1. ELECTRICAL SYSTEM

Electricity billing, Electrical load management and maximum demand control, Power factor improvement and its benefit, Automatic power factor controllers, Selection and location of capacitors, Performance assessment of PF capacitors, Distribution and transformer losses, Energy efficient transformers, Standards & labeling programme of distribution transformers, Assessment of transmission and distribution efficiency, Demand side management, Losses due to harmonics and voltage unbalance.

1.1 Introduction to Electric Power Supply Systems

Electric power supply system comprises of generating units that produce electricity; high voltage transmission lines that transport electricity over long distances; distribution lines that deliver the electricity to consumers; substations that connect the pieces to each other; and energy control centers to coordinate the operation of the components.

The Figure 1.1 shows a simple electric supply system with Generating Station, Power transmission and distribution network and linkages from electricity sources to end-user.

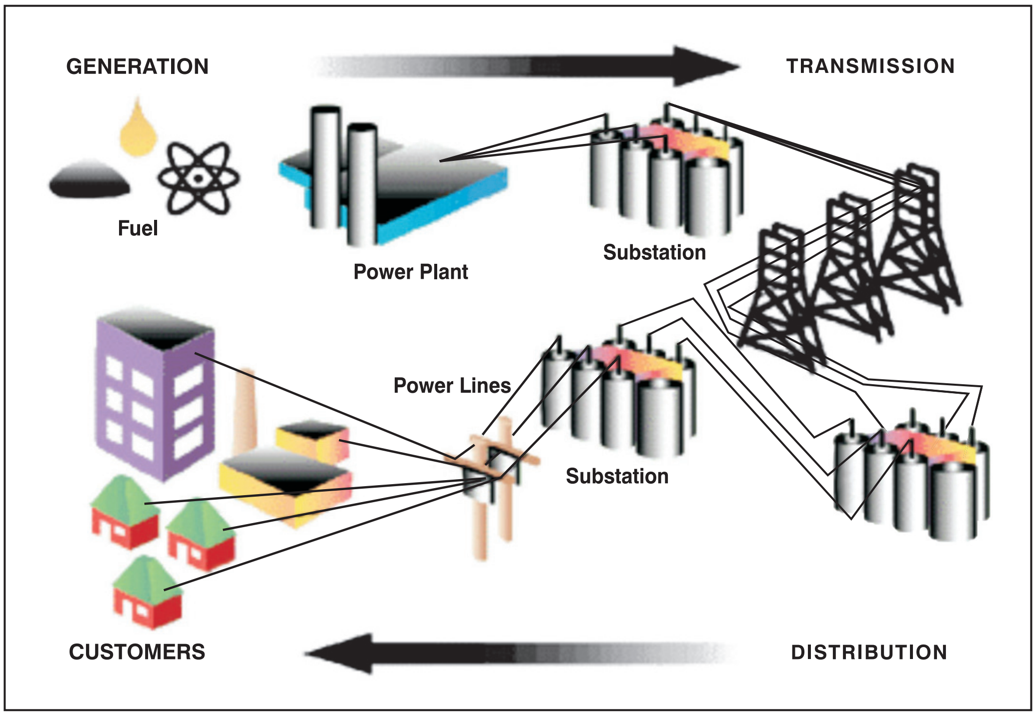

Figure 1.1 Typical Electric Power Supply Systems

Power Generation Plant

The fossil fuels such as coal, oil and natural gas, nuclear energy, and falling water (hydel) are commonly used energy sources in the power generating plant. A wide and growing variety of unconventional generation technologies and fuels have also been developed, including cogeneration, solar energy, wind generators, and waste materials.

About 70 % of power generating capacity in India is from coal based thermal power plants. The principle of coal-fired power generation plant is shown in Figure 1.2. Energy stored in the coal is converted in to electricity in a thermal power plant. Coal is pulverized to the consistency of talcum powder. Then powdered coal is blown into the water wall boiler where it is burned at temperature higher than 1300^{o}C. The heat in the combustion gas is transferred into steam. This high-pressure steam is used to spin the steam turbine. Finally turbine rotates the generator to produce electricity.

