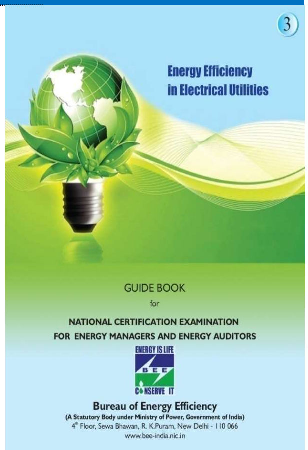
BOOK 3 – ENERGY EFFICIENCY IN ELECTRICAL UTILITIES
Brief Contents



Chapter-2 Electrical Motors
Contents

In this chapter you will learn about

- ✓ Motor types its characteristics
- ✓ Motor selection
- ✓ Factors affecting motor efficiency
- ✓ Rewinding
- ✓ Speed controls
- ✓ Standards and labeling

2.1 Introduction

- Motors convert electrical energy into mechanical energy
- 90 % of industrial motors are induction motors

All motor types have the same **four operating components:**

1. Stator (stationary windings)
2. Rotor (rotating windings)
3. Bearings and
4. Frame (enclosure)

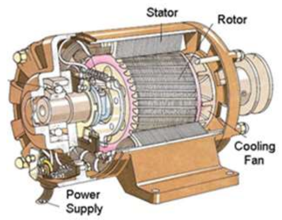


Figure 2.1 Induction Motor

2.2 Type of Motors	Motor Features and Advantages
Induction Motors	Rotor runs slower than the speed of the stator field. rotor of a squirrel cage motor is comprised of aluminum bars embedded in the steel laminations. Ends of the rotor bars are shorted
Slip-ring motor	• ideal for very high inertia loads • used in applications for driving variable torque/ variable speed loads. (printing presses, compressors, conveyer, hoists and elevators)
Direct-Current Motors	• unidirectional, current. • applications- high torque starting or smooth acceleration over a broad speed range is required.
Synchronous Motors	synchronous motor rotate with no slip, i.e., RPM is same as the synchronous speed
Permanent Magnet Synchronous Motor (PMSM)	contain permanent magnets. advantages such as power density, better cooling, smaller size, better efficiency motors perform best when driven by sinusoidal waveforms.
Synchronous Reluctance Motors	rotor is built with magnetic materials superior performance ,achieving IE4 efficiency class rotor losses are very small compared to induction motor.

2.3 Motor Characteristics

1. Motor Speed
The speed of an AC motor depends on the frequency of the input power and the number of poles for which the motor is wound.

$$\text{Synchronous Speed (RPM)} = \frac{120 \times \text{Frequency}}{\text{No. of Poles}}$$

2. Slip: The difference between synchronous and full load speed is called slip and is measured in percent.

$$\text{Slip (\%)} = \frac{\text{Synchronous Speed - Full Load Rated Speed}}{\text{Synchronous Speed}} \times 100$$

3. Power Factor
The power factor of the motor is given as:

$$\text{Power Factor} = \text{Cos}\ \phi = \frac{\text{kW}}{\text{kVA}}$$

2.4 Motor Efficiency

What are the Two most important attributes relating to performance of A.C. Induction motors?

$$Efficiency = \frac{Output}{Input} \times 100 = \frac{Input - Losses}{Input} \times 100$$

$$= \frac{746 \times HP\,Output}{Watts\,Input} \times 100$$

What are the Motor losses?

- **fixed losses** - independent of motor load
- **Variable losses** - dependent on load.
- **Fixed losses =M**agnetic core losses +Friction &Windage losses. Magnetic core losses (Iron losses) consist of eddy current and hysteresis losses in the stator.
- **Variable losses =R**esistance losses in the stator and in the rotor and miscellaneous stray losses.

