VARIABLE SPEED DRIVES FOR ENERGY CONSERVATION APPLICATIONS

Dr. LOCK KAI SANG
Senior Lecturer

Department of Electrical Engineering,
National University of Singapore

PAPER PRESENTED AT 6TH CEPSI MEETING
"UTILITY MANAGEMENT AND CORPORATE
PLANNING" JAKARTA - NOV. 3RD - 7TH 1986

INTRODUCTION

During the last decade the escalating energy cost has forced the implementation of energy conservation programmes in almost every sector of the industry as well as building services. The refineries have reduced the amount of energy they consume to process a barrel of crude by around 30%. The steel industry has saved about 10%, the paper industry 10%, the cement industry 15%, and the aluminium industry 20%.

The present oil glut is due to a great extend is due to the conservation efforts which resulted in an excess of supply over demand. Being a depletable resource, oil is not expected to stay at the current price for long, and hence it should be a wise decision to pursue energy conservation programmes continuously.

Much of the energy savings have been achieved by cutting thermal losses during the process of converting fuel into mechanical energy. Generally 2/3 of fuel energy is lost before getting to the input shaft of the generator. Although the large losses are at the front end of the energy conversion process, it is important to realise that each kW of energy saved in the electrical machines and equipment is reflected by 3 kW saving of fuel energy.

Electrical motors are estimated to consume more than 60% of the electrical energy generarted in the world and hence their applications should be examined seriously in any conservation exercise. A significant amount of energy savings can be achieved by employing variable speed drives (VSD) to match the design characteristics of pumps, fans, compressors and blowers to improve performance.

Over the past two decades the development of the VSD has advanced tremendously, mainly due to the availability of cheaper, faster and more powerful semi-conductor switching devices together with the use of microprocessor control. Before the discussion of the energy conservation applications of VSD, the losses in electrical machines will be examined first.

LOSSES IN ELECTRICAL MACHINES AND THEIR MINIMIZATION

The energy required by a motor is made up of three components :

(1) The mechanical load on the motor.

(2) The mechanical losses in the motor.

(3) The electrical losses in the motor and the electrical supply system.

Mechanical losses are due to bearing, friction and windage losses. Proper lubrication practice will help to reduce unnecessary losses.

The electrical losses in the motors can be separated into two types. No load loss is the amount of losses when the device is idling or in a standby mode. Load losses are the additional or total level of losses at each load increment. The no-load loss mainly consists of eddy current and hysteresis losses which for a given motor, are dependent on the supply voltage, frequency and temperature. The load losses which are also called copper losses are in the form of heat generated by the current squared times winding resistances.

Losses in electrical machines can be reduced by :

(1) proper selection and design

(2) adjusting voltage, current and/or frequency at each speed and torque operating point.

(3) improving the waveforms of the motor power supply.

To optimise the efficiency of use of an electrical machine, it is necessary that the machine is properly matched to its particular application, both in terms of size and performance. Industry has traditionally used oversized motors for a number of reasons. One reason is that motors are made in certain standard ratings. **Engineers deliberately use oversized motors to achieve long life and dependable operation.** The result is that only on few occasions are the motors be required to operate at their full ratings.

Partially loaded motors waste energy because the no-load losses are still the same as that at full load. Considerable energy can be saved by replacing oversized motors with smaller motors which are operated near capacity.

The use of high efficiency motors should be considered seriously for energy conservation. By using more copper, more iron, longer cores, greater slot fill, better steel and thinner laminations, motor manufacturers are able to produce motors which are more efficient than the standard motors. Although the cost of these high efficiency motors are at a premium of about 20%, their use can be justified by the energy saving within a few years if the motors are operated intensively.

Losses in partially loaded motors can also be reduced by electronically lowering the voltage applied to the motors (2, 3). This voltage reduction technique is used in several commercial a.c. voltage controllers which employ thyristors or triacs to regulate the motor voltage as a function of load.

