Technical Guide
"Introduction To Electric Motors"

Small and Medium Enterprises Development Authority
Ministry of Industries & Production
Government of Pakistan

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1. Disclaimer

This information memorandum is to introduce the subject matter and provide a general idea and information on the said matter. Although, the material included in this document is based on data/information gathered from various reliable sources; however, it is based upon certain assumptions, which may differ from case to case. The information has been provided on AS IS WHERE IS basis without any warranties or assertions as to the correctness or soundness thereof. Although, due care and diligence has been taken to compile this document, the contained information may vary due to any change in any of the concerned factors, and the actual results may differ substantially from the presented information. SMEDA, its employees or agents do not assume any liability for any financial or other loss resulting from this memorandum in consequence of undertaking this activity. The contained information does not preclude any further professional advice. The prospective user of this memorandum is encouraged to carry out additional diligence and gather any information which is necessary for making an informed decision, including taking professional advice from a qualified consultant/technical expert before taking any decision to act upon the information.

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2. Introduction to SMEDA

The Small and Medium Enterprises Development Authority (SMEDA) was established in October 1998 with an objective to provide fresh impetus to the economy through development of Small and Medium Enterprises (SMEs).

With a mission "to assist in Employment Generation and Value Addition to the national income, through development of SME sectors, by helping increase the number, scale and competitiveness of SMEs", SMEDA has carried out 'sectoral research' to identify Policy, Access to Finance, Business Development Services, strategic initiatives and institutional collaboration & networking initiatives.

Preparation and dissemination of prefeasibility studies in key areas of investment has been a successful hallmark of SME facilitation by SMEDA.

Concurrent to the prefeasibility studies, a broad spectrum of Business Development Services is also offered to the SMEs by SMEDA. These services include identification of experts and consultants and delivery of need-based capacity building programs of different types in addition to business guidance through help desk services.

2.1 Industry Support Program

In order to enhance competitiveness of SMEs and achieve operational excellence, SMEDA established an Industry Support Cell (ISC) for provision of foreign technical support and knowledge transfer in collaboration with International Development Organizations. SMEDA's Industry Support Program (ISP) initially launched with Japan International Cooperation Agency (JICA) and actively engaged in reducing energy inefficiencies and improving production and quality of products with the support of Japanese Experts. Later on, similar activities with other international partner organizations like German Corporation for International Cooperation (GIZ), Training and Development Centers of the Bavarian Employers' Association (bfz), Germany, and United Nations Industrial Development Organization (UNIDO) were also successfully implemented.

3. What is Electric Motor?

It is an electric machine which converts electrical energy into mechanical energy, through the interaction of magnetic field in the stator and electric current in a wire winding to generate force in the form of torque applied on the shaft.

Following are the main operating components of the motors:

