5. ENERGY PERFORMANCE ASSESSMENT OF MOTORS AND VARIABLE SPEED DRIVES

5.1 Introduction

The two parameters of importance in a motor are efficiency and power factor. The efficiencies of induction motors remain almost constant between 50% to 100% loading (Refer figure 5.1). With motors designed to perform this function efficiently; the opportunity for savings with motors rests primarily in their selection and use. When a motor has a higher rating than that required by the equipment, motor operates at part load. In this state, the efficiency of the motor is reduced. Replacement of under loaded motors with smaller motors will allow a fully loaded smaller motor to operate at a higher efficiency. This arrangement is generally most economical for larger motors, and only when they are operating at less than one-third to one-half capacity, depending on their size.

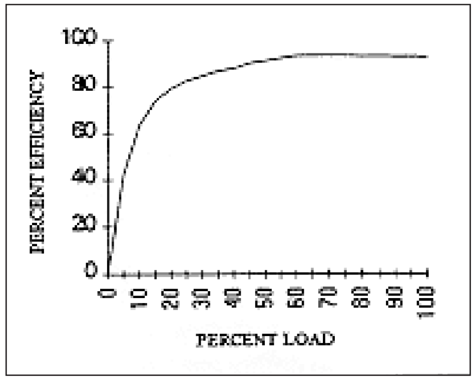

Figure 5.1 Efficiency vs. Loading

5.2 Performance Terms and Definitions

Efficiency :

The efficiency of the motor is given by

$$\eta = \frac{P_{out}}{P_{in}} = 1 - \frac{P_{loss}}{P_{in}}$$

Where P_{out} – Output power of the motor
P_{in} – Input power of the motor
P_{Loss} – Losses occurring in motor

Motor Loading :

$$\text{Motor Loading \%} = \frac{\text{Actual operating load of the motor}}{\text{Rated capacity of the motor}} \text{ x } 100$$

5.3 Efficiency Testing

While input power measurements are fairly simple, measurement of output or losses need a laborious exercise with extensive testing facilities. The following are the testing standards widely used.

Europe: IEC 60034-2, and the new IEC 61972
US: IEEE 112 - Method B
Japan: JEC 37

Even between these standards the difference in efficiency value is up to 3%.
For simplicity nameplate efficiency rating may be used for calculations if the motor load is in the range of 50 -100 %.

Field Tests for Determining Efficiency

(Note: The following section is a repeat of material provided in the chapter-2 on Electrical Motors in Book-3.)

No Load Test :

The motor is run at rated voltage and frequency without any shaft load. Input power, current, frequency and voltage are noted. The no load P.F. is quite low and hence low PF watt meters are required. From the input power, stator I^2R losses under no load are subtracted to give the sum of Friction and Windage (F&W) and core losses. To separate core and F & W losses, test is repeated at variable voltages. It is worthwhile plotting no-load input kW versus Voltage; the intercept is F & W kW loss component.

F&W and core losses = No load power (watts) – (No load current)^2 x Stator resistance

Stator and Rotor I^2R Losses :

The stator winding resistance is directly measured by a bridge or volt amp method. The resistance must be corrected to the operating temperature. For modern motors, the operating temperature is likely to be in the range of 100°C to 120°C and necessary correction should be made. Correction to 75°C may be inaccurate. The correction factor is given as follows :

$$\frac{R_2}{R_1} = \frac{235 + t_2}{235 + t_1}$$, where, t_1 = ambient temperature, °C & t_2 = operating temperature, °C.

The rotor resistance can be determined from locked rotor test at reduced frequency, but rotor I^2R losses are measured from measurement of rotor slip.

Rotor I^2R losses = Slip x (Stator Input - Stator I^2R Losses - Core Loss)

Accurate measurement of slip is possible by stroboscope or non-contact type tachometer. Slip also must be corrected to operating temperature.

Stray Load Losses :

These losses are difficult to measure with any accuracy. IEEE Standard 112 gives a complicated method, which is rarely used on shop floor. IS and IEC standards take a fixed value as 0.5 % of output. It must be remarked that actual value of stray losses is likely to be more. IEEE - 112 specifies values from 0.9 % to 1.8 %.