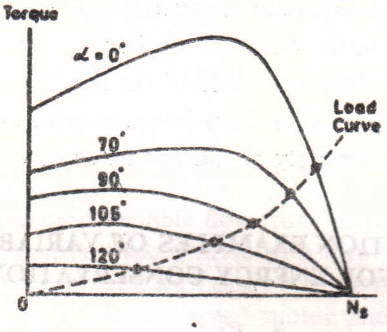


Fig. 1 Speed variation of fan load for different delay angles (α)

The method of stator voltage control is often used in conjunction with a high slip motor (typically 10 to 12%) to regulate flow of pumps or fans. Since the torque varies with square of the voltage at a fixed slip, the fan or pump speed will decrease as the voltage is reduced as shown in Figure 1. Although this is a very simple method of flow control, the efficiency of the motor decreases as slip increases. This is due to the fact that if P_2 is the total power going to the rotor, the power lost as heat in the rotor is S times P_2, where S is the slip of the induction motor. This implies that an induction motor operating at half speed will have an efficiency of less than 50%.

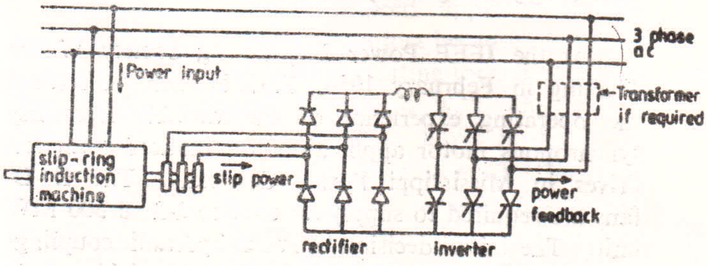


Fig. 2 Slip-energy recovery system

Losses in the rotor of induction motor at high slip can be reduced by slip energy recovery scheme as shown in Fig. 2. In this scheme, the slip power of the rotor is rectified by a diode rectifier and is then pumped back to the a.c. line through a line-commutated inverter. The resulting motor inverter system has a linear torque/current characteristic similar to that of a d.c. motor.

ENERGY CONSERVATION BY VARIABLE SPEED DRIVES

Variable speed drives (VSD) have many industrial applications. Examples of such applications may be found in petrochemical plants, processing machinery pumps, fans, traction, steel and paper mills. The main benefits of operating VSD systems are energy saving, improved control over the process and improved product.

Conventionally, pumping and air handling installations employ constant speed a.c. motors with the fluid flow being controlled by throttling or damping. Great energy savings can be achieved by employing VSD to match the design characteristics of pumps, fans, compressors and blowers to improve performance. Potential energy savings from using variable speed drives may be attributed to three sources: savings in driver, saving in driven equipment and other fringe benefits.

Pumps

In Figure 3, S_1 and S_2 are the pump characteristic curves corresponding to speed n_1 and n_2 respectively. These curves show the relationship between pump flow and discharge pressure. Lines R_1 and R_2 are the pipeline resistance curves, and are determined by the sum of the height (head) of the discharge port from the inlet port and the friction resistance of the liquid flowing through the pipeline H_f. Regulating a valve changes the pipeline resistance with a corresponding change in the curve R. For example, closing the valve can cause the pipeline resistance curve to change from R_1 to R_2.

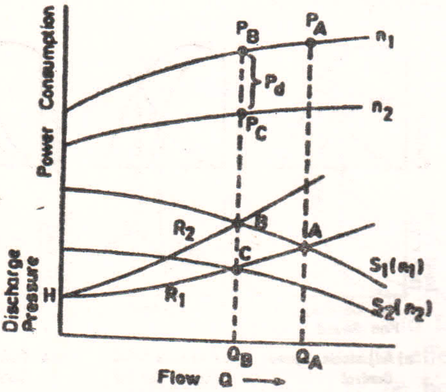


Fig. 3 Flow control of a pump.

