speed, but independent of load;
- stray losses, related to load.

8.1 High Efficiency Motors

When a motor is required to produce a relatively constant and continuous torque, the main selection criterion is its rated load efficiency. If the duty cycle is high then motors with the highest efficiency will offer the lowest running costs.

High efficiency induction motors consume less electricity than comparable standard motors for any given load. They commonly employ the same materials as standard motors, but more copper and iron is used and in some cases the laminations are of a higher quality steel. One of the principal manufacturers of such motors in the UK, Brook Crompton Parkinson, cite four improvements which can contribute towards the energy efficiency of their range.

- Longer core lengths of low-loss steel laminations. These reduce the flux densities and hence the iron losses.
- Copper losses are reduced by maximum utilisation of the slots and by providing 'generous' conductor sizes in the stator and rotor.
- Stray losses are minimised by careful selection of slot numbers and tooth/slot geometry.
- A more efficient motor generates less heat so the cooling fan size can be reduced, leading in turn to lower windage losses and hence less wasted power.

Fig 11 compares the efficiencies of standard motors with those of the ‘Energy Efficient’ range available from Brook Crompton Parkinson.

![Fig 11 Comparison of Full Load Efficiencies of Standard and 'Energy Efficient' 4-Pole Motors](image)
Independent Measurements on High Efficiency Motors

On behalf of the EEO, the University of Surrey tested three Brook Crompton Parkinson 'Energy Efficient' motors and compared their performance against three standard induction motors. The motors tested had ratings of 3, 7.5 and 22 kW.

Typical test data for the 7.5 kW motors is shown in Fig 12. Both efficiency and power factor are superior for the high efficiency motor over the whole operating range. The test confirmed the motor manufacturers' specification test certificates.

![Graph showing efficiency and power factor comparison](image)

Fig 12  Comparison of Efficiency and Power Factor for Standard and 'Energy Efficient' Motors Rated at 7.5 kW

At full load these savings were 3.3% for the 3 kW motor, 6% for the 7.5 kW motor, and 4.5% for the 22 kW motor. The energy savings achieved by the three high efficiency motors (Fig 13) also show that the savings at different motor loadings varied for the 7.5 and 22 kW motors but remained almost constant for the 3 kW motor.

![Graph showing energy savings](image)

Fig 13  Energy Savings Achieved by the 'Energy Efficient' Motors Tested
Fig 14 Reactive Power Consumption in Standard and ‘Energy Efficient’ Motors

Fig 14 shows the reactive power consumption of the 7.5 kW motors. Again, the ‘Energy Efficient’ motor is superior. The only instance when the reactive power of the high efficiency design was more than the standard equivalent motor was when the 3 kW motor was operating at high loads; this was also borne out by the data shown in the manufacturers’ test certificates.

Example of Payback for 7.5 kW ‘Energy Efficient’ Motor

From Fig 12, it is possible to assess the value of the energy savings achieved with a high efficiency motor. The saving at full load is approximately 0.45 kW, which, at a cost of 5p/kWh, is worth 2.25p/hour; this is equivalent to 6% of the motor running cost.

The list price of a standard 7.5 kW motor is £226, while the equivalent high efficiency motor is £330, a premium of £104. From Table 1 the payback period for the ‘Energy Efficient’ motor, on a marginal cost basis, is approximately 5,000 hours, equivalent to 6.8 months of continuous running at rated load. At lighter loads the payback period will be slightly longer.

Table 1 7.5 kW High Efficiency Motor Savings as a Function of Utilisation

<table>
<thead>
<tr>
<th>Utilisation (hours)</th>
<th>Savings (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>45</td>
</tr>
<tr>
<td>4000</td>
<td>90</td>
</tr>
<tr>
<td>6000</td>
<td>135</td>
</tr>
<tr>
<td>8000</td>
<td>180</td>
</tr>
</tbody>
</table>

High efficiency motors are therefore extremely attractive when either a new or replacement motor is needed.

On energy savings alone the cost does not, at present, generally justify replacement of an existing motor with an ‘Energy Efficient’ one; the full cost of the motor plus installation will usually give a payback period in excess of two years, even if the motor runs continuously.
A number of manufacturers offer high efficiency motors, although they are not necessarily marketed as such. When choosing a new motor it is important to obtain technical details on the motor's performance across the full load range. This is important as motors on average operate at between 60% and 80% of rated load. It is also prudent to obtain copies of manufacturers' 'motor type' test certificates showing full performance data.

A calculation of relative operating costs of standard and high efficiency motors is given in Appendix 3, the example showing a payback of 1.2 years.

8.2 Motor Controllers
Some applications require a motor to run for extended periods at light loads, e.g. conveyors, moving walkways, extruders etc. Motor efficiency falls under such conditions as the voltage-related iron losses predominate. The motor controller, sometimes known as a voltage controller, reduces the fall in motor efficiency which occurs as the load drops below 50% of the rated value. It does this by regulating the voltage at the motor terminals in such a way as to provide just sufficient magnetising forces to meet the driven load demand. Thus a corresponding reduction in the iron losses is obtained and the efficiency and power factor are improved.

Motor controllers absorb power due to the voltage drop across the thyristors used in them. At high loads this can lead to a small operating cost penalty and so a knowledge of the duty cycle is important to enable a full cost/benefit analysis to be carried out.

Motor controllers usually incorporate 'soft start' capabilities which progressively adjust the voltage applied to the motor terminals during the starting cycle, thus minimising current inrush and achieving sensitive control over the motor. A 'soft start' also reduces mechanical stresses in the motor windings and external equipment. It is recommended that if a 'soft start' is being purchased, a controller should also be considered, as the additional cost is small.

Independent Tests of Motor Controllers
A number of motor controllers were tested by Surrey University on behalf of the EEO. The controllers were supplied by Fairford (the Fairford type), AECON (the Unsworth type) and Condor (the NASA type). A selection of the test data is shown in Fig 15.

Fig 15 compares the efficiency and power factor for the 7.5 kW standard motor alone and with the Fairford FEL/E75 controller. It can be seen that the controller improves both efficiency and power factor at low motor loads. The two other types of controller were also connected to this motor. The Unsworth type performed in a similar way to the Fairford type, while the Condor NASA type gave smaller savings due to smaller voltage reductions at low loads. There was little difference between the controller types in terms of reactive power savings (Fig 16).

![Fig 15](image-url)
The energy savings achieved on a 3 kW, 7.5 kW and 22 kW standard motor, with a motor controller, are shown in Fig 17. This shows the benefits achieved at light loads and the slight cost penalty, at or near full load.

All motors and motor/controller combinations were capable of delivering rated output power.

Fig 16 Reactive Power Consumption of the 7.5 kW Standard Motor, Showing Similar Performance of the Three Controllers

Fig 17 Energy Savings Achieved with Motor Controllers on the 3, 7.5 & 22 kW Standard Motors
Cyclic Load Tests

Work was also conducted at Surrey University on the cyclic behaviour of standard motors with and without controllers. Table 2 gives the energy savings achieved in kWh and kVAr.

Two loading regimes, i.e. duty cycles, were investigated.

- Duty Cycle 1; 2 minutes at 100% load, 10 minutes at 10% load, repeated 5 times.
- Duty Cycle 2; 10 minutes at 100% load, 50 minutes at 10% load.

The savings in reactive power (Table 2) were significantly higher than those obtained for true power, illustrating the improvement in power factor which takes place with improved matching to the load. In the case of the 3 kW motor the true power savings were also significant.