I. Stator
II. Rotor
III. Bearings
IV. Frame

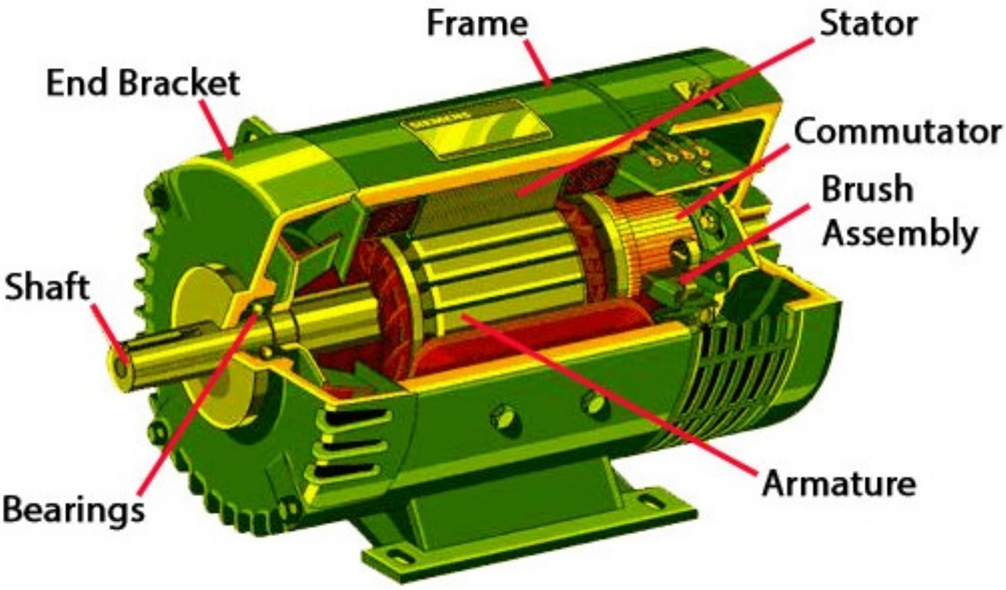

Figure 1: Cross Section – Motor

3.1 Types of Motors

Basically, there are two main types of motors based on the source of current i.e. DC Motors and AC Motors.

3.1.1 DC Motors

This type of motors converts direct current (DC) into mechanical work. The armature and stator are the two main parts of the DC motor. The armature is the rotating part, and the stator is their stationary part. The armature coil is connected to the DC supply.

The armature coil consists the commutators and brushes. The commutator applies electric current to the windings. By reversing the current direction in the rotating windings each half turn, a steady rotating force is produced. Brushes are put over the commutator. As the commutator rotates then brushes, which is stationary, rides on the surface of the commutator. Since brushes are stationary and are making electrical connection with the rotating commutator; so now you can connect electrical wires to the brush to extract the dc power.

The armature is placed between the north and south pole of the permanent or electromagnet.

For simplicity, consider that the armature has only one coil which is placed between the magnetic field shown below in the figure A. When the DC supply is given to the armature coil the current starts flowing through it. This current develops its own field around the coil. Figure B shows the field induced around the coil.

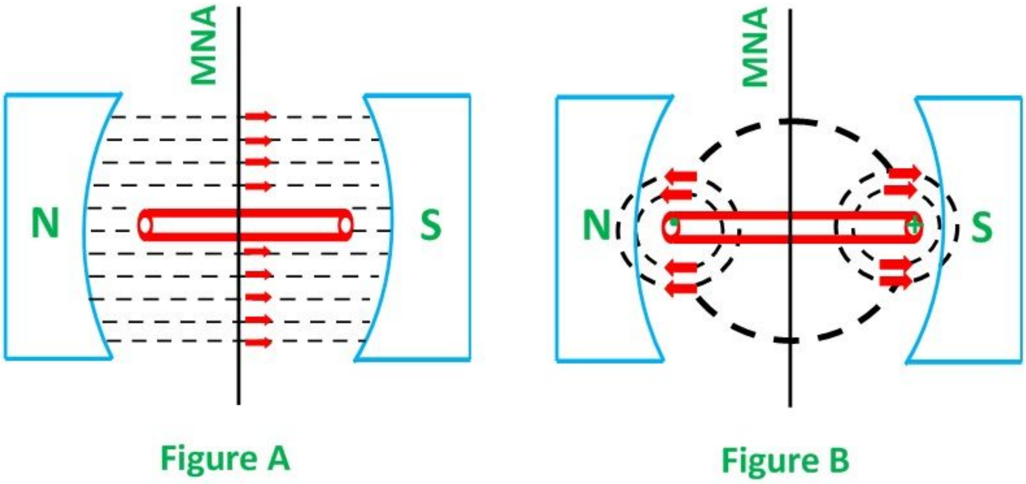

Figure 2: DC Motor Working Principle(i)

By the interaction of the fields (produced by the coil and the magnet), resultant field develops across the conductor. The resultant field tends to regain its original position, i.e. in the axis of the main field. The field exerts the force at the ends of the conductor, and thus the coil starts rotating. (as shown in below figure)