EFFICIENCY/POWER FACTOR vs LOAD
(Typical 3-Phase Induction Motor)

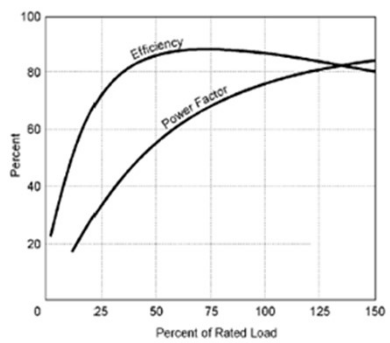


Figure 2.2 % Load vs. Power factor, Efficiency

Field Tests for Determining Motor Efficiency

Example:

Motor Specifications

Rated power = 34 kW/45 HP
Voltage = 415 Volt
Current = 57 Amps
Speed = 1475 rpm
Connection = Delta

No load test Data

Voltage, V = 415 Volts
Current, I = 16.1 Amps
Frequency, F = 50 Hz
Stator phase resistance at 30°C = 0.264 Ohms
No load power, Pnl = 1063.74 Watts

a. Calculate iron plus friction and windage losses

b. Calculate stator resistance at 120⁰C

$$R2 = R1 \times \frac{235 + t_2}{235 + t_1}$$

c. Calculate stator copper losses at operating temperature of resistance at 120⁰C

d. Calculate full load slip(s) and rotor input assuming rotor losses are slip times rotor input.

e. Determine the motor input assuming that stray losses are 0.5 % of the motor rated power

f. Calculate motor full load efficiency and full load power factor

Solution

a)Let Iron plus friction and windage loss, P_i + fw

No load power, P_{nl} = 1063.74 Watts

Stator Copper loss, P st-30⁰C (Pst.cu)

$= 3 \times (16.1 / \sqrt{3})^2 \times 0.264$

= 68.43 Watts

Pi + fw = P_{nl} – Pst.cu

= 1063.74 – 68.43

= 995.3 W

b)Stator Resistance at 120⁰C,

$$R_{120^0C} = 0.264 \times \frac{120 + 235}{30 + 235}$$

= 0.354 ohms per phase

c)Stator copper losses at full load, Pst.cu 120⁰C

$= 3 \times (57 / \sqrt{3})^2 \times 0.354$

= 1150.1 Watts

d) Full load slip

S = (1500 – 1475) / 1500

= 0.0167

Rotor input, Pr = P_{output}/ (1-S) = 34000/ (1-0.0167)

= 34577.4 Watts

e) Motor full load input power, P input

= P_r + Pst.cu 120⁰C + (P_i + fw) + P_{stray}

= 34577.4 + 1150.1 + 995.3 + (0.005* × 34000)

= 36892.8 Watts

*where, stray losses = 0.5% of rated output (assumed)

f) Motor efficiency at full load

$$\text{Efficiency} = \frac{P_{output}}{P_{input}} \times 100 = \frac{34000}{36892.8} \times 100 = 92.2\ \%$$

$$\text{Full Load PF} = \frac{P_{input}}{\sqrt{3} \times V \times I_{fl}} = \frac{36892.8}{\sqrt{3} \times 415 \times 57}$$

=0.90

2.5 Motor Selection Criteria

Factors to be addressed In selection of motor

1. The power drawn **at 75 % of loading** can be a meaningful indicator of energy efficiency.
2. **Reactive power drawn** (kVAr) by the motor.
3. Indian Standard Allows 15 % tolerance on efficiency for motors upto 50 kW rating and 10 % for motors over 50 kW rating.
4. **Stray losses** are assumed as 0.5 % of input power.
5. Procure motors **based on test certificates** rather than labeled values.
6. **kW savings** = **kW output** × **[$1/\eta_{old}$ - $1/\eta_{new}$]** where η_{old} and η_{new} are the existing and proposed motor efficiency values.
7. **Cost benefits** can be worked out on the basis of premium required for high efficiency vs. worth of annual savings.