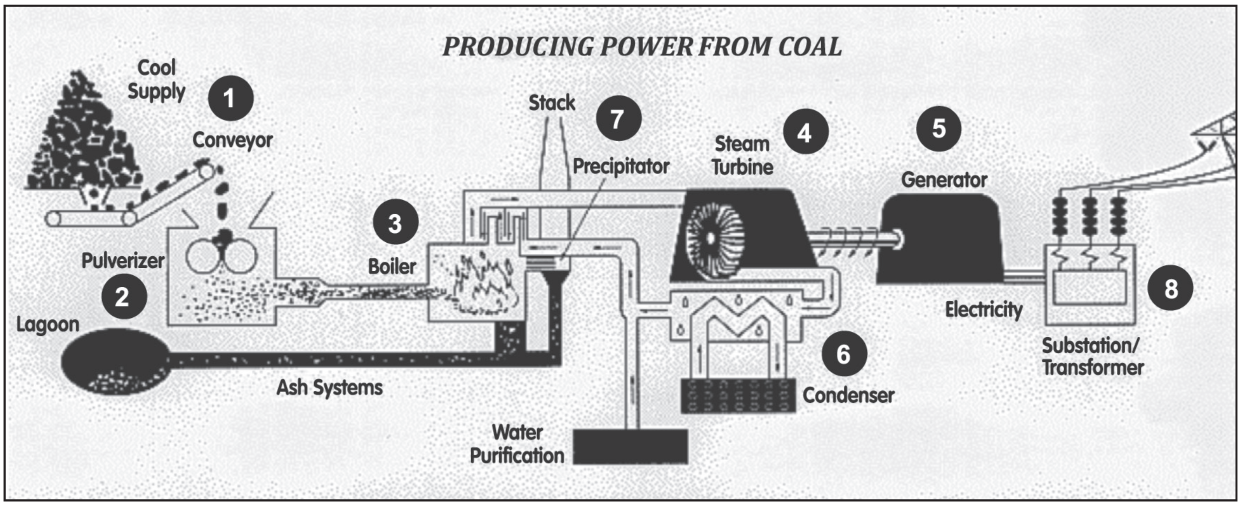

Figure 1.2 Principle of Thermal Power Generation

In India, for the coal based power plants, the overall efficiency ranges from 28% to 35% depending upon the size, operational practices, fuel quality and capacity utilization. Where fuels are the source of generation, a common term used is the "HEAT RATE" which reflects the efficiency of generation. "HEAT RATE" is the heat input in kilo Calories or kilo Joules, for generating 'one' kilo Watt-hour of electrical output. One kilo Watt hour of electrical energy being equivalent to 860 kilo Calories of thermal energy or 3600 kilo Joules of thermal energy. The "HEAT RATE" is inversely proportional to efficiency of power generation i.e., lower the heat rate, higher is the generation efficiency.

Transmission and Distribution Lines:

The power plants typically produce 50 cycle/second (Hertz), alternating-current (AC) electricity with voltages between 11kV and 33kV. At the power plant site, the 3-phase voltage is stepped up to a higher voltage for transmission on cables strung on cross-country towers.

High voltage (HV) and extra high voltage (EHV) transmission is the next stage from power plant to transport A.C. power over long distances at voltages like; 220 kV & 400 kV (Figure 1.3). Where transmission is over 1000 kM, high voltage direct current transmission is also favored to minimize the losses.

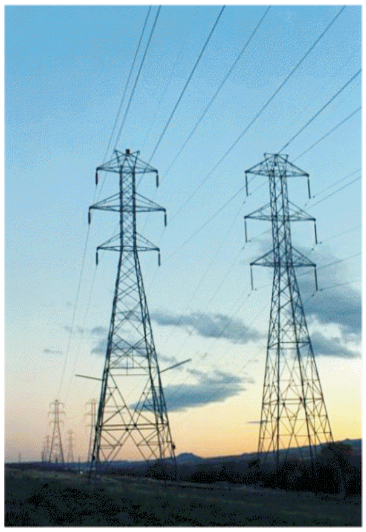

Figure 1.3
High Voltage Transmission Lines

Sub-transmission network at 132 kV, 110 kV, 66 kV or 33 kV constitutes the next link towards the end user. Distribution at 11 kV / 6.6 kV / 3.3 kV constitutes the last link to the consumer, who is connected directly or through transformers depending upon the drawn level of service. The transmission and distribution network include sub-stations, lines and distribution transformers. High voltage transmission is used so that smaller, more economical wire sizes can be employed to carry the lower current and to reduce losses. Sub-stations, containing step-down transformers, reduce the voltage for distribution to industrial users. The voltage is further reduced for commercial facilities. Electricity must be generated, as and when it is needed since electricity cannot be stored virtually in the system. Typical voltage levels in a power system are given in Figure 1.4.