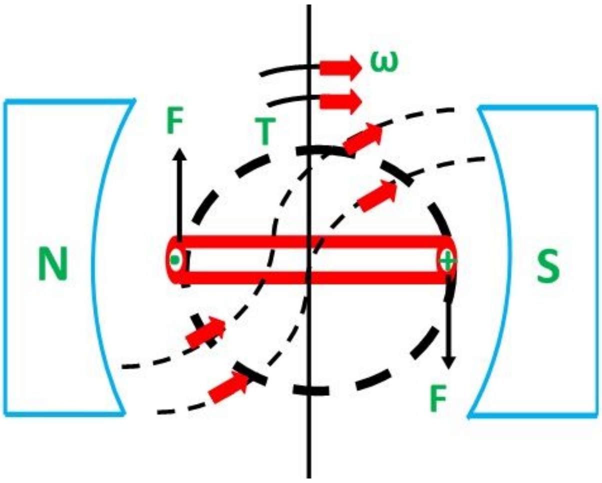

Figure3: DC Motor Working Principle(ii)

3.1.2 AC Motors

AC motor converts the alternating current (AC) into mechanical power by using an electromagnetic induction. This motor is driven by an alternating current. The stator and the rotor are the two most important parts of the AC motors. The stator is the stationary part of the motor, and the rotor is the rotating part of the motor. The AC motor may be single phase or three phase.

The three phase AC motors are mostly applied in the industry for bulk power conversion from electrical to mechanical. For small power conversion, the single phase AC motors are mostly used. The single phase AC motor is nearly small in size, and it provides a variety of services in the home, office, business concerns, factories, etc. Almost all the domestic appliances such as refrigerators, fans, washing machine, hair dryers, mixers, etc., use single phase AC motor.

4. Motor Performance Features

4.1 Motor Speed

Number of revolutions in a given time interval is the motor speed, typically revolutions per minute (RPM). The synchronous speed in RPM is represented by the following formula:

Synchronous Speed (RPM) = 120 x Frequency / Poles

$$Ns = \frac{120f}{P}$$

The difference between the synchronous speed and full load speed is called slip and is calculated in percentage by the following:

Slip (%) = (Synchronous Speed – Full Load Speed / Synchronous Speed) X 100

The amount of slip present is proportional to the load of the motor by the driven equipment.

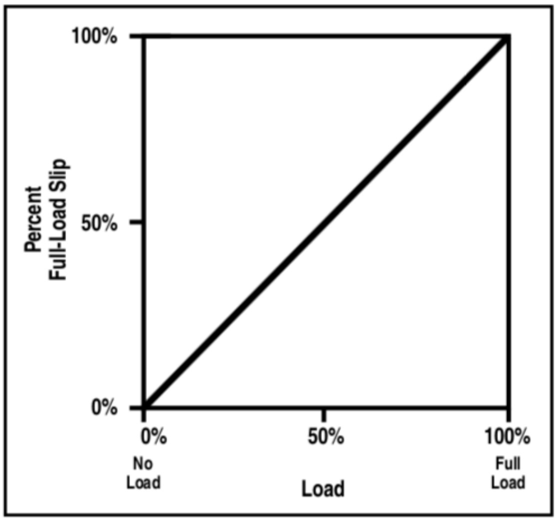

Figure 4: Percent Motor Slip as a Function of Motor Load

By using a tachometer to measure actual motor speed, it is possible to calculate motor loads. The safest, most convenient, and usually most accurate tachometer is a battery powered stroboscopic tachometer. Mechanical tachometers, plug-in tachometers, and tachometers which require stopping the motor to apply paint or reflective tape should be avoided. The motor load can be estimated with slip measurements by the following formula:

$$Load = \frac{Slip}{Ss - Sr} X\ 100$$

where,

Load = Output power as a % of rated power
Slip = Synchronous speed - Measured speed in rpm
S_s = Synchronous speed in rpm
S_r = Nameplate full-load speed