<table>
<thead>
<tr>
<th>Controller</th>
<th>Duty Cycle</th>
<th>Motor Size kW</th>
<th>Savings over Motors without controllers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>kWh</td>
</tr>
<tr>
<td>Fairford</td>
<td>1 2</td>
<td>3</td>
<td>0.17</td>
</tr>
<tr>
<td>FEL/E4</td>
<td></td>
<td></td>
<td>0.18</td>
</tr>
<tr>
<td>Fairford</td>
<td>1 2</td>
<td>7.5</td>
<td>0.21</td>
</tr>
<tr>
<td>FEL/E7.5</td>
<td></td>
<td></td>
<td>0.10</td>
</tr>
<tr>
<td>AECON</td>
<td>1 2</td>
<td>7.5</td>
<td>0.24</td>
</tr>
<tr>
<td>AOPC10</td>
<td></td>
<td></td>
<td>0.14</td>
</tr>
<tr>
<td>Fairford</td>
<td>1 2</td>
<td>22</td>
<td>0.38</td>
</tr>
<tr>
<td>FEL/E22</td>
<td></td>
<td></td>
<td>0.45</td>
</tr>
</tbody>
</table>

Decision Tree

A decision tree for the selection procedure of a constant speed motor is shown in Fig 18.
When a motor has a high duty cycle (i.e. when it is operating at or near full load for most of the time), the use of a high efficiency motor is recommended. However, this is likely to be most cost-effective when motor replacement is needed. For a new system a high efficiency motor should always be considered.

If the load is constant and significantly lower than the rated motor output, a smaller motor could be appropriate. A high efficiency motor should again be considered.

In cases where the motor load varies and is frequently less than 50% of rated load, the addition of a motor controller can be cost-effective. This will still enable the motor to deliver its rated load should it be required for part of the cycle.

8.3 Variable Speed Systems

The objective of all variable speed systems is to enable a machine to run at a speed that more closely matches the desired optimum speed than is possible with a single fixed speed.

Variable speed systems fall into three categories; electronic variable speed drives (VSD's), variable speed motors and electromechanical variable speed systems. Each of these has subdivisions (Fig 19).

Historically, variable speed systems were not installed for energy saving reasons but to satisfy process or environmental requirements. As a result, the degree of sophistication was determined by the requirements of the process and usually meant that the particular speed needed was preselected and controlled manually from the range available.

Today many more options exist and modern electronics, helped by the comparatively high cost of electricity, have brought about a revolution in options. Infinitely variable and constantly changing speed can now be achieved at a relatively modest cost, determined mainly by the degree of flexibility required of the system.

The potential of various systems is now considered, with particular emphasis on those which are suitable for retrofitting.
8.3.1 Electronic Variable Speed Drives (VSD's)

In general, VSD's operate by converting a fixed power source into a variable one. The electronics usually convert the ac mains voltage to a variable dc voltage which is then inverted into a variable voltage, variable frequency ac supply (some ac motors can be controlled by varying the voltage alone).

For the VSD facility to function, there must be feedback from a measured parameter into the VSD control circuit. The parameter can be any significant variable (or variables), providing there is a sensor available to react to the change. For example, VSD's may be controlled from pressure, temperature, speed, volumetric flow, power, or a combination of these. The choice depends only on the VSD's control logic.

Fig 20 shows a VSD application where the pump speed is varied to maintain a constant discharge pressure regardless of user demand.

![Diagram of VSD controlling pump discharge pressure]

Some of the latest equipment employs user-programmable logic and/or sophisticated software enabling complex mathematical models to be incorporated to optimise energy consumption and/or other significant factors.

VSD's are particularly attractive where flow modulation is required. Examples, discussed in more detail in Section 9, include pumps, fans, refrigeration and air compressors. Applications for VSD's also exist where a constant power or torque is required over a speed range. For example, machine tool spindles require constant power while extruders need a constant torque.

**Motors Suitable for VSD Control**

The type of VSD which can be used depends on the type of motor fitted. There are two basic types of ac motor, asynchronous and synchronous. Both of these can be controlled by electronic VSD's.

The main criteria when assessing the suitability of a motor for VSD are: the motor is not overheating in its present application as ventilation will be reduced at lower speeds and marginally more heat will be created in the motor as a result of fitting a VSD; if an increase in speed is anticipated, the motor and its driven parts such as pulleys, belts, gears etc should be able to withstand the increased centrifugal forces resulting from the higher rotational speeds; the motor loading may also increase at higher speeds and limit the maximum speed possible (this should be carefully monitored when the speed is first increased).
**Types of AC Variable Speed Drives**

There are essentially three inverter types. These are:

- the pulse width modulation (PWM) voltage source inverter;
- the six step voltage source inverter;
- the six step current source inverter.

All of these can be retrofitted to existing motors, but some derating of the motor (possibly by up to 10%) is necessary, particularly with six step inverters, to prevent overheating.

**PWM Voltage Source Inverters** extend control down to zero speed and up to three/four times normal synchronous speed. The power factor of the supply current is normally high and relatively constant over the whole speed range. Since the output waveform is close to a pure sine wave there are few problems due to harmonics on the motor. This has become the most popular form of VSD today.

**Advantages:**

- high efficiency;
- good control over speed range, including low speeds;
- high power factor;
- low frequency harmonics not a problem;
- multi-motor operation possible;
- maximum output voltage equal to line voltage;
- area of high innovation – eg, vector drives;
- can be bypassed in event of VSD failure.

**Disadvantages:**

- high frequency harmonics can cause noise in the machines (check with manufacturer);
- complex electronics – high switching frequency can affect reliability.

**Six Step Voltage Source Inverters** are well-proven and used for speeds of between one and two times those derived solely from standard mains frequency. However, as the motor speed falls, so does the power factor. The variable frequency ac waveform produced is derived from a ‘six step’ staircase simulation of the voltage.

**Advantages:**

- high efficiency;
- multi-motor operation;
- well-proven inverter type;
- can be bypassed in event of VSD failure.

**Disadvantages:**

- can have low power factor;
- can induce pulsating torques in rotor at low frequencies;
- poor low speed performance.

**Six Step Current Source Inverters** operate on the six step principle applied to current. The speed range is usually limited to 20-100% of that derived from mains frequency. When applying this type of controller to an existing motor, caution is needed because of harmonics and transient overvoltages. The line currents to the motor contain harmonics which may cause significant overheating, particularly at lower speeds, and so necessitate some derating of the machine. The overvoltages may stress ‘aged’ stator insulation in which case suitable surge dissipation networks should be fitted. The motor power factor is poor at speeds less than 50% of that developed by mains frequency.
Advantages:
- electrically robust;
- well-proven inverter type;
- simple circuit;
- regenerative braking;
- can be bypassed in event of VSD failure.

Disadvantages:
- low speed torque pulsations;
- low starting torque;
- low power factor;
- multi-machine control not so easy;
- slow response;
- careful matching of motor and drive needed to avoid voltage peaks.

Inverter Selection

The type of variable speed drive selected must match the motor, be it asynchronous or synchronous.

Selecting the appropriate VSD depends upon so many factors that it cannot be simply represented in a decision tree. A first screening can be done using the relative advantages listed above. The ability to retrofit the drive may be important, as may multi-motor operation. If performance at low speed is important some inverters would be ruled out.