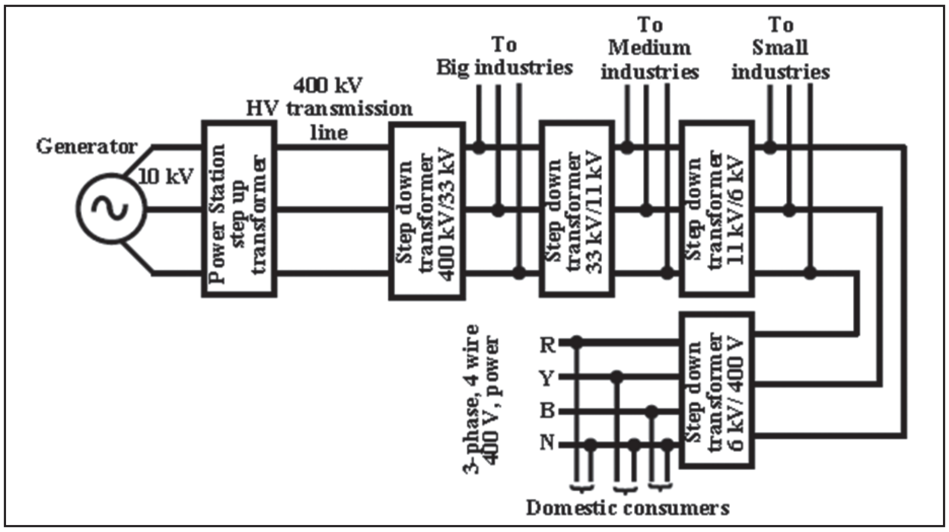

Figure 1.4 Typical Voltage Levels in a Power System

There is no difference between a transmission line and a distribution line except for the voltage level and power handling capability. Transmission lines are usually capable of transmitting large quantities of electric energy over great distances. They operate at high voltages. Distribution lines carry limited quantities of power over shorter distances.

Voltage drops in line are in relation to the resistance and reactance of line, length and the current drawn. For the same quantity of power handled, lower the voltage, higher the current drawn and higher the voltage drop. The current drawn is inversely proportional to the voltage level for the same quantity of power handled.

The power loss in line is proportional to resistance and square of current. (i.e. $P_{Loss}=I^2R$). Higher voltage transmission and distribution thus would help to minimize line voltage drop in the ratio of voltages, and the line power loss in the ratio of square of voltages. For instance, if distribution of power is raised from 11 kV to 33 kV, the voltage drop would be lower by a factor 1/3 and the line loss would be lower by a factor $(1/3)^2$ i.e., 1/9. Lower voltage transmission and distribution also calls for bigger size conductor on account of current handling capacity needed.

Cascade Efficiency

The primary function of transmission and distribution equipment is to transfer power economically and reliably from one location to another.

Conductors in the form of wires and cables strung on towers and poles carry the high-voltage, AC electric current. A large number of copper or aluminum conductors are used to form the transmission path. The resistance of the long-distance transmission conductors is to be minimized. Energy loss in transmission lines is wasted in the form of I^2R losses.

Capacitors are used to correct power factor by causing the current to lead the voltage. When the AC currents are kept in phase with the voltage, operating efficiency of the system is maintained at a high level.

Circuit-interrupting devices are switches, relays, circuit breakers, and fuses. Each of these devices is designed to carry and interrupt certain levels of current. Making and breaking the current carrying conductors in the transmission path with a minimum of arcing is one of the most important characteristics of this device. Relays sense abnormal voltages, currents, and frequency and operate to protect the system.