4.2 Voltage Frequency Relation

Inductors are used to temporarily store electrical energy in the form of a magnetic field. Impedance of an inductor is proportional to frequency. At low frequencies, this impedance approaches zero, making the circuit appear to be short-circuit. The voltage to the motor must be changed in order to maintain a constant flux in the motor. This ratio is constant over most of the entire speed range. By keeping the ratio constant, a fixed speed induction motor can be made to run at variable speed offering constant torque. At low speeds, due to the motor having inherent resistance in the windings, the ratio must be altered to provide enough magnetizing flux to spin the motor. The variable frequency drive (VFD) allows this relationship to be altered by changing the voltage boost parameter.

Variable frequency drive (VFD) is a type of motor controller that drives an electric motor by varying the frequency and voltage supplied to the electric motor. Frequency is directly proportional to the motors speed (rpm). In other words, the faster the frequency, the faster the RPMs go. If an application does not require an electric motor to run at full speed, the VFD can be used to ramp down the frequency and voltage to meet the requirements of the electric motor's load. Advantages of using VFDs include:

- Reduced Energy Consumption and Cost
- Increased Production via Tighter Process Control
- Increased Equipment Life and low Maintenance

Application of variable frequency drives and variable speed drives, for capacity control of pumps, fans, compressors, process control is the most relevant energy conservation opportunity.

4.3 Motor Load

Most electrical motors are designed to run at 50 % to 100% of rated load. Maximum efficiency usually occur near 75% of rated load. A motor's efficiency tends to decrease dramatically below 50 % load. However, the range of good efficiency varies with individual motors and tend to extend over a broader range of larger motors, as shown in below figure.

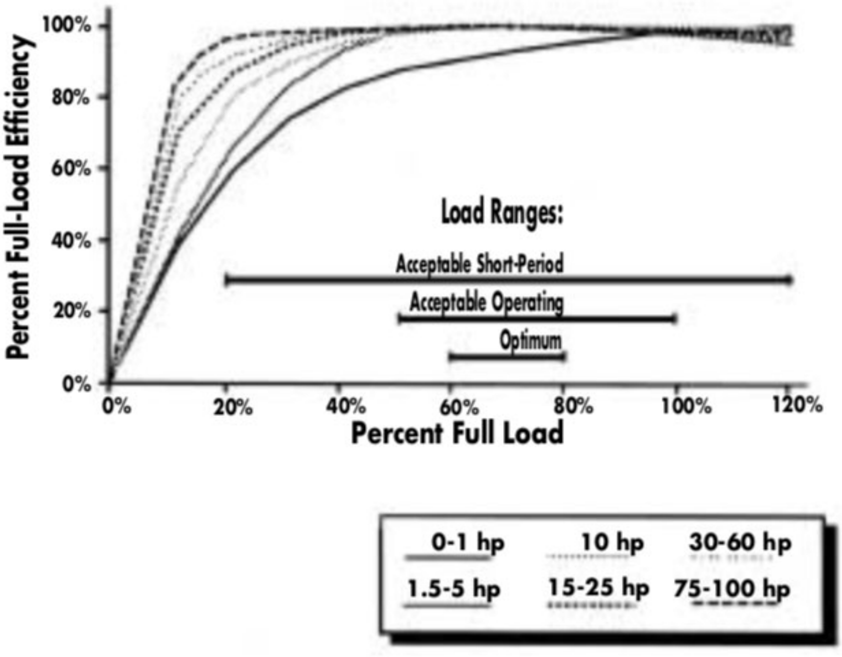

Figure 5: Load Efficiency

A motor is considered under loaded when it is in the range where efficiency drops significantly with decreasing load. Below figure shows that the power factor tends to drop off sooner, but less steeply than efficiency, as load decreases.