Secondly, equipment suppliers should be approached and cost comparisons made. A guide to inverter prices is given in Appendix 4. Suppliers should be asked to indicate any installations of their equipment which are similar to those required. As a rule, initially concentrate on suppliers who deal in a range of VSD types.

Further data on drive selection is given in Section 9.

8.3.2 Variable Speed Motors

Two-Speed AC Motors

These are the simplest form of variable speed motor likely to be encountered and provide a low cost option.

The motor is normally wound for 2- and 4-pole operation with the terminations provided for both configurations. Performance at both speeds is the same as for a single-speed motor operating at that speed.

AC Three-Phase Commutator Motors

Commutator motors are available in a power range from a few kW to 150 kW, and are suitable when accuracy of speed control is not required. They have brushes, putting them in a similar category to dc machines (discussed later) as far as maintenance is concerned.

Advantages:
- simple and reliable;
- negligible impact on mains
- overall system modestly priced.

Disadvantages:
- motor can be expensive;
- efficiency 85% maximum;
- brush gear maintenance needed;
- cannot be bypassed in event of VSD failure.
**Modified Induction Motors**

Voltage control alone, on a modified induction motor, is offered by some manufacturers. The cost of this is less than a standard induction motor plus inverter, but low speed efficiencies are poor and its application should only be considered where speeds in excess of 50% of rated speed are generally expected.

**'Latest Technology' AC Switched Reluctance Motor and Drive Systems**

The switched or variable reluctance motor is the most basic type of stepping motor as it has no rotor windings. The motor works on the principle of magnetic attraction. Current is switched round the stator poles, the rotor being attracted towards the current carrying stator pole. This leads to several major advantages over other VSD systems.

**Advantages:**
- high efficiency;
- simple, rugged motor, easy to control;
- simple power electronics;
- does not fail if a phase is lost;
- wide speed range;
- high accuracy of speed control;
- rapid response.

**Disadvantages:**
- cannot be bypassed in event of failure;
- pulsing can cause noise;
- not widely used yet.

**DC Motor and Drive Systems**

The dc drive with thyristor control remains the most common VSD system, despite the progress made by the ac inverter-based systems. Many of the major suppliers of ac and dc equipment are still investing heavily in dc systems.

**Advantages:**
- control range 0-100%;
- wide power range (1 kW to 10,000 kW);
- high accuracy of speed control;
- dc systems can be cheaper than ac inverter systems for higher powers (>30kW).

**Disadvantages:**
- maintenance costs higher than ac systems;
- drive cannot be bypassed in event of failure;
- may have high harmonics effect on supply;
- sparks from commutator may present fire hazard.

**8.3.3 Electro-Mechanical Drives**

There are three types of drive in this category; the mechanical variators, hydraulic couplings and eddy current couplings.

**Mechanical Variators:** There are two main types; those using V-belts (for lower powers, typically up to 25 kW), and those using steel chains. In combination with gears, a wide range of output speeds can be achieved. The efficiency of the drive alone is about 90% (neglecting the motor efficiency). Manual speed setting is the norm, but automatic adjustment is available. The principal limitation is that the available torque is inversly proportional to the speed.
Of those options which involve no motor changes, the use of adjustable guide vanes gives a better performance than dampers. Although unique to the axial-flow fan type, variable pitch blades rival the best offered by VSD's in efficiency benefits. However, a new fan is needed.

The disc throttle flow control system, developed for centrifugal fans, gives efficiencies midway between those afforded by inlet guide vanes and the variable pitch method on axial fans. However, a new fan is needed. Where several fans are run in parallel, switching off units as demand decreases should be attractive. (See Ref 1 for multiple fan operation and Ref 2 for disc throttle systems).

When a variable speed option is introduced, the opportunities increase considerably. The use of two-speed motors, with the added potential to switch them off in multiple fan banks, can achieve savings at comparatively low capital cost. In addition, two-speed motors can be combined with guide vane control.

The use of fixed speed motor controllers should be considered when running at mainly low loads, in conjunction with effective aerodynamic flow control methods. A fan with the load profile shown in Fig 23 might be a suitable candidate, although a two-speed motor should also be considered as another option.

![Operating Cycle Characteristic of Fan Suitable for a Motor Controller](image)

**Fig 23** Operating Cycle Characteristic of Fan Suitable for a Motor Controller

**Selecting the Optimum System**

Selecting the optimum flow control system depends upon the type of fan, the fan characteristic, and the annual operating load profile of the system. Where the fitting of a VSD is envisaged, the fan's suitability for variable speed operation at the required load should be confirmed. If the fan has not been specified, the relative merits of centrifugal and axial flow systems should be examined. The off-design efficiency advantages of axial flow variable pitch units, over all except the most advanced VSD's should be considered carefully.

Some suppliers of VSD's have produced curves which, for typical operating profiles and technical options, show the electricity savings (kWh) which might be saved in a year (Fig 24).
Fig 24 is based on an operating profile where the fan is running for much of its life at 50% or less of design flow rate (see Fig 23). The annual savings on a 50 kW fan motor running for 8,000 hours/year, arising from the use of a VSD as opposed to inlet guide vane control, is approximately 150 MWh (line 2 in Fig 24). At an electricity cost of 5p/kWh this would be worth £7,500/year giving a payback period of between one and two years.

Fig 24 Energy Savings from Various types of Fan Control (Logarithmic Scales)

A two-speed motor with guide vane control would be another viable option (see Ref 1). Fig 25 shows the relative prices (1986 data) of systems employing ac variable frequency drives, ac commutator motors, dc motors, and eddy current couplings. The lower cost of the eddy current coupling should be set against the higher efficiency of the inverter VSD (see Fig 24).
Summary of Options
The principal options for flow control in fan systems are shown in Fig 26. Suppliers of the dedicated variable speed systems, motors and motor controllers are listed in Appendix 5. Systems which are readily retrofitted include motor controllers and inverters to squirrel cage induction motors. If flow control is not required the use of a high efficiency motor for constant high load use is recommended.
9.2 Pumps

The diversity of pump applications is far greater than that of fans. However, the selection criteria of the appropriate control technique are very similar for both pumps and fans. This is particularly true if speed variation is the chosen method.

Pumps are categorised as centrifugal or positive displacement. However, the centrifugal pump is more common, and most of what follows relates to this type.

**Pump Characteristics**

Pumps have much in common with fans and the laws governing their operation are similar. Head/flow and efficiency curves for a typical centrifugal pump operating at constant speed are shown in Fig 27. The head/flow curve is known as the pump's characteristic curve and usually refers to certain specified speeds and densities of the medium being pumped. The design point in this example is selected so that maximum efficiency occurs at 100% flow. The similarity of the curve with that for the fan (Fig 21) is clear.

![Fig 27 Typical Centrifugal Pump Head/Flow and Efficiency Curves for a Constant Speed Condition](image)

If the pump characteristics are examined when speed variation is introduced, the basic relationships which govern their operation are evident (Fig 28).
Fig 28 Typical Centrifugal Pump Performance Characteristics for variable speed

The pump efficiency shows little reduction over the upper portion of the speed range, but rapidly decreases as the speed falls below 60% of the design value. However, as pump size increases the decline in efficiency with reducing speed tends to become less severe.

The energy expended by the pump motor results from a requirement to move the liquid and, in some instances, to lift it. Thus the working point on the pump curve is determined by the mass flow-related pipeline resistance and any static delivery head which must be overcome if the liquid is to flow.

Those elements which significantly influence the pipeline resistance are:

- pipe diameter and length;
- coefficient of friction;
- liquid specific gravity;
- number of valves and other fittings eg bends, tees etc;
- mass flow velocity.

