ENERGY CONSERVATION WITH EFFICIENT ELECTRIC DRIVES

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Abstract—This paper deals with the basic principle of energy efficient electric drive systems. The economic aspects, including calculation of life-cycle cost versus energy efficiency, have been highlighted. The paper also discusses the general applications of thyristor converter, inverter and chopper to the drive systems. It is expected that the paper will help engineers in industries to conserve energy in electric drives.

INTRODUCTION

The success of energy efficient electric drives depends on the correct choice of driving motor for the particular conditions under which it has to operate. In making this choice, the following factors are to be kept in consideration:

1. Running characteristics
   a. Losses
   b. Power factor
2. Starting characteristics and operation under variable loads
3. Speed control
4. Braking.

RUNNING CHARACTERISTICS

There may be conflicting requirements in the choice of motors, but the correct motor to choose is that which will give the required service at minimum overall cost. There are two cost factors to be kept in view:

a. capital cost and b. running cost.

Today, the running cost of a motor has far greater importance than the capital cost due to the increases in fuel prices and also its limited availability.

The running cost of an electric motor is dependent upon the efficiency of the motor, which is defined as:

\[
\text{Efficiency} = 1 - \frac{\text{Power losses}}{\text{Power input}} \quad (1)
\]

The graph between efficiency and power is given in Fig. 1. The different types of power losses in a conventional electric motor are:

1. Stator loss \( (W_s) \)—This is the \( I^2R \) loss in the stator winding.
2. Rotor loss \( (W_r) \)—This is the \( I^2R \) loss in the rotor winding.
(3) Core loss ($W_c$)—This is the sum of the hysteresis and eddy current losses of the laminated stator and rotor core.

(4) Friction and windage loss ($W_f$)—This is the loss due to fans and the bearing friction.

(5) Stray loss ($W_L$)—This is the lump sum of all losses in the motor which cannot be attributed to one of the other four components. It is principally due to electrical harmonics and stray currents in the motor.

Generally, $W_c$, $W_L$ are variable losses which vary with power output of the motor, and $W_e$, $W_f$ and $W_L$ are the constant losses which are independent of the power output at constant input voltage (and frequency). The maximum efficiency (see Fig. 1) of an electric motor occurs at the output power when the variable losses equal the constant losses.

There are various design steps which can be taken to reduce each of the above components. Some of these steps and associated problems are as follows:

(1) Increasing the amount of copper in the stator (increasing conductor cross section) will lower the stator resistance and, thus, lower the stator losses. The penalty is higher cost.

(2) Reducing the number of turns in the stator winding reduces the stator resistance and stator losses. The penalty is higher magnetic flux density and higher starting current, leading to poorer power factor and higher core losses.

(3) By increasing the air gap, the stray losses can be reduced due to reduction in the harmonics. The penalty is a reduction in the motor power factor.

(4) Use of stalloy (high silicon laminated steel) can reduce the core loss due to decreased hysteresis loss. High silicon steel has a higher reluctance than carbon steel. Cold rolled, grain oriented steel is better.

(5) Use of thinner varnished lamination steel can reduce core loss by reducing eddy current losses.

(6) In squirrel cage induction motors, the use of large high conductivity rotor bars and end rings will reduce the rotor losses. The penalty is that it severely reduces starting torque and increases starting current, causing a large voltage dip at the time of starting: the motor will fail to accelerate to full speed on load.

(7) Stray loss can be reduced by eliminating the skew in the rotor. Without rotor skew, the motor noise level will increase.

(8) Insulating rotor bars from the laminations reduces the stray loss due to stray rotor currents. On aluminium rotors, this is accomplished by anodizing the rotor bars before they are inserted in the core slots.
Table 1. Motor rating and voltage relationships

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>400–600 V</td>
<td>Up through 500 h.p.</td>
</tr>
<tr>
<td>2300–4000 V</td>
<td>300 through 150,000 h.p.</td>
</tr>
<tr>
<td>6–6.9 kV</td>
<td>1500 through 10,000 h.p.</td>
</tr>
<tr>
<td>13–15 kV</td>
<td>3000 h.p. and above</td>
</tr>
</tbody>
</table>

It should be obvious that, to establish maximum efficiency for a given application, the designer must have complete data on the load characteristics and the expected maximum drop in voltage during starting. Environmental requirements, such as noise level, must also be known.