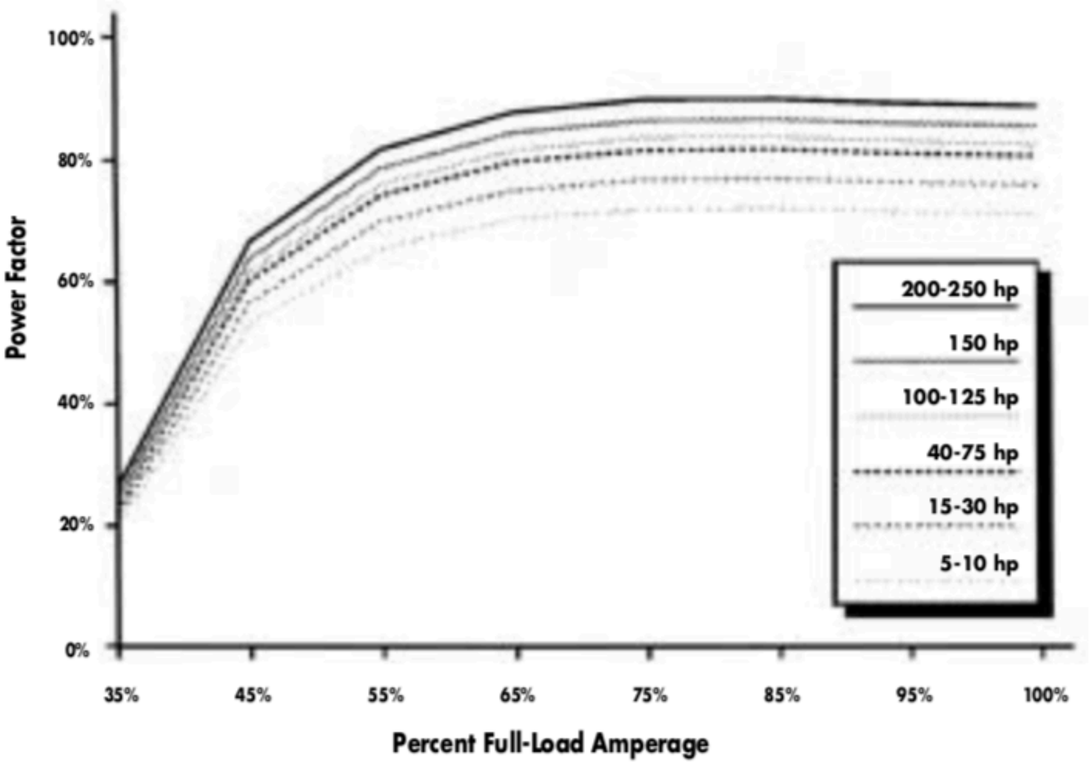

Figure 6: Motor Power Factor (as a Function of % Full-Load Amperage)

Overloaded motors can overheat and lose efficiency. Many motors are designed with a service factor that allows occasional overloading. *Service factor* is the percentage of overloading the motor can handle for short periods when operating normally within the correct voltage tolerances. For example, a 10-hp motor with a 1.15 service factor can handle a load of 11.5-hp for short periods of time without incurring significant damage.

Although many motors have service factors of 1.15, running the motor continuously above rated load reduces efficiency and motor life. Never operate over- loaded when voltage is below nominal or when cooling is impaired by altitude, high ambient temperature, or dirty motor surfaces.

Load can be calculated by the following:

$$Load = \frac{Pi}{Pir} X\ 100\%$$

where,
Load = Output power as a % of rated power
P_i = Measured three phase power in kW
P_{ir} = Input power at full-rated load in kW

$$Pi = \frac{VxIxPFx\sqrt{3}}{1000}$$

where,

P_i = Three Phase Power in kW
V = RMS voltage , mean line to line of 3 phases
I = RMS current , mean of 3 phase
PF = Power Factor

$$Pir = hp\ x\ \frac{0.7457}{\eta fl}$$

where,
P_{ir} = Input power at full rated load in kW
hp = Nameplate rated horsepower
η_{fl} = Efficiency at full rated load

4.4 Motor Efficiency

National Electrical Manufacturers Association (NEMA) of USA defined efficiency as the ratio of its useful power output to its total power input and is usually expressed in percentage.