- Motor choice **depends on the torque required** by the load
- Maximum torque generated by the motor (**break-down torque**) and the torque requirements for start-up (**locked rotor torque**)
- **Duty / load cycle** determines the thermal loading on the motor.
- In TEFC motors -cooling may be insufficient when the motor is operated at speeds below its rated value.
- Ambient operating conditions affect motor choice. special motor **for corrosive or dusty atmospheres**, high temperatures
- if the **load variations are large/** frequent starts and stops of large components like compressors, the resulting large voltage drops could be detrimental to other equipment. (Reliability, Inventory ,Price)

Type of Motors Vs Motor Efficiency

Type of Motors	Rating,Kw	Motor Efficiency,%	Power Factor,PF
DC Motor	1 – 10 KW	70 – 84	-
	- 100	84 – 92	-
	- 1000	92 – 95	-
A.C. SLIP Ring Motor	11 - 100	86 - 93	0.79 - 0.87
	500	95	0.87 - 0.91
A C SQ.Cg Motor	1 KW	53 – 74	0.67 – 0.78
	11 KW	74 – 88	0.81 – 0.85
	132KW	88 – 95	0.86 – 0.88
	400KW`	95 – 97	0.88 – 0.89

2.6 Energy-Efficient Motors

Energy Efficient Motors	
Power Loss Area	**Efficiency Improvement**
1. Iron	Use of **thinner gauge**, lower loss core steel reduces eddy current losses. Longer core adds more steel to the design, which reduces losses due to lower operating flux densities.
2. Stator I^2R	Use of **more copper and larger conductors** increases cross sectional area of stator windings. This lowers resistance (R) of the windings and reduces losses due to current flow (I).
3. Rotor I^2R	Use of **larger rotor conductor** bars increases size of cross section, lowering conductor resistance (R) and losses due to current flow (I).
4. Friction & Windage	Use of **low loss fan design** reduces losses due to air movement.
5.Stray Load Loss	Use of optimized design and strict quality control procedures minimizes stray load losses.

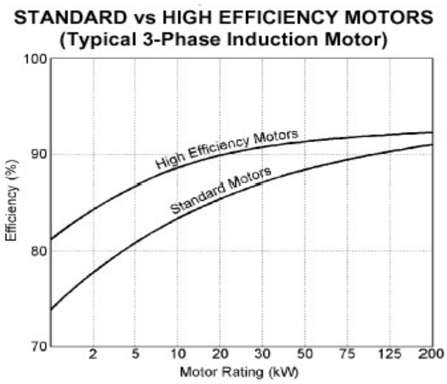


Figure 2.3 Standard vs High Efficiency Motors

2.7 Factors Affecting Energy Efficiency & Minimising Motor Losses in Operation

❑ **Power Supply Quality :**

- The BIS standards specify that a motor should be capable of delivering its rated output with a **voltage variation of +/- 6 % and frequency variation of +/- 3 %.**

❑ **Voltage unbalance** can be more detrimental to motor performance and motor life.

Table 2.4 Example of the Effect of Voltage Unbalance on Motor Performance

Parameter	Percent unbalance in voltage		
	0.30	**2.30**	**5.40**
Unbalance in current (%)	0.4	17.7	40.0
Increased temperature rise (^{0}C)	0.18	10.6	58

The NEMA standard definition of voltage unbalance is given by the following equation:

$$Voltage\,unbalance = \frac{Maximum\ deviation\ from\ mean\ of\ V_{ab}, V_{bc}, V_{ca}}{Mean\ of\ (V_{ab}, V_{bc}, V_{ca})}$$

Example consider a three-phase supply system (volts):

The line-line voltages are: R, Y, B

$V_{ab} = 410$, $V_{bc} = 417$, $V_{ca} = 408$

% Voltage Unbalance = (417 – 411.7/411.667) x 100=1.29 %

Where

Mean = (410 + 417 + 408) / 3 = 411.7

Hence the **voltage unbalance is 1.29%.**

2.7 Factors Affecting Energy Efficiency & Minimising Motor Losses in Operation

❑ Motor Loading

$$\% Loading = \frac{Input\ power\ drawn\ by\ the\ motor\ (kW)\ at\ existing\ load}{Name\ plate\ full\ load\ kW\ rating\ /\ name\ plate\ full\ load\ motor\ efficiency} x 100$$