The preceding discussion has centred around the efficiency of the electric motor itself. In addition, the user should optimize the overall system efficiency and its energy costs by means of system analysis. This optimization includes motor losses, distribution cable losses, transformer losses and utility charges based on system power factor. The system analysis will determine which of the following systems is to be used:

(a) high voltage distribution system with high voltage motor;
(b) low voltage distribution system with low voltage motor; or
(c) high voltage distribution system with step down transformer and low voltage motors.

The decision should be based on energy costs as well as the initial costs of the motors, switch gear and distribution cable costs.

Specifying high voltage for low power motors usually results in a motor which costs more but has lower efficiency and decreased power factor. Appropriate ratings of power and voltage relationships are shown in Table 1.

Running cost of small motors

All motorized household equipment (which consume around 38% of all electricity sold to residential customers) are small in rating (size). Commonly used motors are of fractional horse power (FHP) rating. Alternating current small motors are designed for single-phase lines. Over the past 50 years, small electric motors have undergone marked declines in efficiency. Modern motors are less efficient than the earlier models in the past because the manufacturers have designed them for minimum initial cost to satisfy purchase demands. Apart from lower cost, these modern motors have also become more compact. Because of this trend, the amounts of iron and copper have been reduced and design factors essential to efficient machines have been de-emphasized. Thus, while new motors may be cheaper initially, the extra power they dissipate as waste heat makes them more costly to operate.

Table 2 shows the efficiency of FHP electric motors.

As one solution, the decline in motor efficiency could be reversed by engineering design of carefully analysed massive structures and quality control with the best modern insulating and magnetic materials which would have higher initial cost but would be cheaper in the long term when energy use, maintenance requirements and usable life are considered. A complete conversion to more efficient motors throughout the commercial and residential sectors would reduce the total electrical consumption by 6%.

As an example of the economic benefits which can be gained by using more efficient electrical motors, the total energy savings for a motor can be calculated using variable efficiencies and initial cost as shown in Table 3.

Table 2. Efficiency of FHP motors

<table>
<thead>
<tr>
<th>Rating of motors</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Shaded pole fan 0.1 h.p.</td>
<td>15</td>
</tr>
<tr>
<td>(2) Modern economy 0.25 h.p.</td>
<td>45</td>
</tr>
<tr>
<td>(3) Modern heavy duty 0.25 h.p.</td>
<td>55</td>
</tr>
<tr>
<td>(4) High quality 0.25 h.p.</td>
<td>70</td>
</tr>
</tbody>
</table>
Table 3. Comparison of motor efficiencies and life-cycle costs to deliver $3.6 \times 10^3$ GJ ($10^6$ kWh) of work assuming 267 h/yr operation

<table>
<thead>
<tr>
<th>Description</th>
<th>Motor 1</th>
<th>Motor 2</th>
<th>Motor 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Motor rating [kW(h.p.)]</td>
<td>0.1875 (0.25)</td>
<td>0.375 (0.5)</td>
<td>0.75 (1.0)</td>
</tr>
<tr>
<td>(2) Initial cost (Rs.)</td>
<td>120</td>
<td>300</td>
<td>800</td>
</tr>
<tr>
<td>(3) Motor life span (yr)</td>
<td>5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>(4) Efficiency (%)</td>
<td>50</td>
<td>60</td>
<td>80</td>
</tr>
<tr>
<td>(5) Number of motors</td>
<td>4000</td>
<td>2000</td>
<td>500</td>
</tr>
<tr>
<td>(6) Cost of motors (Rs.)</td>
<td>480,000</td>
<td>600,000</td>
<td>400,000</td>
</tr>
<tr>
<td>(7) Annual energy cost at Rs. 0.50/kWh</td>
<td>20,000</td>
<td>16,800</td>
<td>12,500</td>
</tr>
<tr>
<td>(8) Worth of AEC at 50 yr (at $i = 10%$, PWF = 0.915)</td>
<td>200,000</td>
<td>165,500</td>
<td>124,000</td>
</tr>
<tr>
<td>(9) Life cycle cost</td>
<td>680,000</td>
<td>765,500</td>
<td>524,000</td>
</tr>
</tbody>
</table>