The operating point of a pump is determined by the intersection of the pump resistance and pump characteristic curves. For a speed of n_1 and pump resistance curve R_1, the flow is Q_A corresponding to operating point A. The power consumption is P_A on curve P_1. If the flow is to be reduced to Q_B by valve operation, the new operating point is B, corresponding to power consumption of P_B. The change of consumption of P_B. The change of power consumption from P_A to P_B is small.

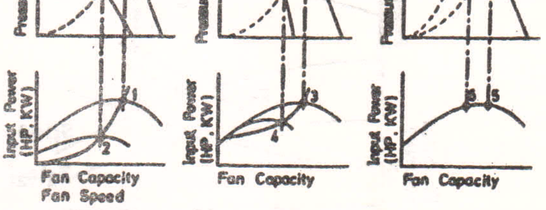
Flow can also be controlled by changing the speed of the drive from n_1 to n_2. The operating point is C with a power consumption of P_c. In figure 3 P_d, the difference between P_B and P_c, is the saving available from using a variable speed drive.

As the throttling energy saved is proportional to the difference between the pump resistance and pump characteristic curves, the steeper the slope of the pump curve, the greater the savings. Another important factor which determine the amount of energy saved is the amount of time a pump operates at less than its rated point. The greater the time a pump operates at reduced flow and the greater the reduction in flow, the more will be the energy loss due to throttling.

Fans and Blowers

The flow control mechanism of fans and blowers is very similar to that of the pumps. Most fans and blowers have relatively little static back pressure to pump against. Because of this and the fact that their pressure/flow curves slope downward sharply, they offer good potential.

Air flow of fans and blowers can be controlled by outlet damper, inlet guide vanes or adjustable speed. Fig 4 (a) shows the pressure/flow and power/flow relationship. System head resistance is added by the damper to force operation back up the head/flow curve to reduce the flow. Point 1 is for wide open damper and point 2 for partially closed. The power reduction which accompanies the flow reduction of this system is relatively small.



a) Adjustable Speed Control

b) Variable Inlet Vane Control

c) Outlet Damper Control

Fig. 4 Variable air volume control

Fig. 4 (b) illustrates the results of air flow control by variable inlet vanes which produce inlet whirl, thus reducing the pressure producing capability of the fan. Point 3 is for wide open vanes and point 4 is for partially closed. Some reduction in power consumption is obtained at reduced air flow.

The most efficient flow control, as shown by Fig. 4 (c), is the method employing variable speed system. The head/flow curve is reduced similar to the case for a pump. The power consumption drops drastically with speed. This is because the power requirement of the fan varies as the cube of the speed whilst flow reduces linearly and pressure reduces as the square with speed reduction.

In general for pumps, fans, blowers and compressors, the following characteristics will suggest opportunities for energy saving projects (1).

- step head/flow curve
- low static pressure
- large variation in flows
- steep system head curve
- system friction increases with age
- a variety of fluid densities.

APPLICATION EXAMPLES OF VARIABLE SPEED DRIVES FOR ENERGY CONSERVATION

Variable speed drives are used extensively in industry. As discussed in the previous section, the use of variable speed drives in pumping and air handling applications can lead to large energy savings.

In the power supply industry, the forced draft (FD) fans traditionally employs constant speed a.c. motors. The air flow is controlled by either inlet guide vanes or outlet dampers. This type of application offers large energy saving potential when adjustable VSD systems are employed. In the past, reliability concerns of the power electronics systems have often eliminated the consideration of this type of VSD for application in FD fans. The impact of recent technology developments has, however, increased greatly the reliability and performance of this VSD systems which are now increasingly being accepted for FD fans.