$$\eta = \frac{0.7457\text{x hp x load}}{\text{Pi}}$$

where,
η= Efficiency as operated in %
hp = Nameplate rated horsepower
Load = Output power as a % of rated power
P_i = Three- phase power in kW

International Electrotechnical Commission (IEC) 60034-30 standard classified the electrical motors into three.
IE_1 = Standard Efficiency
IE_2 = High Efficiency
IE_3 = Premium Efficiency

IEC 60034-30 covers almost all motors, with the notable exceptions of motors made solely for converter operation and motors completely integrated into a machine.

Output kw	IE1 - Standard Efficiency			IE2 - High Efficiency			IE3 - Premium Efficiency		
	2 pole	4 pole	6 pole	2 pole	4 pole	6 pole	2 pole	4 pole	6 pole
0.75	72.1	72.1	70.0	77.4	79.6	75.9	80.7	82.5	78.9
1.1	75.0	75.0	72.9	79.6	81.4	78.1	82.7	84.1	81.0
1.5	77.2	77.2	75.2	81.3	82.8	79.8	84.2	85.3	82.5
2.2	79.7	79.7	77.7	83.2	84.3	81.8	85.9	86.7	84.3
3	81.5	81.5	79.7	84.6	85.5	83.3	87.1	87.7	85.6
4	83.1	83.1	81.4	85.8	86.6	84.6	88.1	88.6	86.8
5.5	84.7	84.7	83.1	87.0	87.7	86.0	89.2	89.6	88.0
7.5	86.0	86.0	84.7	88.1	88.7	87.2	90.1	90.4	89.1
11	87.6	87.6	86.4	89.4	89.8	88.7	91.2	91.4	90.3
15	88.7	88.7	87.7	90.3	90.6	89.7	91.9	92.1	91.2
18.5	89.3	89.3	88.6	90.9	91.2	90.4	92.4	92.6	91.7
22	89.9	89.9	89.2	91.3	91.6	90.9	92.7	93.0	92.2
30	90.7	90.7	90.2	92.0	92.3	91.7	93.3	93.6	92.9
37	91.2	91.2	90.8	92.5	92.7	92.2	93.7	93.9	93.3
45	91.7	91.7	91.4	92.9	93.1	92.7	94.0	94.2	93.7
55	92.1	92.1	91.9	93.2	93.5	93.1	94.3	94.6	94.1
75	92.7	92.7	92.6	93.8	94.0	93.7	94.7	95.0	94.6
90	93.0	93.0	92.9	94.1	94.2	94.0	95.0	95.2	94.9
110	93.3	93.3	93.3	94.3	94.5	94.3	95.2	95.4	95.1
132	93.5	93.5	93.5	94.6	94.7	94.6	95.4	95.6	95.4
160	93.7	93.8	93.8	94.8	94.9	94.8	95.6	95.8	95.6
200	94.0	94.0	94.0	95.0	95.1	95.0	95.8	96.0	95.8
250	94.0	94.0	94.0	95.0	95.1	95.0	95.8	96.0	95.8
315	94.0	94.0	94.0	95.0	95.1	95.0	95.8	96.0	95.8
355	94.0	94.0	94.0	95.0	95.1	95.0	95.8	96.0	95.8
375	94.0	94.0	94.0	95.0	95.1	95.0	95.8	96.0	95.8

Table 1: IEC 60034-30;2008 Efficiency Limits

5. Motor Losses

Losses are not easily calculated but can be determined based on test data, following are the major losses occur in the electric motors:

5.1 Core Losses

Core loss is around 22 % of total loss at full speed. It is constant and is independent of the motor load current , therefore ,it accounts for a much higher percentage of the losses at lower motor loads.

5.2 Stator and Rotor Resistance Losses

This loss is about 56 % of total loss at full speed and it happens due to the current flow through the motor conductors of resistance. Loss is proportional to the square of the stator and rotor current and is called I2R loss.