Speed control of the pump (Fig 29) is one method of changing the design point.
The available methods of controlling centrifugal pumps are similar to those of controlling fans.

The most common method is ‘throttling’ by means of a control valve. The effect of throttle control on efficiency, in terms of system power demand, is shown in Fig 30. While throttling is better than recirculation in terms of energy use, (ie venting part of the flow into a bypass for recirculation), VSD's allow the pump's characteristic curve to be followed much more effectively.

In many applications the static delivery head is relatively small. Notable exceptions are ‘mains’ water systems and boiler feed pumps which operate against a high pressure.

Under zero static delivery head conditions the power input to a pump varies as the cube of the flow; thus if 100% flow requires full power, 80% flow will only need half full load power. A further flow reduction to 70% leads to a power requirement of one third full load power.

Fig 29  Flow variation with Speed Reduction

Fig 30  Power requirement, as a function of Flow for Various Pump Control Methods
The effect of speed control on the energy consumption of a typical centrifugal pump is shown by comparing Fig 31 with Fig 32. A comparison of the relative energy losses in the two cases may be gauged from the shaded areas in the figures.

![Fig 31 Power Consumption in Fixed Speed Pumping](image1)

![Fig 32 Power Consumption using a VSD, and Power Saved](image2)

Speed control methods are most appropriate where the friction losses dominate in the system characteristic. In cases where the static delivery head is the principal component, speed control will show less benefit.

Cyclic control (Fig 30) is effected by continually stopping and starting the pump to maintain a flow less than the design value. However, frequent starting can adversely affect the power factor of the supply (leading to increased electricity charges) and increase wear. Such an operating technique may benefit from the use of ‘soft start’ equipment.

Alternatively, the base flow may be provided by a constant speed pump with the control range achieved by using a speed-controlled pump. If the two pumps are of the same capacity, a reasonable reduction in energy consumption within the 50-100% control range can be expected. Where several pumps are operating in parallel, simple on-off control of one or more pumps may be sufficient, depending on the complexity of the application. In multi-pump installations, the savings from variable speed control are generally reduced (Ref 3). Unless smoothness of control is an important aspect, more than one VSD may be unnecessary.

**Selecting the Optimum System**

The selection of the optimum system for reducing energy costs is a function of several parameters. For a centrifugal pump, the operating characteristic, load profile and system power input have a bearing on the equipment which might be considered.

The extent of savings will vary with:

- the degree of pump turn-down;
- the gradient of the head flow curve;
- the gradient of the system curve;
- reduction in static delivery head;
- number of hours run;
- energy costs.

In addition, the pump duty cycle and data on control methods employed and their relative efficiencies will be required.
Having outlined the factors which influence the energy savings from the use of a VSD, it is possible to identify applications where the financial benefits are likely to be most attractive. A paper given to the I.Mech.E by Bower (Ref 3) covers these in some detail. The principal areas are:

- mains water supplies, process usage and similar applications where flow varies along extensive pipework systems, and frictional losses dominate;
- applications in which the pump is switched between alternative systems having different characteristics;
- test facilities where varying flow rates and pressures may be required;
- batch processes involving cycles where varying flow rates are required although batch processes are, by their nature, generally less amenable to rapid paybacks;
- systems where the capacity must be kept constant, independent of system pressure which may be varying. Processes involving liquids which may change in viscosity would be an example.

In addition to the energy cost reductions achievable, other benefits can arise from the use of VSD's. These include the elimination of problems created by water hammer, the reduction of hydraulic loading on impellers (which can be caused by other control techniques such as the use of throttle valves), and improved product quality.

From Bower’s data, it is possible to determine graphically the additional cost of pump operation arising from inefficiencies in the mechanical drive system, assuming a knowledge of the duty cycle of the pump. Fig 33 shows the additional running costs resulting from drive losses.

Fig 33 Additional Running Costs Resulting from Drive Losses
From this, the cost penalty can be determined for each representative operating period. For example, a 100 kW pump running 12 hours per day (i.e. an operation factor of 50%), with a drive efficiency of 90%, would cost an additional £2,000/year to operate due to drive losses.

**Specific Options**

The options available for the operation of pumps are shown in Fig 34.

- **High Efficiency Motors**: In cases where design load duties are expected, it is sensible to consider installing high efficiency motors on new installations or where motors need replacing.

- **Two-speed Motors**: The use of two-speed motors can be beneficial where the demand on the pump follows an appropriate characteristic, or in conjunction with switching off in multiple pump installations.

- **Variable Speed Drives**: VSD's are appropriate to pumps. The relative merits are listed in Section 8.3.

Fig 35 shows the relationship between cost savings and the flow and system head for a 100 kW pump VSD. A reduction in flow of only 25% from the design point will give an annual saving of £10,000, or a payback period of slightly over one year (based on capital costs derived from Fig 46 in Appendix 4). Further data is given in Ref 4 and Ref 5.
9.3 Compressors

Compressors, like pumps and fans, fulfil a wide variety of roles in many industrial sectors, as well as in buildings. The function of compressors is to raise the pressure of gases, the most common being air and refrigerants. Natural gas and industrial gases are also compressed, but the compressors used in these duties frequently lie outside the power range covered by this Guide.

Statistics for energy consumption in compressor duties in the UK suggest that there is scope for considerable cost savings. It is estimated that approximately 10% of all industrial electricity consumed in the UK can be attributed to the use of compressors. A survey of large users of refrigeration carried out in 1984 showed that better system control, including compressor control, could give savings worth £12.5M/year.

Compressor thermodynamics follow the same laws regardless of the type of compressor being used, although efficiencies can vary considerably from one type to another. In addition, each type of compressor has its own characteristics which influence the way in which its performance can be controlled. The compressors of principal interest are categorized as positive displacement machines.

Most of the discussion relates to new compressors, where energy-saving techniques are now regularly incorporated.

The most common types of positive displacement compressor are the reciprocating compressor and the various rotary types such as screw and rotary vane. Centrifugal compressors are at the top end of the size range, as is the more recently introduced scroll compressor. The latter is becoming popular in some refrigeration/air conditioning duties.

Reciprocating Compressors

The volumetric flow of a positive displacement compressor is the product of displacement, volumetric efficiency (which is the ratio of the delivered volume to the displacement), and the rotational speed. All relevant parameters are at suction, i.e. compressor inlet side conditions.

For a constant pressure ratio, the volume per stroke is fixed by the design of the machine. Thus the volumetric flow is determined solely by the speed of the compressor.
The volumetric efficiency of a reciprocating compressor should not be confused with the mechanical or work efficiency; it is solely the ratio of the capacity of the compressor actually being used to the nominal displacement. One form of compressor control involves the use of 'clearance pockets' which can be automatically opened to alter the compressor volumetric efficiency, thus changing the gas discharge rate. The volumetric efficiency can be reduced from 90% to 30% using this method.

A common technique of capacity control on reciprocating compressors is to 'unload' cylinders by holding the suction valve on the appropriate cylinder(s) open through the complete cycle. This is an attractive method from the point of view of energy expenditure, as rotation of the shaft is not stopped when the cylinder is, in effect, removed from service. Losses arise principally from the fact that flow passes in both directions through the suction valve, and friction losses remain in the unloaded parts of the system.