Transformers are placed at strategic locations throughout the system to minimize power losses in the T&D system. They are used to change the voltage level from low-to-high in step-up transformers and from high-to-low in step-down units.

The power source to end user energy efficiency link is a key factor, which influences the energy input at the source of supply. If we consider the electricity flow from generation to the user in terms of cascade energy efficiency, typical cascade efficiency profile from generation to 11 – 33 kV user industry will be as follows:

Generation Efficiency η_1	Efficiency ranges 28-35 % with respect to size of thermal plant, age of plant and capacity utilization
↓	
Step-up Station η_2	Step-up to 400 / 800 kV to enable EHV transmission. Envisaged max. losses 0.5 % or efficiency of 99.5 %
↓	
EHV Transmission & Station η_3	EHV transmission and substations at 400 kV / 800 kV. Envisaged maximum losses 1.0 % or efficiency of 99 %
↓	
HV Transmission & Station η_4	HV transmission & Substations for 220 / 400 kV. Envisaged maximum losses 2.5 % or efficiency of 97.5 %
↓	
Sub-transmission η_5	Sub-transmission at 66 / 132 kV Envisaged maximum losses 4 % or efficiency of 96 %
↓	
Distribution Station η_6	Step-down to a level of 11 / 33 kV. Envisaged losses 0.5 % or efficiency of 99.5 %
↓	
Primary Distribution η_7	Distribution is final link to end user at 11 / 33 kV. Envisaged losses maximum 5 % of efficiency of 95 %
↓	
End user Premises	**Cascade efficiency from Generation to end user** $= \eta_1 \times \eta_2 \times \eta_3 \times \eta_4 \times \eta_5 \times \eta_6 \times \eta_7$

The cascade efficiency in the T&D system from output of the power plant to the end use is 87% (i.e. 0.995 x 0.99 x 0.975 x 0.96 x 0.995 x 0.95 = 87%)

After power generation at the plant it is transmitted and distributed over a wide network. The standard technical losses are around 17 % in India (Efficiency=83%). But the figures for many of the states show T & D losses ranging from 17 – 50 %. All these may not constitute technical losses, since un-metered and pilferage are also accounted in this loss.

Industrial End User

At the industrial end user premises, again the plant network elements like transformers at receiving sub-station, switchgear, lines and cables, load-break switches, capacitors cause losses, which affect the input-received energy. However the losses in such systems are meager and unavoidable.

A typical plant single line diagram of electrical distribution system is shown in Figure 1.5