5.3 Friction and Windage Losses

This loss is about 11 % of total loss at full speed and it happens due to the friction within the shaft bearing and the resistance to air being circulated through the motor by cooling fans.

5.4 Stray Load Losses

Stray load loss is about 11 % of total loss at full speed and it results because of magnetic flux leakage and depends on the rotor slot design.

Stator Resistance Loss %	Rotor Resistance Loss %	Core Loss %	Friction and Windage Loss %	Stray Load Loss %	Total Losses %
30	20	19	13	18	100

Table 2: Losses – 15 HP induction Motor

6. Energy Efficiency Opportunities

There are many ways to conserve the energy in motors, which can broadly be divided into two categories of approaches; System Approach and Operational Measures.

6.1 System Approach

Significant energy saving involves set procedures:

- Switched off equipment when not in use
- Provide energy efficient capacity controls
- Process Re-engineering to reduce the work

6.2 Operational Measures

There are various measures that can be taken, which are not limited to the followings:

6.2.1 Maintain Voltage Close to Rating

Motors operate generally within 10% of the voltage mentioned on the nameplate, large variations reduce the efficiency, power factor and life. When operate at less than 95% of design voltage , motors typically lose 2 to 4 points of efficiency and temperature may increase upto 20^{o}F Running on above the design voltage also reduce the power factor and efficiency