If 'on-off' control is an option, valve unloading will also reduce the wear and extra energy associated with starting and stopping the compressor. In single cylinder compressors, 'unloaders' can be used to provide on-off operation between two pressure limits. Cylinder unloading and the use of clearance pockets give capacity control with a stepwise characteristic. Where constant pressure or flow is necessary, other variables become important. In this case speed control is especially useful.

Starting torques on reciprocating compressors can be high and therefore great care should be taken in selecting the VSD system. Eddy current drives can give high starting torques although, as an alternative, the VSD controlled compressor can be started in the fully unloaded mode, thereby eliminating this constraint.

In multiple compressor installations, on-off control is quite common. Where a substantial base load exists, a mix of screw and reciprocating compressors might be used. As screw units exhibit poor operating characteristics at part load, their use should be restricted to base load duty while the reciprocating compressors, with cylinder unloading, satisfy load variations.

Some manufacturers select two-speed motors as an option for energy efficiency. This allows equipment selection on the basis of the highest coefficient of performance (COP) at, or close to, the load conditions at which the compressor will be operating for most of its annual running time.

Fig 36 highlights the poor performance of gas bypass control, which is another frequently applied capacity control method. It is also applicable to other types of compressor, in addition to reciprocating units. Fig 36 also shows that at high capacities the added benefits of variable speed control are not significant.
Different compressor types exhibit different efficiency characteristics but the reciprocating machine is generally superior to its common competitors at both full load conditions, and under part load operation (Fig 37). However, this data is general and for particular compressor models the manufacturers should be consulted for accurate efficiency data.

**Fig 37  Part Load Power Consumption of Compressors**

**Rotary Compressors**

The control options for rotary compressors are similar to those for reciprocating units, with the exception of cylinder unloading, which is unique to the latter type.

The centrifugal compressor, which tends to be used at the top end of the power range considered in this Guide, is subject to surge, i.e. pulsating flow reversals brought about by a reversal of the slope of the head/flow characteristic. Recirculation of gases via a bypass can be used to overcome the problem.

The surge limit characteristic of a typical centrifugal compressor may be used to illustrate the effect of inlet guide vane control on compressor turn/down performance (Fig 38). It is claimed that this method of control can rival that of VSD's. An example is quoted by Shinskey (Ref 11) of a centrifugal compressor with guide vane throttling at 70% flow, as using approximately 72% of design power; suction valve throttling would require 75% of power. By comparison the use of a VSD would require 68% of design power for the same load.

**Fig 38  Inlet Guide Vanes to Modulate Centrifugal Compressor**
Extra energy is also required at high load/high power conditions on the larger machines and this highlights the care needed in selecting equipment to match the specified load profile characteristics.

![Graph showing power savings with motor controller](image)

**Fig 41** Net Power Savings Using a Motor Controller

**Variable Speed Drives on Compressors**

The discussion on VSD’s on compressors relates to factory-fitted systems. Retrofitting is not normally practised, and system design has to take into account features such as the natural frequencies of compressor components.

**The Margaux CVC System**

The Margaux VSD system, initially designed for chillers and refrigerators, is now being directed at broader HVAC applications. The continuously variable capacity (CVC) system is based on an inverter. This is linked to a controller which offers either close temperature control or close suction pressure control, in addition to the usual protection and data accumulation/transfer capabilities possible with modern software and sensors.

The controller reduces speed, and hence capacity of the compressor, to maintain the set point condition (i.e. temperature or suction pressure). Reaction to a load reduction, for example, leads to a lower speed and capacity, while a fall in ambient temperature has a similar effect, initiated by the lower condensing temperature.

The inverter used by Margaux incorporates ‘soft-start’ and controlled deceleration facilities. Software is used to help maintain a high power factor and to match torque needs to those of the compressor. For example, a high torque is needed when external conditions require operation at a high pressure ratio. The controller/inverter is also pre-programmed to exclude operation at specific speeds. This can be used to avoid coincidence with resonant frequencies.
The speed range of the reciprocating compressors used is 400 to 2,000 rpm, as compared to the normal 1,450 rpm. The higher speeds are used to meet any peak loads which occur on the hottest days. The size range, in terms of capacity, is 6 to 470 kW.

The Margaux CVC system was monitored under an EEO feasibility study at a supermarket. The results showed a 56% power saving on dairy cases, which are at the higher temperature end of chilling, and a 30% saving on frozen foods. Fig 42 shows power consumptions per day for conventional operation versus CVC operation for both freezing and defrost.

![Dairy/chilled food cases power usage](image)

**Fig 42** Comparisons in Electricity Consumption:
The Margaux CVC System against Conventional Control Refrigeration

**Other Refrigeration VSD Systems**
A number of companies are now manufacturing compressor VSD systems. For further information see M.Mills, Variable speed drives (Ref 8).

Larger packaged air conditioning and heat pump units are now available with inverters fitted as standard equipment. The results of a study carried out by the International Energy Agency (Ref 9) into inverter-driven heat pumps, has produced some interesting findings which are also applicable to refrigeration and air conditioning systems. Although the units tested were 5 kW or smaller, and not therefore representative of industrial scale units, larger reciprocating, rotary vane and scroll compressors were also investigated.

In reciprocating compressors, speed variation was found to be limited at the bottom end of the scale due to lubrication problems and at the top end (3,000 rpm) by valve losses and oscillator forces.

At low speeds, inverter (PWM) losses were considered important, whilst rotary vane compressors suffered from decreasing volumetric and isentropic efficiencies at speeds below and above the optimum of 5,000 rpm. Scroll and small screw machines had limited speed ratios because of internal friction losses.
PART C: FURTHER INFORMATION

11. WHAT TO DO NEXT

There are a number of sources where advice can be obtained. These include equipment suppliers, the network of regional Government offices and ETSU.

It is helpful to have a list of the details which the supplier will need. Examples of the data likely to be requested are given later in this section.

11.1 Sources of Assistance

**Regional Government Offices**

There are 12 regional Government offices located throughout the UK who are able to supply information on a variety of energy efficiency related topics. They have a local knowledge of industry in their region and will be able to help on matters relating to motors and drives technology. For further information on this network, contact the Department of the Environment, tel. 0171 273 3000.

**ETSU**

ETSU manages, on behalf of the Department of the Environment, a series of R&D and demonstration projects in the field of motors and drives. Information on these projects can be obtained from the ETSU enquiries bureau, tel. (01235) 433066.

**Electricity Supply Industry (ESI)**

The ESI, particularly the Area Electricity Boards, are able to advise on all aspects of the efficient and economic use of electricity. In addition there is an award scheme which can, if appropriate, feature motors and controllers. The Boards can also assist with any supply problems associated with motor and drive installation or operation.

**Equipment Suppliers**

Equipment suppliers produce a range of informative literature which can help system selection. By using a supplier who can offer several systems, e.g. dc and ac, or several VSD types, a higher degree of objectivity might be obtained.

**Consultants**

Some consulting engineers specialise in motors and drives, and for large installations it may be worth using their services. Alternatively, electrical contracting engineers specialising in the field might be approached, although they may only have experience in a narrow range of equipment.

**Software Suppliers**

The use of computer models can allow different VSD systems to be assessed before hardware is purchased. Such models are used by many equipment suppliers, but software is now available at a comparatively modest cost, which permits users to perform their own reviews of the options.
Sets of programs are available which comprise a number of ac drive model simulators, including PWM, voltage and current source inverters, cycloconverters and capacitor induction drives. It is advisable to narrow the choice of drive before deciding on the software packages needed. The software comprises full steady state models of each drive system, permitting the computer to be operated as if it was the real drive.