Motor Rating	Stray Losses
1 – 125 HP	1.8 %
125 – 500 HP	1.5 %
501 – 2499 HP	1.2 %
2500 and above	0.9 %

Points for Users :

It must be clear that accurate determination of efficiency is very difficult. The same motor tested by different methods and by same methods by different manufacturers can give a difference of 2 %.

Estimation of efficiency in the field can be summarized as follows:

a) Measure stator resistance and correct to operating temperature. From rated current value, I^2R losses are calculated.
b) From rated speed and output, rotor I^2R losses are calculated
c) From no load test, core and F & W losses are determined for stray loss

The method is illustrated by the following example :

Example :

Motor Specifications

Rated power	=	34 kW/45 HP
Voltage	=	415 Volt
Current	=	57 Amps
Speed	=	1475 rpm
Insulation class	=	F
Frame	=	LD 200 L
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, P_{nl}	=	1063.74 Watts

a) Calculate iron plus friction and windage losses

b) Calculate stator resistance at 120°C

$$R_2 = R_1 \times \frac{235 + t_2}{235 + t_1}$$

c) Calculate stator copper losses at operating temperature of resistance at 120°C

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, Pnl = 1063.74 Watts
Stator Copper loss, P st-30°C (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 120°C,

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

= 0.354 ohms per phase

c) Stator copper losses at full load, Pst.cu 120°C
$= 3 \times (57 / \sqrt{3})^2 \times 0.354$
= 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 120°C + (P_i + fw) + P_{stray}
= 34577.4 + 1150.1 + 995.3 + (0.005* x 34000)
= 36892.8 Watts

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

f) Motor efficiency at full load

$$\text{Efficiency} = \frac{P_{output}}{P_{input}} \times 100$$

$$= \frac{34000}{36892.8}$$

= 92.2%

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

$$= \frac{36892.8}{\sqrt{3} \times 415 \times 57}$$

$$= 0.90$$

Comments :

a) The measurement of stray load losses is very difficult and not practical even on test beds.
b) The actual value of stray loss of motors up to 200 HP is likely to be 1 % to 3 % compared to 0.5 % assumed by standards.
c) The value of full load slip taken from the nameplate data is not accurate. Actual measurement under full load conditions will give better results.
d) The friction and windage losses really are part of the shaft output; however, in the above calculation, it is not added to the rated shaft output, before calculating the rotor input power. The error however is minor.
e) When a motor is rewound, there is a fair chance that the resistance per phase would increase due to winding material quality and the losses would be higher. It would be interesting to assess the effect of a nominal 10 % increase in resistance per phase.

5.4 Determining Motor Loading

1. By Input Power Measurements

- First measure input power **Pi** with a hand held or in-line power meter
  Pi = Three-phase power in kW
- Note the rated kW and efficiency from the motor name plate
- The figures of kW mentioned in the name plate is for output conditions.
  So corresponding input power at full-rated load

$$P_{ir} = \frac{\text{Nameplate full rated kW}}{\eta_{fl}}$$

η_{fl} = Efficiency at full-rated load
P_{ir} = Input power at full-rated load in kW

- The percentage loading can now be calculated as follows

$$Load = \frac{P_i}{P_{ir}} \; x \; 100\%$$

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 %

2. By Line Current Measurements

The line current load estimation method is used when input power cannot be measured and only amperage measurements are possible. The amperage draw of a motor varies approximately linearly with respect to load, down to about 75% of full load. Below the 75% load point, power factor degrades and the amperage curve becomes increasingly non-linear. **In the low load region, current measurements are not a useful indicator of load.** However, this method may be used only as a preliminary method just for the purpose of identification of oversized motors.

$$\%\ Load = \frac{Input\ load\ current}{Input\ rated\ current} *100 \text{ (Valid up to 75\% loading)}$$

3. Slip Method

In the absence of a power meter, the slip method can be used which requires a tachometer. This method also does not give the exact loading on the motors.

$$Load = \frac{Slip}{S_s - S_r} *100\%$$

Where:
Load = Output power as a % of rated power
Slip = Synchronous speed - Measured speed in rpm
S_s = Synchronous speed in rpm at the operating frequency
S_r = Nameplate full-load speed

Example: Slip Load Calculation

Given: Synchronous speed in rpm = 1500 at 50 HZ operating frequency.
(Synchronous speed = 120f/P) f: frequency, P: Number of poles
Nameplate full load speed = 1450
Measured speed in rpm = 1480
Nameplate rated power = 7.5 kW

Determine actual output power.

$$Load = \frac{1500 - 1480}{1500 - 1450} *100\% = 40\%$$

From the above equation, actual output power would be 40% x 7.5 kW = 3 kW

The speed/slip method of determining motor part-load is often favored due to its simplicity and safety advantages. Most motors are constructed such that the shaft is accessible to a tachometer or a strobe light.