PWF = Present worth of a cash flow = \( \frac{1}{(1+i)^N} \) where $N$ = No. of years and $i$ = interest factor.

Table 4. Comparison of motor efficiencies and life-cycle costs to deliver $7.2$ GJ (2000 kWh) of work assuming 267 h/yr operation

<table>
<thead>
<tr>
<th>Description</th>
<th>Motor 1</th>
<th>Motor 2</th>
<th>Motor 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Size [kW(h.p.)]</td>
<td>0.375 (0.5)</td>
<td>0.375 (0.5)</td>
<td>0.375 (0.5)</td>
</tr>
<tr>
<td>(2) Initial cost (Rs.)</td>
<td>250</td>
<td>300</td>
<td>350</td>
</tr>
<tr>
<td>(3) Life span (yr)</td>
<td>3.3</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>(4) Efficiency (%)</td>
<td>50</td>
<td>60</td>
<td>75</td>
</tr>
<tr>
<td>(5) Annual energy cost at Rs. C.50/kWh</td>
<td>100.0</td>
<td>83.5</td>
<td>66.8</td>
</tr>
<tr>
<td>(6) Present worth of AEC at 10 years (Rs.)</td>
<td>610</td>
<td>510</td>
<td>410</td>
</tr>
<tr>
<td>(7) Life-cycle cost (Rs.)</td>
<td>1360</td>
<td>1110</td>
<td>660</td>
</tr>
<tr>
<td>(8) Saving (%) (compared to base)</td>
<td>Base</td>
<td>18</td>
<td>44</td>
</tr>
</tbody>
</table>

Table 4 shows the cost comparison for motors of the same rating and different efficiencies. Finally, more energy is required to manufacture a more efficient motor. At roughly 100 MJ/kg to manufacture, the more efficient motor requires 3000 MJ vs 2400 MJ for the less efficient one.

If the 10 yr output of two motors is 27 GJ, the 60% efficient unit requires 45 GJ vs 36 GJ for the 75% efficient unit. Thus, the added energy investment of 0.6 GJ to produce the more efficient unit saves 9 GJ when the electrical power conversion efficiency is considered.

Thus, a possible alternative is to construct motors with designs similar to those of 30–40 yr ago, but with the best modern insulating materials and magnetic materials for optimum performance with minimum losses, and finally, bearings should be of the best quality and easily replaceable with ordinary tools as is now done for better quality motors. The result will be extremely long lived motors. The high initial cost could partially be offset by complete standardization of frame and mounts.

**Large electric motors**

These are the motors which are rated above 50 h.p. Motors of this type are normally a.c. polyphase, either synchronous or squirrel cage induction motors. These motors operate on voltages ranging from 440 V to 11 kV.

Large motors are usually custom designed to meet specific customer application requirements, which account for all the requirements of the driven load and of the electrical systems supplying power to the motor. Such factors as load speed–torque characteristics, load inertia, duty cycles, impact loading and voltage drop while starting and running must be considered. Custom specifications on power factor and efficiency are also considerations.

The user must realize that there are many application requirements which must take priority over motor efficiency. Safe acceleration of the load without injurious thermal and mechanical strain on the motor is required. The environment in which the motor will operate dictates the minimum requirements of motor enclosure to protect the electrical parts. Open motors have maximum efficiency, but a protective enclosure is required in many applications, such as a chemically corrosive atmosphere. An example is the flame proof enclosure for motors used in mines.