Models can take into account circuit resistance and reactance, power losses, and motor slip speed. The reaction of the drive to input changes can be observed, and parameters such as voltage, speed, power rating and system efficiencies can be altered. Graphics and data tabulation are often built into such programs.

Programs are available which can forecast energy savings and power factor improvements for lightly loaded induction motors. Program inputs often require catalogued slip, efficiency and power factor data for the motor and details of load torque demands.

11.2 Information Needed by Supplier

The type of information which the supplier might require includes: system behaviour, motor/drive characteristics and the load requirements.

**System Behaviour:** The effect of the electrical system on the motor/drive and vice-versa must be considered. This involves:
- speed;
- torque over whole range;
- efficiency;
- power factor;
- reactance (steady state and transient).

**Motor Characteristics** of interest are:
- system voltage and variation;
- system frequency and variation;
- effect of starting current on voltage;
- effect of reactive kVA;
- effect on motor/drive of system voltage transients.

**Load Requirements** — necessary data includes:
- speed requirements;
- torque requirements over whole range;
- type of load and typical cycles;
- effect of system transients on load.

**The Inverter Enquiry Form**

When advice is being sought from a supplier of, say, VSD's, it may be necessary to complete an enquiry form. The type of information which may be required includes:
- application;
- motor size (kW);
- current (A);
- motor speed (rpm);
- speed range required;
- inverter volts input (V);
- motor volts input (V);
- duty cycle;
- ramp rate up (secs);
- ramp rate down (secs);
- controls required remote or local;
- chassis or box;
- ambient temperature (°C);
- humidity (% RH);
- special features or requirements;
- quantity;
- date required.
12. REFERENCES


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Pumps  


Refrigeration Equipment  


Financial  


### APPENDIX 1

**GLOSSARY OF TERMS**

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<th>Term</th>
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<tr>
<td>Alternating current</td>
<td>a current which alternates between positive and negative values at the frequency of the system.</td>
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<tr>
<td>Asynchronous</td>
<td>a machine in which voltage is constant and speed may vary.</td>
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<tr>
<td>Brush gear</td>
<td>electrographitic brushes which have a sliding contact with the commutator and are used in the transfer of current to the rotor.</td>
</tr>
<tr>
<td>Coefficient of Performance (CoP)</td>
<td>a measure of the efficiency of a refrigerator. It is the ratio of the heat removed from the cold body to the work done by the machine.</td>
</tr>
<tr>
<td>Commutator</td>
<td>hard drawn wedge-shaped copper bars fixed to the rotor upon which the carbon brushes ride to transfer the current to the rotor.</td>
</tr>
<tr>
<td>Commutator, slip rings and brushes</td>
<td>devices used in the transfer of current between the rotor and control unit.</td>
</tr>
<tr>
<td>Compound wound</td>
<td>a motor with some field coils in series and the rest in parallel with the armature.</td>
</tr>
<tr>
<td>Contactor</td>
<td>electro/mechanical solenoid operated switching device.</td>
</tr>
<tr>
<td>Copper losses</td>
<td>losses caused by current passing through copper conductors.</td>
</tr>
<tr>
<td>Eddy current losses</td>
<td>losses due to circulating currents set up in the iron core laminations.</td>
</tr>
<tr>
<td>Electric flux density</td>
<td>the quantity related to the charge displaced within a dielectric by application of an electric field.</td>
</tr>
<tr>
<td>Fairford type</td>
<td>developed by Fairford Electronics: microprocessor based development on NASA principle offering self calibration, no drift and reliable fixed speed controller.</td>
</tr>
<tr>
<td>Flux density</td>
<td>vector quantity producing a torque on a plane current loop.</td>
</tr>
<tr>
<td>4 Pole</td>
<td>a machine with four magnetic poles, thereby determining the speed of the motor.</td>
</tr>
<tr>
<td>Harmonics</td>
<td>a non-sinusoidal complex wave which is composed of sinusoidal components called harmonics, having frequencies which are integral multiples of the fundamental frequency.</td>
</tr>
<tr>
<td>High voltage</td>
<td>voltage greater than 1000 V ac or 1500 V dc.</td>
</tr>
<tr>
<td>Hysteresis losses</td>
<td>losses in a motor due to characteristics of steel/iron core and dependent on quality of the iron.</td>
</tr>
<tr>
<td>Induced current</td>
<td>a current produced in a coil by the movement of a magnetic flux relative to the coil.</td>
</tr>
</tbody>
</table>
Inverted — dc current changed to ac current.
Iron losses — due to hysteresis and eddy currents.
Isentropic efficiency — assuming perfect compression.
KVARh — Reactive kilo volt-ampere hours which are an indication of the power factor of the system.
Low voltage — normally exceeding 50 V ac or 120 V dc but not exceeding 1000 V ac or 1500 V dc between conductors, or 600 V ac or 900 V dc between conductors and earth.
Mathematical model — a mathematical representation of the behaviour required or expected of a controlled device.
Motor and drive systems — comprise a motor and a controller, giving a variable output from the motor.
Moving magnetic field — the magnetic field produced by the sinusoidal movement of the currents in the windings.
NASA type — fixed speed motor power factor controller using electronic control to match continuously the input of the motor to its load demands. Conceived by NASA in the USA, the principle is based on a correlation between motor power factor and motor load.
OEM — Original Equipment Manufacturer.
On-peak to off-peak — the time of day when premium or cheap rate electricity is charged.
Output waveform — the shape of the output voltage which should be as near sinusoidal as possible for best results.
Point of supply — the position at which electricity is made available by the Area Board.
Power capacitors — these are normally static capacitors which reduce the magnetising current drawn from the supply by inductive loads such as motors, furnaces etc.
Pulse width mod.(PWM) — a term used in a specific type of frequency inverter used for motor control, with a variable voltage and frequency output.
Reactive — wattless; where the current either lags or leads the voltage by 90°.
Regenerative braking — used with adjustable voltage control systems to obtain rapid stopping of an ac synchronous motor, while driving a dc generator.
Rewind — to replace existing motor windings with new windings.
<table>
<thead>
<tr>
<th>Term</th>
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<tbody>
<tr>
<td>Resistive, inductive and capacitive</td>
<td>types of load in which the current cycle is in phase with the voltage cycle for resistive loads, the current lags the voltage for inductive loads and the current leads the voltage for capacitive loads.</td>
</tr>
<tr>
<td>Rotary motor generator set</td>
<td>a combination of a motor driving an ac generator to give a specific output voltage and frequency.</td>
</tr>
<tr>
<td>Series wound</td>
<td>field coils in series with armature (rotor).</td>
</tr>
<tr>
<td>Shunt wound</td>
<td>field coils in parallel with armature (rotor).</td>
</tr>
<tr>
<td>Sine wave</td>
<td>pattern of ac voltage.</td>
</tr>
<tr>
<td>Six step current source inverter (CSI)</td>
<td>a frequency inverter where the supply is converted to a variable dc voltage. The dc is then inverted to a variable frequency by stepping the current waveform to the motor.</td>
</tr>
<tr>
<td>Six step voltage source inverter (VVI)</td>
<td>a frequency inverter where the supply is converted to a variable dc voltage. The dc is then inverted to a variable frequency by stepping the voltage waveform to the motor.</td>
</tr>
<tr>
<td>Slots</td>
<td>formed grooves in the rotor and/or stator in which the winding coils are laid.</td>
</tr>
<tr>
<td>Slot numbers and tooth/slot geometry</td>
<td>a design consideration to minimise stray losses.</td>
</tr>
<tr>
<td>Soft start</td>
<td>adjustable reduced voltage for starting motors to give smooth stepless acceleration.</td>
</tr>
<tr>
<td>Squirrel cage motor</td>
<td>induction motor which has its rotor bar conductors and endings cast in one operation with no external electrical connections.</td>
</tr>
<tr>
<td>Static rectifiers</td>
<td>device for converting alternating current to direct current with no moving parts.</td>
</tr>
<tr>
<td>Supply capacity</td>
<td>the nominated level of electricity supply in kVA or kW as agreed between the customer and the Electricity Board.</td>
</tr>
<tr>
<td>Synchronous</td>
<td>a synchronous machine is one which operates at a constant speed. Voltage may vary.</td>
</tr>
<tr>
<td>Synchronous speed</td>
<td>the speed at which the magnetic flux rotates round the motor stator poles.</td>
</tr>
<tr>
<td>Three phase</td>
<td>an electricity supply system whose voltage source comprises three components vectorially 120° apart.</td>
</tr>
<tr>
<td>Thyristor</td>
<td>a semiconductor device used in controlled rectifiers and inverters.</td>
</tr>
<tr>
<td>Unsworth type</td>
<td>second generation fixed speed controller developed in the UK.</td>
</tr>
</tbody>
</table>
User-programmable logic — digital representation of decision making which can be understood by the microprocessor.