At the IEEE Power Engineering Society Winter Meeting in February 1984, T. O. Holderer discussed the operating experience of the variable frequency synchronous motor application for induced draft fan drives in Mississippi Power Company. The I. D. fans are required to supply air to a coal-fired 500 MW unit. The initial decision to utilize hydraulic couplings and induction motors to drive the fans at variable speeds was reconsidered because of the potential advantages that the variable frequency drives offered. It was concluded in a study that the variable frequency drives would have a $ 7.5 million cost savings over the hydraulic coupling for the life of the unit. $ 6.5 million of this amount was attributed to the energy savings to be realized by the VSD. The efficiency of the drive was projected to surpass the hydraulic couplings in every operating circumtances. Other considerations favouring the electronic drives were the avoidance of oil handling problems, cooling water corrosion problems, and additional heat rejection to the thermally limited cooling tower. The initial cost would be nearly the same for each option. Since the installation of the LCI-synchronous motor drives the operation has been satisfactory, apart from some initial start up problems.

Another application of adjustable frequency drive for FD fan was reported by J.D. Rozner, *et al*,. The 300-hp FD fans were used to supply air to a boiler at Sohio Chemical Company. The payback period when compared with the inlet guide vane control was 2.8 years.

R. G. Gutzwiller, *et al* has evaluated the comparative costs of using various types of drives for a 10,000 hp compressor for a petrochemical plant. To obtain the required variable flow from the compressor, a case using constant-speed drive with throttling of the compressor is compared with cases using variable speed drives utilizing a constant-speed motor and hydraulic coupling, an adjustable-frequency drive, and a steam turbine drive. The analysis resulted in the installation of the load commutated inverter (LCI) — synchronous motor drive system, which would yield an acceptable return over the throttling or coupling alternatives With the LCI application, about $ 3.4 million is saved over throttling and about $ 1.9 million over the hydraulic coupling during the 15-year life. Apart from the economic advantage the LCI system also offers many technical benefits.

TYPES AND CHARACTERISTICS OF VARIABLE SPEED DRIVES

Traditionally, variable speed applications have been the domain of the d. c. motors because their speed can be controlled easily by regulating the armature and field supply voltages. Compared with their d. c. counterpart, the a. c. machines have, however, the advantages of lower cost, higher power/inertia ratio, better efficiency, and are more rugged and reliable. In addition, the absence of brushes and commutator in a. c. machines means that they are more suitable for application in dirty and explosive environment.

These merits of the a. c. motors have, however, been off-set by the more complex and hence more expensive converters and their associated control systems. The higher cost of the a.c. VSD systems have in the past prevented them for seriously challenging the d.c. drives in the field of conventional VSD applications.

The research and development activities over the last two decades have made great advances in the technology of solid-state speed control of a.c. machines. In recent years, the availability of cheaper, faster and more powerful semiconductor switches advanced permanent magnet materials for synchronous motor, custom-designed VLSI circuits or microprocessor control techniques have pushed a.c. drives to a new position comparable to d.c. drives in terms of cost and control performance. The a.c. VSD has begun to displace d.c. drives for many applications.

As most of the industrial drives employ a.c. motors, the discussion will be confined to a.c. drives only. The two commonly used a.c. motors are the induction motor and synchronous motor.

Induction Motors

The operation of an induction motor depends on a slip between the rotor and the rotating field of the stator. Speed control can be achieved by regulating the slip or varying the supply frequency of the stator. The four common methods for controlling the speed of induction motors are :

(1) regulation of stator voltage at constant frequency

(2) control of slip power

(3) variable-frequency, variable-voltage control

(4) variable-frequency, variable-current control.

The first two methods can only be employed for sub-synchronous speed control and their principles of operation are well-established. Only operating principles and characteristics of variable frequency a.c. drives will be examined in this paper.

Because the reactances of the a.c. machines vary linearly with frequency, it is usually a requirement that the motor voltage is varied in direct proportion to frequency to maintain both stator current and torque constant. At low frequency operation, the effect of stator resistance requires that the voltage be boasted above this constant Volt/Hertz ratio if constant torque operation is to be maintained (11). Figure 5 illustrates the voltage frequency relation of an induction motor and Figure 6 shows the torque/speed curves with variable-voltage variable-frequency power supply.

