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**CLASSIFICATION AND EVALUATION OF
ELECTRIC MOTORS AND PUMPS**

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2. Comprehensive Picture of Losses

There are two types of losses which are associated with electric motor design and operation—intrinsic losses and extrinsic (system) losses. Intrinsic losses occur internally to the motor and determine the efficiency with which motors transform electrical energy into mechanical energy; these losses can be affected only by motor design changes. Extrinsic losses occur externally to the motor, but are caused by factors inherent to motor design and operation which determine efficiency and power factor. These extrinsic losses can be affected by motor design changes, as well as by application of power factor correction capacitors, or speed and voltage control devices external to the motor which essentially adjust the motors peak power to the load.

a. Intrinsic Losses

By definition, intrinsic losses are those which are internal to the motor and are determinants of motor efficiency. Motor efficiency is defined as follows:

$$\text{Efficiency, } \eta = 1 - \left[\frac{\text{Input} - \text{Output}}{\text{Input}} \right] = 1 - \frac{\text{Losses}}{\text{Input}}$$

Losses can be categorized into groups: no-load losses and load losses. No-load losses occur when the motor is energized, but unloaded, and are relatively constant over the entire load range. The two components are friction and windage losses and core losses. Load losses vary with motor load and are comprised of three components: stator I²R losses, rotor I²R losses, and stray load losses. Definitions of each type of loss follow:

- **Friction and Windage:** This is the input power required to make up bearing and fan windage losses. Since speed varies so little from no-load to full-load, this loss is constant, unaffected by load.
- **Core Loss:** Core loss is made up primarily of hysteresis losses in rotor and stator iron caused by the 60-Hz magnetization of the core. This loss is also independent of load.
- **Stray Load Loss:** Stray load loss also occurs in the rotor and stator iron, is roughly proportional to current (or load) squared, and is induced by leakage fluxes caused by load currents.
- **I²R Losses:** These are heating losses in rotor and stator conductors caused by the current flowing through the conductor resistance. Because it varies as the square of the current, it is generally small at no-load, but of major proportion at full-load.

The total of these losses under any operating condition is used to determine motor efficiency.

A portion of the losses is the result of the magnetizing component of current required to produce motor action. This magnetizing current and the resulting reactive power requirement of a motor are found only in AC motors and determine the power factor characteristics of a motor. The importance of power factor will be discussed later in this Section.

From the efficiency equation, it is evident that the only way to improve efficiency is to reduce losses. Generally speaking, reduction of losses involves a variety of interrelationships

between a number of motor design parameters. Changes made to one or two parameters can impact on other parameters with either a positive or negative effect on efficiency. For example, as will be discussed, losses can be reduced by lowering motor currents. One method of reducing line current is to decrease the magnetizing component, which involves lowering the operating flux density and/or reducing the air gap. However, lowering operating flux density will reduce motor torque which is undesirable. Therefore, it is important to recognize that efficiency improvement is not merely a matter of making a few apparently simple design changes. Efficiency improvement in electric motors involves a complex set of highly interrelated and dependent design parameters which must be evaluated and balanced to achieve the desired results.

Recognizing that these complex interrelationships exist when making modifications for efficiency improvement, one can identify the major technical changes which can result in improved efficiency:

- **Friction and Windage(F/W):** These losses result from bearing friction, windage, and circulation of air through the motor. They can be minimized through proper maintenance of bearings and design of smaller, more efficient fans;
- **Core Losses:** Comprised of eddy current and hysteresis losses, core losses can be reduced by utilizing different grades and gauges of steel. Thinner gauge steel will reduce eddy current losses caused by circulating currents within core steel laminations. Higher grade steels, with improved core loss characteristics, will reduce hysteresis losses.
- **PR Losses:** These losses are the result of line current in both stator and rotor conductors and can be reduced by decreasing conductor resistance or line current. Conductor resistance varies inversely with the cross-section and conductivity of material. Therefore, increasing conductor cross-section and/or utilizing high-conductivity material will decrease resistance. Reducing motor current is most readily accomplished by decreasing the magnetizing component of current, which involves decreasing operating flux density and/or shortening the air gap.
- **Stray Load Losses:** These losses are affected by a variety of different factors, including air gap length, number of slots, slot geometry, rotor slot insulation, leakage flux, and manufacturing process considerations.

As the foregoing illustrates, there are many interrelated factors involved in the process of improving motor efficiency and reducing intrinsic motor losses.

Reference was made earlier to the effect of power factor on intrinsic motor losses. In an electric motor, the magnetic flux necessary for motor operation must be established by the magnetizing component of motor current. The magnetizing current lags the active-power current by 90 degrees and produces the reactive power requirement of the motor. The vector sum of the active-power current and the magnetizing current is the motor line current. Similarly, the vector sum of the active and reactive power requirements is the total motor power requirement. These relationships are shown in Figure 3-2.

Power factor is defined as the ratio of active power ($kW = \text{volts} \times \text{active current}$) to total power ($kVA = \text{volts} \times \text{total line current}$). The active power requirement of a given horsepower rating will always remain the same. Therefore, as can be seen from Figure 3-2, the effect of

$$I = \frac{.746 \times \text{hp}}{E \times K \times \eta \times \text{p.f.}}$$

where

K	= 1.0 for DC and 1 ϕ AC	p.f.	= 1.0 for DC
K	= 1.42 for 2 ϕ AC	E	= voltage
K	= 1.73 for 3 ϕ AC	η	= efficiency.

From this equation and the foregoing discussion, it is apparent that, as the efficiency and power factor are improved, motor line current will decrease, as will the motor's contribution to extrinsic losses.

Whereas power factor improvement had only minimal impact on motor efficiency, there are significantly greater impacts on system losses. The power factor at which an AC motor operates is an important feature, since a low power factor affects system operation in three ways:

- Generators, transformers, and transmission equipment are rated in terms of kVA rather than kW because their losses and heating are determined principally by voltage and current, regardless of power factor. Therefore, a low power factor (large power angle) decreases the amount of active power (kW) which the system transmits to the motor;
- Low power factor means more motor current and greater copper losses in the generating and transmitting equipment;
- Low power factor results in poor system voltage regulation.

Obviously, each of these carries an economic penalty. The cost of AC apparatus is roughly proportional to kVA rating. Therefore, the investment in generators, transformers, and transmission equipment necessary to supply a given, useful amount of active power will be roughly inversely proportional to the power factor.

Power factor improvement can have substantial impact on extrinsic system losses. The reduction, in percent, in line current or in power requirements associated with a given improvement in power factor can be determined as follows:

$$\Delta I_{\text{LINE}} (\%) = \frac{\eta_2 - \eta_1}{\eta_2}$$

where

η_2	= new efficiency
η_1	= old efficiency.

For example, if the full-load power factor of a motor is increased from 76% to 95%, a 25% improvement, there will be a 20% reduction in the motor line current and in power requirements. Copper losses in the transmission and distribution system represent an important cost to both the supplier, and ultimately to the customer, since they represent power that must be produced (at cost) but never sold. This cost must be recovered by increasing the price the consumer must pay.