Vectorially — a quantity having magnitude and direction as shown on a vector diagram.

Wound rotor — where an insulated winding is provided on the rotor, the terminal of each phase is connected to a slipring on the shaft.
APPENDIX 2

MONITORING EQUIPMENT SUPPLIERS

This Appendix gives details of suppliers of monitoring equipment and equipment rental companies.

The list is not exhaustive. The listing of an organisation does not constitute an endorsement by the DOE of its competence, and non-listing of an organisation does not discriminate against its competence.

Crest Energy Ltd
Station Road, Strines, Stockport SK12 3AQ
Tel 01663 64833. Telex 666850

The company supplies portable energy monitors and transmitters for use in energy audits and surveys. The PCT 3 Energy Monitor can be installed in a variety of applications and, using appropriate transducers, can measure kW, kVA, amps, temperature and fluid flows. Results are displayed on a four-colour printer/plotter. The Triline PC 5 is a more sophisticated device with a large memory facility which can be interfaced with IBM-compatible PCs for further data processing.

Grant Instruments (Cambridge) Ltd
Barrington, Cambridge CB2 1BR
Tel 01763 62600/60811. Fax 01763 62410. Telex 81328

The Squirrel Memory Logger (1200 series)

This portable instrument can meter and record a range of physical parameters in analogue (dc) or digital form; ac signals would require conditioning networks. It is equipped with computer data transfer facilities.

The Squirrel logger can be used in conjunction with the Responder 3, a three-phase energy meter, manufactured by the Response Company Ltd.

Response Company Ltd
PRI House, Moorside Road, Winnall Industrial Estate
Winchester, Hampshire SO23 7RX
Tel 01962 840048. Fax 01962 841046. Telex 477583 METERS G

The company manufacturers a complete range of products for the measurement, communication and management of electrical power, such as the Responder series of meters, for both single- and three-phase systems. Multi-function models are available for power and energy recording.

Northern Design
228 Bolton Road, Bradford BD3 0QW
Tel 01274 729533

The company manufacturers a range of portable and panel mounted power, energy and power factor instruments. Clamp-on CTs are available up to 5,000 amps. Model ND306 uses a 6-channel chart recorded and can be interfaced with remote computer logging systems.
HEME International Ltd
Unit 11, Seddon Place, Stanley Industrial Estate
Skelmersdale, Lancashire WN8 8EB
Tel 01695 20535. Fax 01695 50279. Telex 629792

The Company produces a range of instruments and devices for measuring electrical parameters. These include Clip-on Current Meters, Clip-on Power Meters, Clip-on Current Probes and Current Transducers.

Elcomponent Ltd
Unit 5, Southmill Trading Centre, Bishops Stortford, Herts CM23 3DP
Tel 01279 503173. Fax 01279 54441. Telex 818146

The company manufacturers a number of instruments for line monitoring of single- and three-phase electrical systems. The Micrvip is a portable analyser complete with display and integral printer. When fed from suitable transducers it can record up to ten electrical parameters. A portable system harmonic analyser is also manufactured.

Advanced Energy Monitoring Systems Ltd
The Energy Centre, Finnemore Ind Est, Ottery St Mary, Devon EX11 1NR
Tel 01404 812294/5470. Fax 0140481 2603

The company produce the Yatesmeter which measures the hydraulic efficiency of a pump or turbine using the thermodynamic method. This requires only the measurement of temperature and pressure either side of the pump. An electric power multi-parameter monitor is also available.

Solex International
95 Main Street, Broughton Astley, Leicestershire LE9 6RE
Tel 01455 283486. Fax 01455 283912. Telex 342523 Solex

Solex International supply various types of test and measuring equipment including electronic tachometers for the measurement of shaft speed.

Equipment Hire

Aughton Hire
Dixon Road, Knowsley Industrial Park (North), Kirkby, Liverpool L33 7XP
Tel 0151 548 0000. Fax 0151 549 1428

IR Group
Dorcan House, Meadfield Road, Langley, Berks SL3 8AL
Tel 01753 58000. Fax 01753 582843

Livingston Hire Ltd
Livingston House, 2-6 Queens Road, Teddington, Middlesex TW11 0LB
Tel 0800 88 6000. Fax 01977 6431
APPENDIX 3

FINANCIAL ANALYSIS METHODS

The benefits of investing in more efficient motors and drives can be summarised as follows:

- electricity cost saving;
- reduced maintenance costs arising out of improved utilisation of assets;
- improvements in the production process, or product, resulting from better control.

The financial considerations can be summarised as follows:

- planning costs;
- acquisition costs;
- cost of spares;
- cost of modifications to existing equipment;
- cost of production down-time during installation;
- cost of writing-off existing motor and/or drive.

With planning costs, an allowance should be made for monitoring the existing system, and the possible use of consultants. In-house liaison costs may be covered by overheads. Acquisition costs cover purchase and installation of the equipment, while the cost of spares may include the purchase of back-up motors and/or electronic equipment to ensure rapid replacement in the event of breakdown.

Payback Period

A first estimate of a project's cost-effectiveness may be obtained by calculating either the payback period or the return on investment. The information needed is very basic, and generally easy to obtain. The following data is required:

- capital and installation cost of equipment;
- any extra annual operating cost (e.g. maintenance);
- annual electricity savings (kWh);
- electricity price (p/kWh);
- equipment life (years).

The payback period may be calculated from:

\[
\text{Payback period} = \frac{\text{Installed cost}}{\text{(annual electricity savings} - \text{extra operating costs)}}
\]

The principal disadvantage of the simple payback method is that it does not consider cash flows beyond the payback period. Also, there is no scope for comparing projects which have identical payback periods but different annual returns.

For example, one project may save £5,000 in the first year of operation, and another £7,000. A reversal of savings in the second year would make the payback equal, but the benefits in terms of a return on earnings would be greater for the unit recovering £7,000 in the first year.