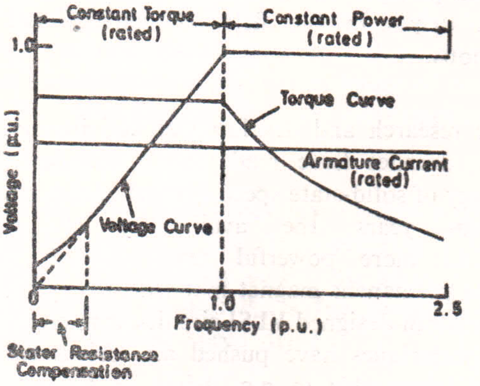


Fig. 5 Voltage-frequency relation of induction motor.

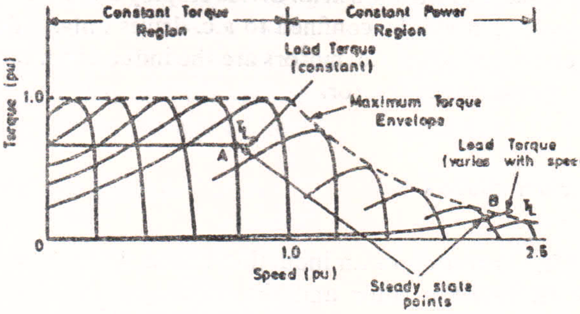


Fig. 6 Torque-speed curves of induction motor with variable-voltage variable frequency power supply.

The performance of the variable-speed induction motor drive depends on the type of inverter to which the motor is connected. The three most common inverters are :

(1) the six-step voltage source inverter (VSI),

(2) the pulse-width modulated (PWM) inverter, and

(3) the six-step current source inverter (CSI)

These three inverters are classified as d.c. link converters because the a.c. supply is rectified to d.c. before it is filtered and then transformed to a variable frequency a.c. by the inverter. The first two types are voltage source inverter (VSI) because the output waveshapes of the inverters are defined with the current waveforms being determined by the load characteristics. The current source inverter (CSI) is so called because inverter output current waveform is predetermined, with the output voltage waveform being a function of the load.

The power circuit of a VSI is shown in Figure 7. CSI has the same circuit configuration, except that it has a large d.c. link inductor and that the link capacitor is not required. S_1 to S_6 are semiconductor switches which can be thyristors or power transistors. The feedback diodes D_1 to D_6 provides a path for the flow of reactive energy. The inverter output frequency and waveform are controlled by the pattern and switching rate of the semiconductor switches.

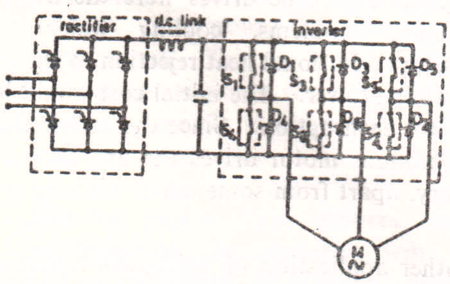


Fig. 7 Basic d.c. link converter circuit with a six-step voltage source inverter

The voltage and current waveforms of an induction motor fed with these three different inverters are shown in Figure 8. In term of current harmonics the PWM inverter is more superior.

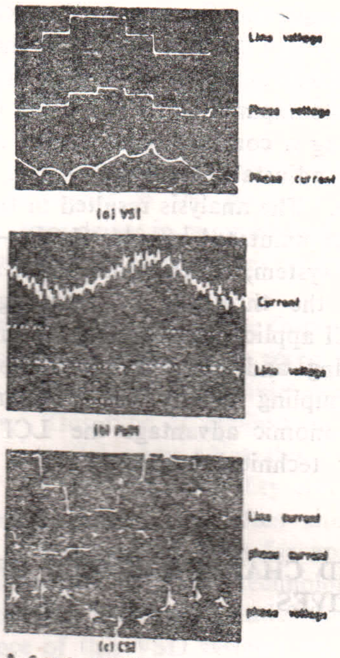


Fig. 8 Current and voltage waveforms of a inverter-fed induction motor

The harmonic currents present in an inverter-fed motor reduce the efficiency of the motor by causing additional copper and core losses. A standard induction motor usually has, therefore, to be derated by around 10 to 15% when it is operated from an inverter supply. The low order harmonic content may also produce torque pulsation as well as instability on the drive system (12,13).