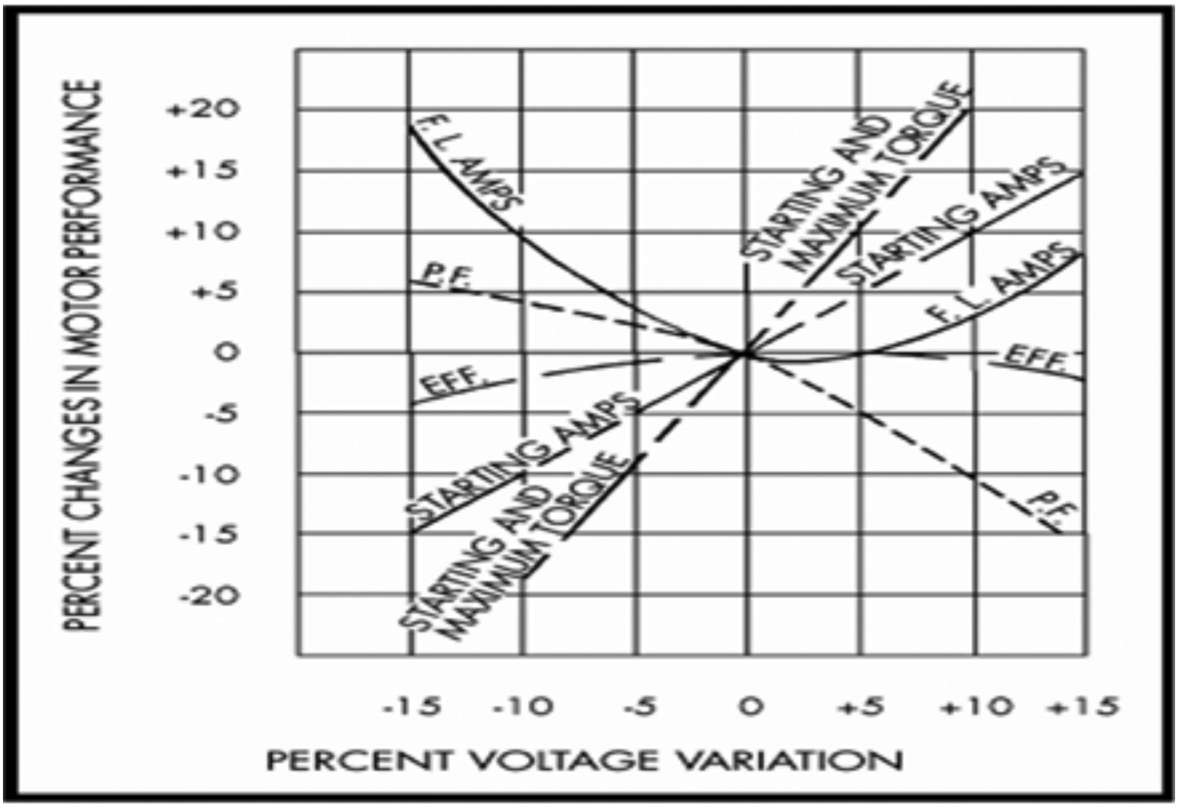

Figure 7: Effect of Voltage Variation on Motor Performance

6.2.2 Minimize Phase Imbalance

The voltage of each phase in a 3 phase system should be of equal magnitude, symmetrical and separated by 120°. Phase balance should be within 1% to avoid de-rating of the motor. There are several factors which contributes in voltage imbalance which includes: single phase loads on any one phase, different cable sizing or faulty circuits.

Characteristic	**Performance**		
Average Voltage	230	230	230
Percent Unbalanced Voltage	0.3	2.3	5.4
Percent Unbalanced Current	2.4	17.7	40
Increase Temperature (°C)	< 1	11	60

Table 3: Effect of Voltage Unbalance on 5HP Motor

6.2.3 Minimize Rewind Losses

Rewinding can lower motor efficiency and reliability. In many industries, motors are rewound rather than replace this is economical option but downside is that there is no assurance of quality.

The only areas of possible loss reduction available during the rewinding process is the copper (I2R) losses in the motor. Reduction is achieved by rewinding the motor with a large diameter wire so the effective conductor area is increased, where slot area permits, resulting in a lower winding resistance.

In majority of industries, more than 50% motors are rewound and it would be useful to evaluate all such motors and introduce the phase out program and a quality assurance program motor motor efficiency based on load loss measurement etc.

6.2.4 Optimize Transmission Efficiency

Motor power transmission equipment, including shafts, belts, chains and gears, should be installed and maintained. When possible use flat belts in place of V-belts. Helical gears are more efficient than worm gears; use worm gears only with motors under 10hp. As far as possible, it is better to have direct drive, thus avoiding losses in the transmission system.

7. Load and Performance Assessment

Motor load survey is a useful activity in audit, to tap the opportunity of energy saving in motors. The steps involved are:

1. List down the inventory that includes all motors, installed locations, type of equipment and usage hours.
2. Document all name plate data
3. Measure run values of input power parameters, alongside machine side parameters
4. Document and maintain the record of following:
    a. Motor burnout repeated cases
    b. Motors with high no load losses
    c. Percentage of motor loading in kW as against rated input kW
    d. Occurrence of voltage imbalance, low power factor, loose connections and low terminal voltage
    e. Occurrence of mechanical problems like slippages, local heating, vibration, mis-alignment, inadequate ventilation and dusty conditions.
    f. Inefficiencies in machines like idle operations, throttling of pumps, damper operations in fans and leakages
5. Identify the area for VFD applications for energy efficiency

8. Tips for Motors and Drives

- Use Proper sized motors to the load for optimum efficiency.
- Use energy-efficient motors where economical.
- Use synchronous motors to improve power factor.
- Check alignment.
- Provide proper ventilation. (For every 10^{O}C increase in motor operating temperature over the recommended peak, the motor life is estimated to be halved.)
- Check for under-voltage and over-voltage conditions.
- Balance the three-phase power supply. (An imbalanced voltage can reduce motor input power by 3%–5%.)
- Demand efficiency restoration after motor rewinding. (If rewinding is not done properly, the efficiency can be reduced by 5%–8%.)

For Drives:

- Use variable-speed drives for large variable loads.
- Use high-efficiency gear sets.
- Use precision alignment.
- Check belt tension regularly.
- Eliminate variable-pitch pulleys.
- Use nylon sandwich type energy efficient flat belts as alternatives to old v-belts.
- Eliminate inefficient couplings.
- Shut them off when not needed adopting interlocks, controls.