There are situations in which the simple calculation of payback period can be of value. Firstly, a rapid payback period may be the prime criterion when the investor has funds available for only a short time. Secondly, a speculator is interested in a quick return, and this technique, in spite of its shortcomings, is valid here. Thirdly if the expected life of the assets is difficult to predict, the payback period is helpful in assessing the likelihood of achieving a successful investment.

More accurate methods for determining payback period, and other financial analysis methods, are discussed in the accounting texts in the Bibliography.
In particular, the above method does not take into account the payment of interest on borrowed capital. Where a quick estimate of this effect on payback period is required, the graph in Fig 44 may be used ('r' is the interest rate on borrowed capital).

![Graph showing Payback Time as a Function of Net Capital Investment, Energy Savings and Interest Rates]

**Fig 44  Payback Time as a Function of Net Capital Investment, Energy Savings and Interest Rates**

**Example for High Efficiency Motor**

The annual energy cost savings, $S$, for two motors having different efficiencies but operating at the same load, can be calculated using the equation:

$$S = P \times D \times H \times [(100/E1) - (100/E2)]$$

where $P$ is the motor power (kW), $D$ the energy cost (£/kWh), $H$ the annual running hours, and $E1$ and $E2$ the efficiencies of the two systems being compared.

For a 110 kW 4-pole induction motor, operating for 6,000 hours/year at an electricity cost of 4p/kWh, a comparison between a standard motor of 93% efficiency (full load) and an energy efficient motor of 95.5% efficiency reveals the following:

$$S = 110 \times 0.04 \times 6000 \times [(100/93) - (100/95.5)]$$

$$= £743/\text{year.}$$

However, there is a price premium for the high efficiency motor which, in the case of the 110 kW unit, is £918 (£4,587 as opposed to £3,669 for the standard motor). Thus:

$$\text{Payback Period} = \frac{£918}{£743}$$

$$= 1.24 \text{ years.}$$
It is assumed that a new motor is needed, be it standard or high efficiency.

**Return on Investment**

Return on investment takes into account equipment depreciation and may be calculated from:

\[
\text{Return on investment} = \frac{(C \times D) - B - \text{Depreciation charge})}{A}
\]

where \(A\) = total cost of equipment, \(B\) = annual operating cost, \(C\) = annual savings (kWh), and \(D\) = electricity price (£/kWh). Depreciation charges are set depending on the nature of the equipment.

This technique does not take into account the timing of the cash flows, and is based on the concept of ‘original book value’ which generally does not include all costs. It therefore results in only a rough approximation of an investment’s value.

**Life Cycle Analysis**

Life cycle analysis offers a more detailed approach to investment appraisal and is particularly relevant in energy efficiency projects. However, this technique is often unnecessarily complicated at the outset by definitions and the number of variables.

Firstly, what is the life cycle? This can be determined by a number of factors:

- operating life of the electric motor and/or drive;
- operating life of the driven equipment;
- operating life of the process etc.

The operating life of an electric motor is well documented, although most of the data is from the USA. However, detailed analysis shows that ordinary motors of 1-4 kW have an average life of 17 years, while those of 100 kW have an average life of 28 years.

In cases where the operating life of the driven equipment is 5 to 10 years, this can be used for any life-cycle calculations. Where projected life is greater than 10 years, motor life may have to be taken into account, either using figures extrapolated from the average motor lives, or based on data from the equipment supplier.

These figures are averages; if the system is operating under adverse conditions they should be regarded as optimistic. Factors such as excessive loading and voltage should also be considered.

A life cycle analysis takes into account the time value of money and energy cost inflation.

Based on a knowledge of the return (R1) on the investment and the anticipated rate of inflation of energy costs (R2), the effective interest rate (i) can be obtained from:

\[
i = \frac{(1 + R1)}{(1 + R2)} - 1
\]

The present worth may be calculated using \(i\) in the following equation:

\[
PW = \frac{(1+i)^n - 1}{i(1+i)^n}
\]

where \(n\) is the operating life.

A quantity known as the present worth evaluation factor (PWEF) is calculated:

\[
PWEF = D \times H \times PW
\]

where \(D\) is the energy cost (£/kWh), and \(H\) the operating hours per year.
The present worth, or value, of the life cycle savings can be determined on the basis of the investment in the more efficient system (in this case a motor), using the following equation:

\[ P_{WS} = P \times P_{WEF} \times \frac{100}{(E1 - E2)} \]

**Example**

A motor has a rating of 110 kW and an operating current energy cost of £0.04/kWh. It operates for 6,000 hours/year. Assume the energy inflation rate is 7%, the required return on investment (RoI) 25% and an anticipated motor life of 8 years.

The effective interest rate \( i \) is:

\[
i = \frac{(1 + 0.25)}{(1 + 0.07)} - 1
\]

\[
= 0.168
\]

\[
PW = \frac{(1 + 0.168)^8 - 1}{0.168(1 + 0.168)^8}
\]

\[
= 4.23
\]

\[
P_{WEF} = 0.04 \times 6000 \times 4.23
\]

\[
= 1,015.2
\]

\[
P_{WS} = 110 \times 1015.2 \times \frac{100}{(93 - 95.5)}
\]

\[
= 110 \times 1015.2 \times (0.028)
\]

\[
= £3,127
\]

In this example the present value of the savings should be compared with competing investment claims and those with the highest \( P_{WS} \) selected.
APPENDIX 4

CAPITAL COSTS OF MOTOR CONTROLLERS AND INVERTER DRIVES

Introduction
Information is given on the costs of motor controllers and ac inverter variable speed drives. The data has been collected from a variety of sources, including published papers and manufacturers' price lists. Most date from 1987 and 1988.

The data is presented in graphical form in Figs 45 (motor controllers) and 46 (ac inverters). The costs for inverters are principally for the PWM type.

The price range figures quoted are for 'one off' purchases. Where an original equipment manufacturer (OEM) is involved in buying motors and drives, substantial discounts may be negotiated. A potential user will be able to use his purchasing ability to undercut some of the unit prices.

The motors and drives industry is a highly competitive sector. Thus competitive pricing may assist the buyer in obtaining a deal which will give a better payback than indicated by some of the figures listed.

In addition, equipment suppliers may be prepared to negotiate special arrangements. For instance, a company found one equipment supplier to be particularly helpful in setting up trials at a number of sites. Many units were offered on the basis of payment following demonstration of satisfactory performance.

Note: Data presented are for the capital cost of equipment only, i.e. installation is not included.

Fig 45  Equipment Capital Costs: Motor Controllers
Fig 46  Equipment Capital Costs: Inverters (VSD's)
APPENDIX 5

MOTOR AND DRIVE MANUFACTURERS AND SUPPLIERS

Lists of equipment suppliers are published in the trade journals and by trade associations. The GAMBICA Association publishes a list of suppliers of Electronic Variable Speed Drive Systems and a list of suppliers of Electronic Soft Start Motor Control Systems.

The GAMBICA Association Limited
Leicester House
8 Leicester Street
London WC2H 7BN
Tel: 0171 437 0678
Fax: 0171 494 0391
For further information on this or other Best Practice programme publications please contact BRECSU or ETSU.

For buildings-related projects: Enquiries Bureau, BRECSU, Building Research Establishment, Garston, Watford WD2 7JR.
Tel No: 01923 664258. Fax No: 01923 664787.

For industrial projects: Energy Efficiency Enquiries Bureau, ETSU, Harwell, Didcot, Oxfordshire OX11 0RA.
Tel No: 01235 436747. Fax No: 01235 433066. Telex No: 83135.