There are many modulation strategies which attempt to optimise the waveform of the output voltage of PWM inverters (14, 15, 16, 17). One method of sinusoidal pulse-width-modulation is illustrated in Fig. 9 which shows the switching of inverter being determined by the intersection of a sinewave and a triangular carrier wave. Each half cycle of the output voltage waveform is made up of a number of pulses of equal amplitude and the fundamental component is controlled by variation of the total voltage-time area for a half cycle. The carrier frequency which directly influences the harmonic content of the output voltage is limited by the available turn-on and turn-off times of the switching devices. Faster switching rate, however, results in higher inverter losses and the trade-off between efficiency and harmonic content should be weighed by the drive designer.

The main advantages of PWM inverter drive are its low speed capability and good dynamic performance. The reduction in low order harmonics of PWM essentially eliminates the low speed ' stepping ' or ' cogging ' problem. The drive is capable of quick response to load demands because both voltage and frequency are controlled within the inverter.

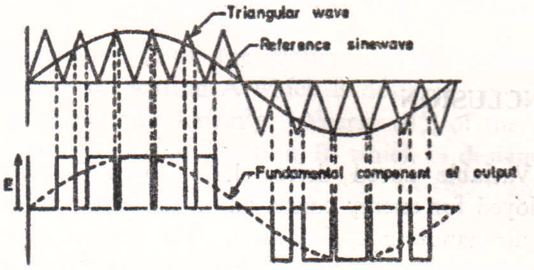


Fig. 9 Principle of Pulse width Modulation.

The operational advantages of the PWM inverter have been gained at the expense of higher inverter losses and more complex control and power circuit configurations. With the advent of fast-switching thyristors, GTOs and improved power transistors, together with the adoption of microprocessor control techniques, many practical operating constraints have been removed. Power transistor has the advantage of very fast switching rate and that it can be turned off simply by removing the base drive current. At present, transistor PWM inverter drives are popularly employed for ratings up to 100 kW.

The main advantages of the CSI drive are its simple and robust circuit and inherent four-quadrant operation. The presence of the large d.c. link permits the inverter to recover from accidental short circuit at the output terminals. Regeneration is achieved by delaying the firing angle of the ractifier beyond 90° to obtain a reversal of the d.c. link voltage.

The main disadvantages of CSI drive are the high voltage stresses on the thyristors during commutation and the low speed torque pulsation. The commutation time of the thyristors is linked to the leakage reactances of the motor. The CSI is usually custom-designed for a single motor or a number of similar motors which are coupled mechanically.

The effects of harmonics can be minimised by matching a motor to its inverters, bearing in mind, that the leakage reactance limits harmonic currents on VSI and harmonic voltages of CSI. The leakage reactance of an induction motor, however, varies for each NEMA design. According to NEMA classification, the general-purpose induction motors are available in four standard designs to meet various starting and running requirements. The torque/speed characteristics of the various designs are shown in Figure 10.

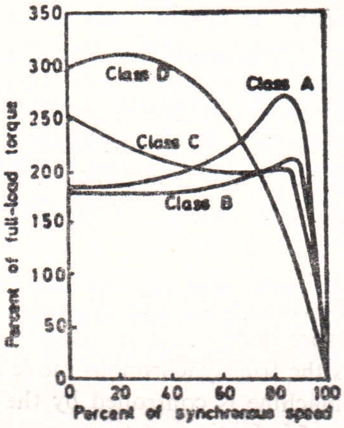


Fig. 10 Typical torque-speed curves of general-purpose induction motors.