The accuracy of the slip method, however, is limited. The largest uncertainty relates to the accuracy with which manufacturers report the nameplate full-load speed. Manufacturers generally round their reported full-load speed values to some multiple of 5 rpm. While 5 rpm is but a small percent of the full-load speed and may be considered as insignificant, the slip method relies on the difference between full-load nameplate and synchronous speeds. Given a 40 rpm "correct" slip, a seemingly minor 5 rpm disparity causes a 12% change in calculated load.

Slip also varies inversely with respect to the motor terminal voltage squared. A voltage correction factor can, also, be inserted into the slip load equation. The voltage compensated load can be calculated as shown

$$Load = \frac{Slip}{(S_s - S_r)\ \text{x}\ (V_r/V)^2}\ x\ 100\%$$

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

V = RMS voltage, mean line to line of 3 phases

V_r = Nameplate rated voltage

5.5 Performance Evaluation of Rewound Motors

Ideally, a comparison should be made of the efficiency before and after a rewinding. A relatively simple procedure for evaluating rewind quality is to keep a log of no-load input current for each motor in the population. This figure increases with poor quality rewinds. A review of the rewind shop's procedure should also provide some indication of the quality of work. When rewinding a motor, if smaller diameter wire is used, the resistance and the I^2R losses will increase.

5.6 Format for Data Collection

The motor loading survey can be performed using the format given below:

Motor Field Measurement Format

Company________________________

Date ________

Location______________________

Process_______________________

Department____________________

General Data

Driven Equipment_________________

Motor Name Plate Data

Manufacturer ____________________

Model __________________________

Serial Number ___________________

Type :Squirrel cage/Slp ring__________

Size (hp/kW)______________________

Synchronous Speed (RPM) __________

Full-Load Speed (RPM) ____________

Voltage Rating ___________________

Full-Load Amperage _______________

Full-Load Power Factor (%) _________

Full-Load Efficiency (%) ___________

Temperature Rise _________________

Insulation Class __________________

From Test Certificate

Load	100%	75%	25%	No Load
Current				
PF				
Efficiency				

Stator resistance per phase =

Rewound ▫ Yes ,if yes How many times rewound ?---
▫ No

Motor Loading %________________

Motor Operating Profile:

No of hours of operation

I Shift _____________

II Shift _____________

III Shift _____________

Annual Operating Time ______ hours/year

Type of load

1.Load is quite steady, motor "On" during shift

2.Load starts, stops, but is constant when "On"

3.Load starts, stops, and fluctuates when "On"

Measured Data

Supply Voltage

By Voltmeter

V_{RY} ________

V_{YB} ________ V avg ______

V_{BR} ________

Input Amps

By Ammeter

A a __________

A b __________ A avg ______

A c __________

Power Factor (PF) _____________________

Input Power (kW) _____________________

Motor Operating Speed ____________RPM

At frequency of __________

Driven Equipment Operating Speed

__________RPM

Type of Transmission (Direct/Gear/Fluid coupling)

The monitoring format for rewound motor is given below:

Section	Equipment Code	Motor Code	Motor Type		No Load Current				Starter Resistance/phase		No load loss	
			Sq.Cage	Slip Ring	New Motor		After Rewinding		New	Rewound	New	Rewound
					A	V	A	V			Watts	Watts

5.7 Application of Variable Speed Drives (VSD)

Although there are many methods of varying the speeds of the driven equipment such as hydraulic coupling, gear box, variable pulley etc., the most possible method is one of varying the motor speed itself by varying the frequency and voltage by a variable frequency drive.