Actual input power Measured

Rated Input power Output/Eff.

$$\% Loading = \frac{Input\ power\ drawn\ by\ the\ motor\ (kW)\ at\ existing\ load}{\sqrt{3}\ x\ kV\ x\ I\ x\ Cos\phi}\ x\ 100$$

Actual input power Measured

Rated Input power Calculated name plate full load current

Example: The nameplate details of a motor are given as Power = 15 kW, Efficiency η = 0.9. Using a power meter the actual three phase power drawn is found to be 8 kW. Find out the loading of the motor.

Input power at full-rated power in kW, P_{ir} = 15 /0.9
= 16.7 kW

Percentage loading = 8/16.7= 48 %

Motor Load Survey: Methodology

The observations during survey and indicate:

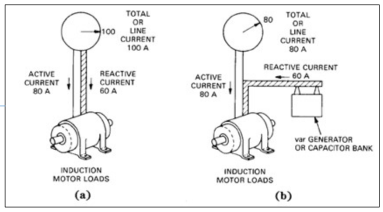
- % loading on kW, % voltage unbalance if any, voltage, current, frequency, power factor,
- **Machine side conditions** like load / unload condition, pressure, flow, temperature, damper / throttle operation, whether it is a rewound motor, idle operations, metering provisions, etc.

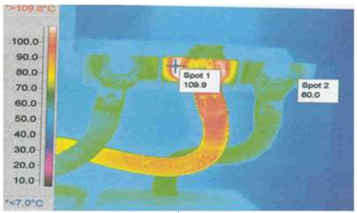
Energy Saving Recommendations in motors include:

- Identify motors with <u>less than 50 % loading</u>, <u>50 – 75 % loading</u>, <u>75 – 100 % loading</u>, <u>over 100 % loading.</u>
- Identify motors with low voltage / power factor / voltage imbalance for needed improvement measures.
- Identify motors with idle operations, throttling / damper operations for avenues like automatic controls / interlocks,VFD.
- The Saving potential in motor efficiency is **less than 10 %** , but the load survey would help to **bring out savings in driven machines / systems**, which can give **30 – 40 % energy savings.**

Energy Saving Case Studies

- ❑Reducing Under-loading
- ❑Improve Motor Loading by Star Mode Operation
- ❑Sizing to Variable Load
- ❑Power Factor Correction
- ❑Proper Maintenance





Case Study of Over Sizing motor

	Case I (7.5 Kw)	Case II (11 Kw)	Case III (15 KW)
Load KW.	7.5	7.5	7.5
Efficiency,%	88	84	79
Input	8.5	9.0	9.5
KWH (5000 Hrs/yr)	42500	45000	47500
Cost	127500	135000	142500

Actual LOAD 7.5 KW

Power transmission

Case I- Direct coupling

Case II-Gear drives

Case III-Belt drives

Increase 100% rating 11% energy effects of oversized motors

Due to

- Low efficiency
- Low power factor
- Higher power consumption

Case Study
Comparison of power consumption with Delta / Star mode operation

Equipment: Agitator 3131:
Motor rating 22 KW ; 1440 RPM,Tub capacity = 68 M^3

Tub Capacity	Mode of operation	Voltage	I (Amps)	P.F. (Cos Ø)	Power KW	Motor Loading,%
15M^3	Delta	406	22	0.47	7.16	32.5
	Star	413	9	0.84	5.41	24.6
30M^3	Delta	411	23	0.61	9.68	44.0
	Star	413	14	0.91	9.51	43.2
60M^3	Delta	412	25	0.62	10.62	48.2
	Star	411	14	0.90	9.4	42.7