The most common motor designs are class A and class B. The Class A motor is the basic standard design in sizes below about 5 and above 150 kW. The class B is the commonest in the 5 to 150 kW power range. A class B motor has approximately the same starting torque as a class A motor, but it has lower breakdown torque and higher slip. The starting current of a class B motor is reduced by designing for higher leakage reactance, and the starting torque is maintained by higher rotor resistance. This implies that this type of motor is more suitable for VSI than a class A motor. On the other hand, the class A motor is better for CSI because the lower leakage reactance results in less harmonic voltages.

The class C motor is usually designed with double cage rotor winding to enhance rotor winding deep bar effect. The result is higher starting torque with low starting current but somewhat lower efficiency and higher slip than the class A and class B designs. The double cage rotor is very undesirable for adjustable-frequency control operation because the high rotor frequencies associated with harmonics result in high rotor resistance and high harmonic losses with both type of inverters.

The design D motor has high starting torque and high slip. This is achieved by using high rotor resistance. This type of motor has low running efficiency and its principal uses are for driving intermittent loads involving high accelerating duty and for driving high impact loads such as punch presses and shears. Because of the large harmonic losses associated with high rotor resistance, this class of motor is not suitable for both types of inverters.

Synchronous Motors

Because of the higher cost compared with induction machines, the synchronous machine has been employed for VSD requiring its special features. These applications include very high power drives and those demanding precise speed control such as textile machinery. With the development of improved permanent magnet (PM) materials, the PM machine is increasingly being used for low to medium power drives. Because of the absence of field losses PM machine has a high efficiency. The new generation of PM machines can provide very desirable features, such as high power/weight ratio, high torque/current ratio and fast dynamics.

There are basically two different modes of operation for variable speed synchronous motor drives. The first method is the true synchronous mode in which the speed of the machine is controlled by the VSI or CSI as in the case of induction motors.

Synchronous machine under the second mode of operation is called d.c. brushless motor or electronically commutated motor where the inverter firing signals are derived from rotor shaft position sensors. In the load commutated synchronous machine drive, the emf of the motor phases can be used to turn off an inverter thyristor by firing the incoming thyristors. This load commutated inverter drive is commonly used for high power applications, such as fans, pumps and compressors.

THE BURNING PROBLEM

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SELECTION OF DRIVES

The selection of suitable drive should be based on an overall evaluation of technical merits, economic benefits, reliability and the possible effects of the drives on the electrical supply system. The three basic types of inverters which have been discussed are complementary to each other. Each has strong points giving it major advantages in specific cases dependent upon the relative importance of the various requirements of the application. Apart from the motor drives, the use of steam turbine mechanical drives should also be seriously considered in certain applications, especially when the opportunity exists for cogeneration.

A simple system is usually adequate for many energy conservation applications, such as pumping and air handling equipment. These kinds of applications do not require fast responding, precise, wide speed range regenerative drives as are often needed in traditional VSD. The insertion of unnecessary technical features in the purchase specifications will likely push up the cost of the drive system. If an existing motor can be retrofit with an inverter to satisfy the load requirements, the cost is usually lower.

CONCLUSION

Variable speed drives have been successfully employed for energy conservation projects in pumping and air handling applications. The impact of recent technological development has resulted in higher efficiency and reliability of the variable speed a.c. drives, together with a reduction of their cost relative to alternative drive systems. It is expected that the a.c drives will be increasingly used where energy saving is an important consideration. In the power supply industry, the synchronous motor drives using self-commutated current source inverters will be the popular choice because of the large power requirement.

ENERGY CONSRVATION PROMOTES ECONOMIC DEVELOPMENT

Energy conservation can do more than alleviate problems of power supplies, of course. **It also reduces the demand on developing countries' foreign exchange and capital savings, thus promoting economic development.** Energy conservation reduces the need to import oil and relieves some of the pressure on the Government to build additional power plants. The end result is the availability of more foreign exchange and capital to invest in the country's economic and social development."

(UPDATE — SEPT: 1986)