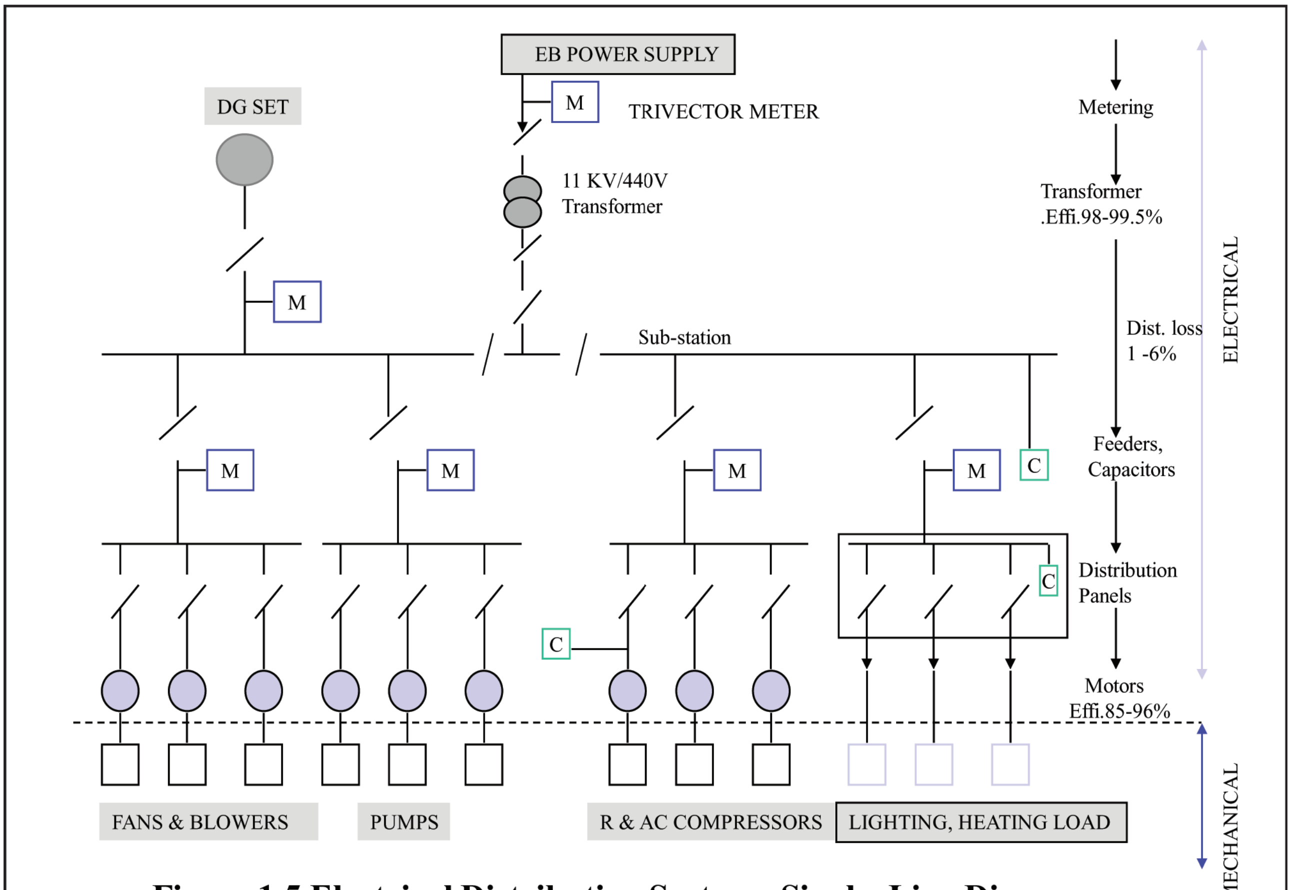

Figure 1.5 Electrical Distribution System –Single Line Diagram

ONE Unit saved = TWO Units Generated

When the power reaches the industry, it meets the transformer. The energy efficiency of the transformer is generally very high. Next, it goes to the motor through internal plant distribution network. A typical distribution network efficiency including transformer is 95% and motor efficiency is about 90%.

Another 30 % (Efficiency=70%) is lost in the mechanical system which includes coupling/ drive train, a driven equipment such as pump and flow control valves/throttling etc. Thus the overall energy efficiency becomes 50%. (0.83 x 0.95x 0.9 x 0.70 = 0.50, i.e. 50% efficiency)

Hence one unit saved in the end user is equivalent to two units generated in the power plant. (1Unit / 0.5Eff = 2 Units)

1.2 Electricity Billing

The electricity billing by utilities for medium & large enterprises, in High Tension (HT) category, is often done on two-part tariff structure, i.e. one part for capacity (or demand) drawn and the second part for actual energy drawn during the billing cycle. Capacity or demand is in kVA (apparent power) or kW terms. The reactive energy (i.e.) kVArh drawn by the service is also recorded and billed for in some utilities, because this would affect the load on the utility. Accordingly, utility charges for maximum demand, active energy and reactive power drawn (as reflected by the power factor) in its billing structure. In addition, other fixed and variable expenses are also levied.

The tariff structure generally includes the following components:

a) *Maximum demand Charges*

These charges relate to maximum demand registered during month/billing period and corresponding rate of utility.

b) *Energy Charges*

These charges relate to energy (kilowatt hours) consumed during month / billing period and corresponding rates, often levied in slabs of use rates. Some utilities now charge on the basis of apparent energy (kVAh), which is a vector sum of kWh and kVArh.

c) *Power factor* penalty or bonus rates, as levied by most utilities, are to contain reactive power drawn from grid.

d) *Fuel cost* adjustment charges as levied by some utilities are to adjust the increasing fuel expenses over a base reference value.

e) *Electricity duty charges* levied with respect to units consumed.

f) *Meter rentals*

g) *Lighting and fan power consumption* is often at higher rates, levied sometimes on slab basis or on actual metering basis.

h) *Time of Day (TOD) rates* like peak and non-peak hours are also prevalent in tariff structure provisions of some utilities.

i) *Penalty for exceeding contract demand*

j) *Surcharge if metering is at LT side in some of the utilities*

Analysis of utility bill data and monitoring its trends helps energy manager to identify ways for electricity bill reduction through available provisions in tariff framework, apart from energy budgeting.