2.8 Rewinding Effects on Energy Efficiency

Case Study

Motor burning rate

- < 10 HP : 60 – 100 Nos per year
  >10 HP : 5 Nos per year

Major reasons

- Electrical overloading
- Mechanical / bearing failure
- Oil leaks & Water leaks while cleaning

Rewinding Quality

- Motor rewinding carried out by outside contractor
- No load current is checked for rewound motor
  if < 40% load , accepted with 6 months guarantee
  if > 40% load motor is returned for rework

- Population of rewound motors may exceed 50 %
- Rewinding can reduce motor efficiency and reliability.
- Majority of the users would wish to rewind the motor.
- Rewind-versus-replace decision
- Compare of no load current and stator resistance per phase of a rewound motor with the original no-load current and stator resistance at the same voltage to assess the efficacy of rewinding.

2.9 Principle of VFDs

The VSD's basic principle of operation is to convert the electrical system frequency and voltage to the frequency and voltage required to drive a motor at a speed other than its rated speed.

RPM = (f x 120) / p

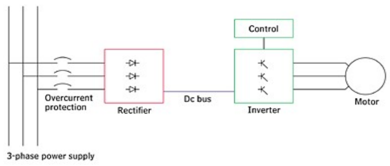
Need for VFD

Torque α speed^2

Power α speed^3

- Variable speed, depending upon the load requirement, **provides significant energy saving.**

- The basic function of the VFD is to act as a variable frequency generator in order to vary speed of the motor as per the user setting.
- The rectifier and the filter convert the AC input to DC with negligible ripple.



Components of a Variable Speed Drive

Driven Load Types and Characteristics

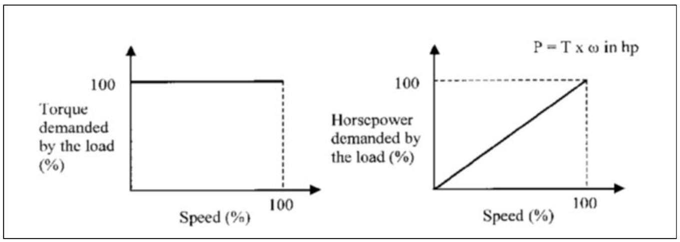
Constant Torque Load &Variable Torque Load

Constant Torque Load(CT): In this type, the torque demanded by the load is constant throughout the speed change.

The load requires the same amount of torque at low speeds as at high speeds. Loads of this type are essentially friction loads

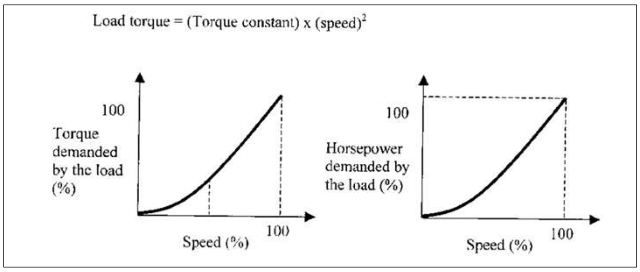
A CT load implies that the load torque seen at motor shaft is independent of motor speed.

Ex: Conveyors, Reciprocating and screw compressors,Extruders.



Variable Torque Load (VT) :A VT load implies that the load torque seen at the motor shaft is dependent upon the motor speed.

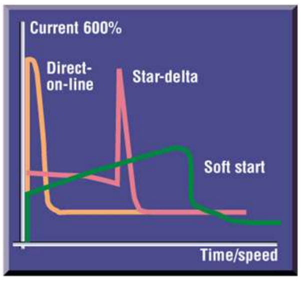
Ex. centrifugal fans & pumps and centrifugal compressors.



VFD Selection : The size of the VFD depends mainly on driven load type and characteristics. This will determine the drive capacity in terms of full load current (FLC) and power delivered (KW).