When the load demand is fluctuating with time, in order to make the motor operate efficiently, a group drive is used. A large number of smaller units with higher cost and the same total (peak)
horse power is used. Thus, one can make all motors to operate at full load and peak efficiency (see Fig. 1), when the sum of the power outputs is less than the peak demand by keeping a few motors off in the group drive. This tends to reduce the cost of energy.

Effect of power factor on reduction in energy cost

A typical power factor versus load curve is shown in Fig. 1 for an induction motor (a common large motor). The motor power factor is better at higher loads, especially near rated load.

Figure 1 shows that there is a reduction in cost per kW with an increase in output. This is due to an improvement in efficiency and power factor.

STARTING CHARACTERISTICS AND SPEED FLUCTUATION

Attention must be given to the starting characteristics of motors in order to ensure that the available torque will be sufficient to start and accelerate the motor and its load in a reasonably short time. It also ensures the capability of the motor to supply the necessary torque for acceleration and deceleration of the load under variable load operation.

Further, to give large starting or accelerating torque, some motors need currents several times larger than the full load current, and such large currents are frequently inadmissible on account of the danger of overheating the motor due to excessive energy loss at the time of starting, acceleration or deceleration. It can also overheat the supply cable or cause a voltage drop in the supply due to the large current rise, with consequent disturbance to the customers.

The energy loss in the armature circuit of a shunt characteristics motor during starting is important from the viewpoint of design of an efficient drive system. This energy loss is

\[
W_{st} = \frac{k J \omega^2}{2} \text{ Joules}
\]

where \( J = \text{inertia of the rotating parts.} \)

\( W_{st} \) is independent of armature circuit resistance and is equal to the amount of kinetic energy stored in the rotating parts of the motor at the steady speed. If the inertia \( J \) of the rotating part is increased, then the transient loss for the same change in speed would be more. In the above case, the load torque is assumed to be negligible.

If the load torque is not neglected, then the amount of energy loss increases. The new loss expression would be

\[
W_{st} = \frac{J \omega^2}{2} + T_L F
\]

where \( T_L = \text{load torque and } F = \text{shaded area shown in Fig. 2}. \)
Energy loss in fluctuating load

Figure 3 illustrates a typical fluctuating load curve of a reversible rolling mill for rolling steel billets to rails and other sections. It can be seen that the load varies from a very heavy peak when the billet is being rolled to a light load period when only the friction load is met.

During varying loads the speed also varies rhythmically. The load and speed fluctuations give extra energy losses.

The energy loss due to speed fluctuation in a fluctuating load is given by

\[ W_n = k \left( \frac{\omega_0^2}{2} - \frac{\omega_i^2}{2} + (\Delta \times \omega_h) \right) \]  

where

- \( \omega_0 \) = final speed
- \( \omega_i \) = initial speed
- \( \Delta = (\omega_0 - \omega_i) \).

From the equation, it is clear that, if the speed difference is kept low, the energy loss in the armature circuit will be reduced during transients.

Ways of reducing losses in electric drives during transient conditions

Starting. The energy loss during starting can be reduced by decreasing the moment of inertia of the electric drive, which can be done by using a number of smaller machines, as in a group drive, or by use of elongated rotors.

Another method for reduction of starting losses is by raising the applied voltage step by step. A considerable number of steps can be provided by the adjustable voltage system which is commonly used for wide ranges and smooth speed control. A simplified relationship for energy loss \( \Delta W_{st} \) will be

\[ \Delta W_{st} = \Delta W_{st} \frac{1}{m} \]  

where \( m \) is the number of steps at starting.
Thus, this technique reduces energy losses considerably during starting and braking.

*Fluctuating load.* Load equalization is commonly accomplished by means of a flywheel. During peak loads, the flywheel decelerates and gives up some energy, thus reducing the load demanded from the supply, and during the light load periods, the flywheel accelerates and replenishes its stored energy for the next cycle (see Fig. 4). In Fig. 4, the shaded areas bearing the negative sign represent the amount of energy given by the flywheel and those bearing the positive sign represent the energy supplied to the flywheel by the motor.