5.7.1 Concept of Variable Frequency Drive

The speed of an induction motor is proportional to the frequency of the AC voltage applied to it, as well as the number of poles in the motor stator. This is expressed by the equation:

$$RPM = (f \times 120) / p$$

Where f is the frequency in Hz, and p is the number of poles in any multiple of 2.

Therefore, if the frequency applied to the motor is changed, the motor speed changes in direct proportion to the frequency change. The control of frequency applied to the motor is the job given to the VSD.

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. The two most basic functions of a VSD are to provide power conversion from one frequency to another, and to enable control of the output frequency.

VSD Power Conversion

As illustrated by Figure 5.1, there are two basic components, a rectifier and an inverter, to accomplish power conversion.

The rectifier receives the 50-Hz AC voltage and converts it to direct current (DC) voltage. A DC bus inside the VSD functions as a "parking lot" for the DC voltage. The

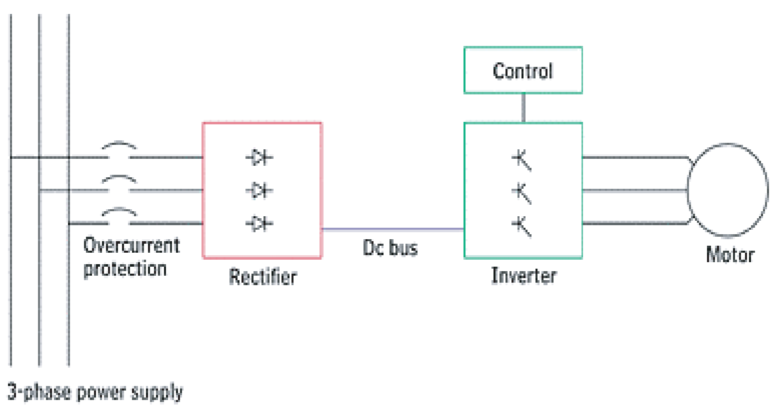

Figure 5.1 Components of a Variable Speed Drive

DC bus energizes the inverter, which converts it back to AC voltage again. The inverter can be controlled to produce an output frequency of the proper value for the desired motor shaft speed.

5.7.2 Factors for Successful Implementation of Variable Speed Drives

a) Load Type for Variable Frequency Drives

The main consideration is whether the variable frequency drive application require a variable **torque or constant torque** drive. If the equipment being driven is centrifugal, such as a fan or pump, then a variable torque drive will be more appropriate. Energy savings are usually the primary motivation for installing variable torque drives for centrifugal applications. For example, a fan needs less torque when running at 50% speed than it does when running at full speed. Variable torque operation allows the motor to apply only the torque needed, which results in reduced energy consumption.

Conveyors, positive displacement pumps, punch presses, extruders, and other similar type applications require constant level of torque at all speeds. In which case, constant torque variable frequency drives would be more appropriate for the job. A constant torque drive should have an **overload current capacity** of 150% or more for one minute. Variable torque variable frequency drives need only an overload current capacity of 120% for one minute since centrifugal applications rarely exceed the rated current.

If tight process control is needed, then you may need to utilize a sensor less vector, or flux vector variable frequency drive, which allow a high level of accuracy in controlling speed, torque, and positioning.

b) Motor Information

The following motor information will be needed to select the proper variable frequency drive:

Full Load Amperage Rating. Using a motor's horsepower is an inaccurate way to size variable frequency drives.

Speed Range. Generally, a motor should not be run at any speed less than 20% of its specified maximum speed allowed. If it is run at a speed less than this without auxiliary motor cooling, the motor will overheat. Auxiliary motor cooling should be used if the motor must be operated at very slow speeds.

Multiple Motors. To size a variable frequency drive that will control more than one motor, add together the full-load amp ratings of each of the motors. All motors controlled by a single drive must have an equal voltage rating.

c) Efficiency and Power Factor

The variable frequency drive should have an efficiency rating of **95% or better at full load.**

Variable frequency drives should also offer a **true system power factor of 0.95 or better** across the operational speed range, to save on demand charges, and to protect the equipment (especially motors).

d) Protection and Power Quality

Motor overload Protection for instantaneous trip and motor over current.