Soft Starter

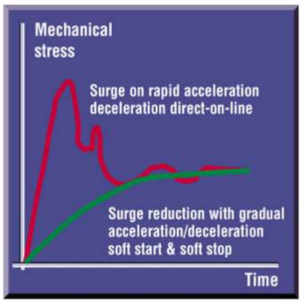
- **DOL**: When starting, AC Induction motor develops more torque than is required at full speed. This stress is transferred to the mechanical transmission resulting in wear and failure of chains, belts, gears, mechanical seals, etc. Rapid acceleration also has a impact on electricity supply charges with high inrush currents drawing +600% of the normal current
- The use of **Star Delta** only provides a partial solution
- **Soft starter** provides a solution to problems by delivering a controlled release of power to the motor, thereby providing smooth, stepless acceleration and deceleration. Motor life will be extended as damage to windings and bearings is reduced



Advantages of Soft Start

- Less mechanical stress
- Improved power factor.
- Lower maximum demand.
- Less mechanical maintenance

Motor running with DG Set power needs soft starter



Soft Starter: Starting current, Stress profile during starting

2.10 Star Labeling of Energy Efficient Induction Motors

- The schedule specifies the requirements for participating in the energy labeling scheme for 3 phase squirrel cage induction motor in 2 Pole, 4 Pole and 6 Pole for continuous duty (S1) operation, suitable for voltage and frequency variation as per IS 12615:2011 having rated output from **0.37 to 375 kW.** this scheme specifies the following:

1. Rated output (rating)
2. Efficiency Class based on IS 12615:2011 i.e. (IE2, IE2(+), IE3, IE3(+) and IE3 (++))

Solved Example:

During an energy audit following data were obtained on a 3 phase induction motor:

Rated values: 37 kW,415V, 66 A,0.88 pf

Operating values: 410 V, 49A, 0.76 pf

Note: Motor efficiency in this particular case does not change between 50 –100 % loading.

The plant operates for 7000 hours per year with the electricity cost of Rs. 6.00 per unit.

It is proposed to replace the existing motor by a 30 kW energy efficient motor with 92% efficiency.

- Determine the rated efficiency and the loading of the existing motor.
- Calculate the loading with energy efficient motor.
- If replacing the existing motor with energy efficient motor which costs Rs.75,000, determine the payback period for the investment required for the energy efficient motor over the existing motor. Consider the salvage value of the existing motor as Rs.10,000/.

Rated input power	1.732 × 0.415 × 66× 0.88
	41.746 kW
Rated efficiency of the motor	37/ 41.746 =88.63%
Actual input power drawn	1.732 × 0.410 × 49 × 0.76
	26.44 kW
Loading of the motor	26.44/41.746 = 0.633 or 63.3%
Shaft power or motor output	37x0.633= 23.44 kW
Energy efficient motor rating	30 kW
Actual output required	23.44 kW
% loading of the motor	23.44/30 =78 %
Annual energy savings	23.44(1/0.8863 – 1/0.92) x 7000 x Rs.6
	Rs.40,740/-
Payback period	(75,000-10,000)/40740
	1.59 years

QUESTIONS	
Objective Type Questions	
1.	With decrease in speed of the motor, the required capacitive kVAr: **a) increases** b) decreases c) does not change d) none of the above
2.	Reduction in supply voltage by 10% will change the torque of the motor by a) 38% **b) 19%** c) 9.5% d) no change
3.	One low investment measure to improve efficiency of a squirrel cage induction motor, which operates consistently below 40% of its rated capacity, is by **a) operating it in star mode** b) replacing it with a correctly sized motor c) operating in delta mode d) none of the above
4.	In an induction motor, Magnetic field is established in a) stator winding only b) rotor winding only c) **stator and Rotor Windings** d) none of the above
5.	A 7.5 kW, 415 V, 14.5 A, 1460 RPM, 3 phase rated induction motor with full load efficiency of 88%, draws 10.1 A and 5.1 kW of input power. The percentage loading of the motor is about a) 60 % b) 70 % c) 50% d) none of the above

Thank You

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