The fluctuating load causes fluctuations in the motor torque and current, which also increase the variable losses of the motor. By smoothing out the loading, it is possible to reduce these losses. This is illustrated by Table 5.

### SPEED CONTROL

When the motors have run up to full speed, an increase of speed is still possible by cutting out some of the field turns of a d.c. series motor by means of tappings or by diverter shunt. It is usual to not have more than two tappings, giving 15 and 30% increases in speed. A decrease of speed below the normal value can, of course, be obtained by inserting resistance in series with the armature.

In the case of a single phase a.c. series motor, the voltage can be reduced on starting without the use of resistances, and this gives a large saving of energy. In the a.c. system, as the power is supplied from the line by a transformer, all that is necessary is a number of tappings on the secondary of this transformer. A preventive coil is used to ensure satisfactory operation in a manner shown in Fig. 5. In the case shown, there are five notches, and at each position, two adjacent contactors are closed. The preventive coil ensures that the part of the transformer secondary

<table>
<thead>
<tr>
<th>Load fluctuation</th>
<th>Percent loss reduction due to flywheel</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) 3:1</td>
<td>20</td>
</tr>
<tr>
<td>(2) 5:1</td>
<td>44</td>
</tr>
<tr>
<td>(3) 7:1</td>
<td>56</td>
</tr>
<tr>
<td>(4) 9:1</td>
<td>64</td>
</tr>
</tbody>
</table>
between the two contactors is not shorted. A very important advantage of this method is that each notch is a running position, so that there are available many speeds of running.

Another efficient system recently developed utilizes silicon controlled rectifiers as choppers. This system pulses full power to the motor, then cuts it off repeatedly, far faster than a mechanical switch can operate. In this way, the battery is not subjected to sudden overloads, and power is not lost through resistor dissipation. The solid state controller has, typically, an efficiency of 97%. The inductance of the motor field, as well as the inertia of the motor, has the effect of a low pass filter on the chopped power pulses, and the motor responds as though it were getting a smooth signal, Fig. 6. The speed of the motor depends on the rate at which it is switched onto the battery or the duration of the power pulses. Whether the motor speed depends on the switching rate or the pulse rate duration is determined by the type of solid state controller used.

The chopper operates from a fixed d.c. voltage $V_0$ and controls the average motor voltage $V_m$ from zero to $V_0$. The SCR acts as a switch which is closed and opened at the rate of several hundred cycles per second. The relative on-to-off time of the SCR determines the average motor voltage. The SCR is unable to turn itself off when carrying current, thus it requires a commutating circuit which imposes a negative voltage on the SCR for a short period of typically 40 $\mu$s to turn it off. The commutating circuit is represented by a switch. The waveforms of the circuit are shown in Figs 7 and 8. In Fig. 7, the chopper is operating at about 0.2 $V_0$ motor voltage when the SCR is turned on by a gating signal at $t = 0$. The armature current $i_a$ is delivered from the battery and rises as the circuit inductance absorbs the volt time area of the difference between $V_0$ and the armature e.m.f. $e_a$. When the thyristor is turned off after the time $t_1$, the armature current decays through the freewheeling diode as the energy stored in the circuit inductance is applied to the armature. As the ratio of on-to-off time $t_1/t_2$ is increased, the average motor voltage $V_m$ rises as shown in Fig. 8.

The chopper circuit requires inductance to store energy. Usually, a series motor is employed, and the field winding serves as the inductance. However, shunt motors can be employed with external inductors and normal field winding supplied from the d.c. source. The chopper can be controlled by pulse width or pulse frequency. The motor operates as though it were subjected to voltage control, not to resistance control, because the average motor voltage $V_m$ is independent of the armature current.
SPEED CONTROL

Today, thyristorized converters are used for the control of speed. For d.c. drives, dual converters are used, and for a.c. drives, voltage or current source inverters are used for speed control. In these converters, the output voltage contains large amounts of harmonics, in addition to the desired component, due to the nature of fabrication of the output voltage by the converter. The present trend is to reduce the harmonic content in the output waveforms by using suitable techniques which would improve the running efficiency of the drive.