Additional Protection: Over and under voltage, over temperature, ground fault, control or microprocessor fault. These protective circuits should provide an orderly shutdown of the VFD, provide indication of the fault condition, and require a manual reset (except under voltage) before restart. Under voltage from a power loss shall be set to automatically restart after return to normal. The history of the previous three faults shall remain in memory for future review.

If a built-up system is required, there should also be externally-operated short circuit protection, door-interlocked fused disconnect and circuit breaker or motor circuit protector (MCP)

To determine if the equipment under consideration is the right choice for a variable speed drive:

The load patterns should be thoroughly studied before exercising the option of VSD. In effect the load should be of a varying nature to demand a VSD (refer figure 5.3 & 5.4).

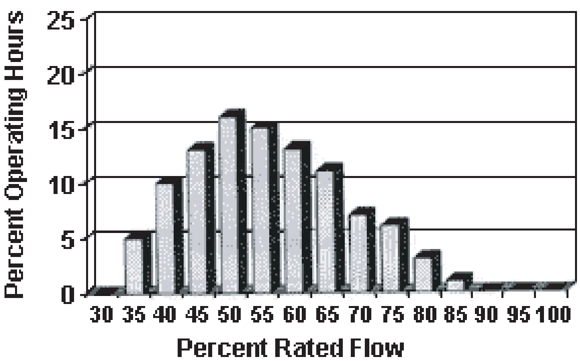

Figure 5.3 Example of an excellent variable speed drive candidate

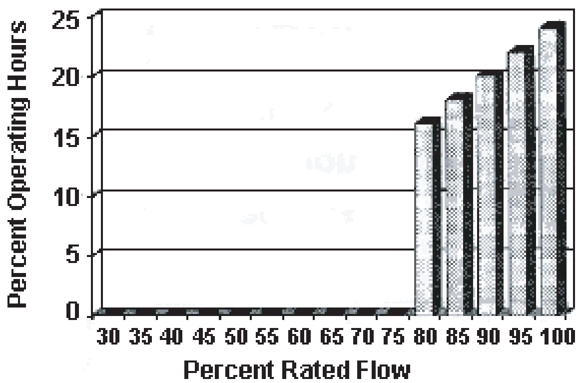

Figure 5.4 Example of a poor variable speed drive candidate

The first step is to identify the number of operating hours of the equipment at various load conditions. This can be done by using a Power analyzer with continuous data storage or by a simple energy meter with periodic reading being taken.

5.7.3 Information needed to Evaluate Energy Savings for Variable Speed Application

1. Method of flow control to which adjustable speed is compared:
   - o output throttling (pump) or dampers (fan)
   - o recirculation (pump) or unrestrained flow (fan)
   - o adjustable-speed coupling (eddy current coupling)
   - o inlet guide vanes or inlet dampers (fan only)
   - o two-speed motor.
2. Pump or fan data:
   - o head v's flow curve for every different type of liquid (pump) or gas (fan) that is handled
   - o Pump efficiency curves.

3. Process information:
    - o specific gravity (for pumps) or specific density of products (for fans)
    - o system resistance head/flow curve
    - o equipment duty cycle, i.e. flow levels and time duration.

4. Efficiency information on all relevant electrical system apparatus:
    - o motors, constant and variable speed
    - o variable speed drives
    - o gears
    - o transformers.

If we do not have precise information for all of the above, we can make reasonable assumptions for points 2 and 4.

QUESTIONS	
1)	Define motor efficiency.
2)	Why it is difficult to measure motor efficiency at site?
3)	Describe the various methods by which you calculate motor loading.
4)	If no instrument other than tachometer is available, what method you would suggest for measuring the motor load?
5)	A 20 kW rated motor is drawing actual measured power of 14 kW. If the rated efficiency is 92%, determine the motor loading?
6)	What are the limitations of slip method in determining motor loading?
7)	A 4 pole motor is operating at a frequency of 50 Hz. Find the RPM of the motor?
8)	What are the two factors influencing the speed of induction motor?
9)	A fan's operating hours and loading are given below: 15 hours at 100% load 8 hours at 95% load 1 hour at 40% load Is the application suitable candidate for application of VSD?
11)	The losses in a variable speed drive is a) 12% b) 8% c) <5% d) no losses at all

REFERENCES

1. Motor challenge: Office of Industrial Technologies, Department of Energy, USA
2. Energy audit Reports of National Productivity Council