Harmonic reduction in dual converters

It is found that, by increasing the pulse number $p$ of the converter, it is possible to raise the frequency of the lowest harmonic component, and this also reduces the amplitude of the lowest harmonic component. Table 6 gives the relative amplitude and frequency of harmonics in a dual converter output with increase in pulse numbers.

Therefore, by having a 12 pulse converter, one needs a light weight reactor to remove harmonics in the motor.

Harmonic reduction in inverters

A lot of work has been done on the reduction of harmonics at the output of inverters. Presently, pulse width modulated inverters are used for reduction in harmonic amplitudes. The number of pulses per output cycle has also been carefully chosen so that the lowest harmonic remains further from the wanted frequency component.

<table>
<thead>
<tr>
<th>Pulse number $(P)$</th>
<th>Lowest harmonic frequency</th>
<th>Maximum amplitude of lowest harmonics</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>$2\pi$</td>
<td>$V_m$</td>
</tr>
<tr>
<td>3</td>
<td>$3\pi$</td>
<td>0.866 $V_m$</td>
</tr>
<tr>
<td>6</td>
<td>$6\pi$</td>
<td>0.5 $V_m$</td>
</tr>
<tr>
<td>12</td>
<td>$12\pi$</td>
<td>0.26 $V_m$</td>
</tr>
</tbody>
</table>

$\pi =$ frequency in Hz and $V_m =$ maximum phase voltage.
Recently, a new combination for the PWM inverter has been developed which greatly reduces the harmonics which cause maximum harm to the motor.

**BRAKING**

Regenerative braking for both d.c. and a.c. drives are very popular in industrial applications. These techniques reduce the loss in energy at the time of braking. The rotor kinetic energy is fed back to the supply in the form of electrical energy, thus saving the mechanical energy stored in the flywheel and other rotating parts which otherwise would have been lost if dynamic braking or mechanical brakes were used.

**Example 1**

A 100 h.p. series motor rated at 180 A is operating in a chopper circuit from a 500 V d.c. source. The armature and field inductance is 0.060 H. At the minimum ratio \( t_1/(t_1 + t_2) \) of 0.20 as shown in Fig. 7, find the pulse frequency to limit the amplitude of the armature current excursion to 10 A.

**Solution**

For a pulse ratio of 0.20, the average armature voltage is

\[ 0.2 \times 500 = 100 \text{ V}. \]

The volt time area applied to the inductance is \((500 - 100)t_1 \text{ Vs.}\) Then, the rise of current is

\[ \Delta i_a = \frac{400t_1}{0.060} = 10 \text{ A} \]

\[ t_1 = \frac{0.6}{400} = 1.5 \times 10^{-3} \text{ s} \]

\[ t_1 + t_2 = \frac{1.5 \times 10^{-3}}{0.2} = 7.5 \times 10^{-3} \text{ s} \]

Pulse frequency \( = \frac{1}{7.5 \times 10^{-3}} = 133 \text{ pulse/s.} \)

**CONCLUSION**

The paper has presented an overview of different methods that can be used for obtaining better energy efficiency in electric drive systems. It has been shown that economic benefits can be gained with the help of reduced life-cycle cost by using more energy efficient motors. It has been also pointed out that a flywheel energy storage system can contribute to peak load management of electric drives. Also, a flywheel can smooth the fluctuating load on the motor and, thereby, reduce the losses. More efficient starting and speed control aspects of electric motors have been discussed in the paper. The chopper circuit using thyristors seems to be the best option for speed control of d.c. drives. In a general way, the paper has shown how engineers can conserve energy in industries with more efficient electric drives.

**REFERENCES**