The utility employs an electromagnetic or electronic trivector meter, for billing purposes. The minimum outputs from the electromagnetic meters are:

- Maximum demand registered during the month, which is measured in preset time intervals (say of 30 minute duration) and this is reset at the end of every billing cycle.
- Active energy in kWh during billing cycle
- Reactive energy in kVArh during billing cycle and
- Apparent energy in kVAh during billing cycle

It is important to note that while maximum demand is recorded, it is not the instantaneous demand drawn, as is often misunderstood, but the time integrated demand over the predefined recording cycle.

As an example, in an industry, if the drawl over a recording cycle of 30 minutes is:

2500 kVA for 4 minutes
3600 kVA for 12 minutes
4100 kVA for 6 minutes
3800 kVA for 8 minutes

The MD recorder will be computing MD as:

$$\frac{(2500 \times 4) + (3600 \times 12) + (4100 \times 6) + (3800 \times 8)}{30} = 3606.7 \text{ kVA}$$

The month's maximum demand will be the highest among such demand values recorded over the month. The meter registers <u>only if the value exceeds</u> the previous maximum demand value and thus, even if, average maximum demand is low, the industry / facility has to pay for the maximum demand charges for the <u>highest value registered</u> during the month, <u>even if it occurs for just one recording cycle duration i.e., 30 minutes during whole of the month</u>. A typical demand curve is shown in Figure 1.6.

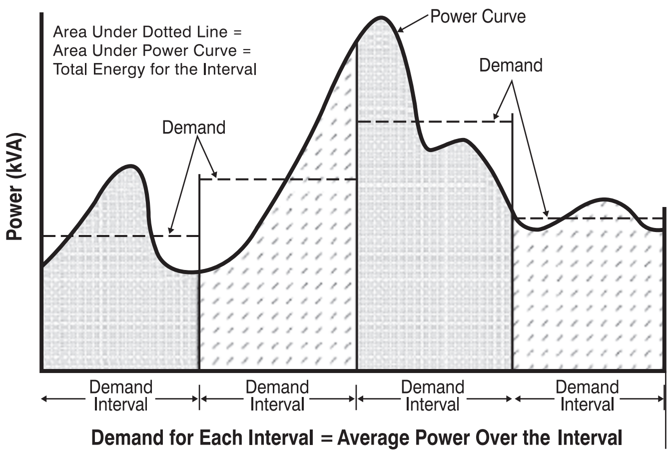

Figure 1.6 Demand Curve

As can be seen from the Figure 1.6 above the demand varies from time to time. The demand is measured over predetermined time interval and averaged out for that interval as shown by the horizontal dotted line.

Of late most electricity boards have changed over from conventional electromechanical trivector meters to electronic meters, which have some excellent provisions that can help the utility as well as the industry. These provisions include:

- Substantial memory for logging and recording all relevant events
- High accuracy up to 0.2 class

- Amenability to time of day tariffs
- Tamper detection /recording
- Measurement of harmonics and Total Harmonic Distortion (THD)
- Long service life due to absence of moving parts
- Amenability for remote data access/downloads

Trend analysis of purchased electricity and cost components can help the industry to identify key result areas for bill reduction within the utility tariff available framework in Table 1.1.

Table 1.1 Purchased Electrical Energy Trend

Month & Year	MD Recorded kVA	Billing Demand* kVA	Total Energy Consumption kWh	Energy Consumption During Peak Hours (kWh)	MD Charge Rs./kVA	Energy Charge Rs./kWh	PF	PF Penalty /Rebate Rs.	Total Bills Rs.	Average Cost Rs./kWh
Jan.										
Feb.										
…….										
…….										
Dec.										

*Some utilities charge Maximum Demand on the basis of minimum billing demand, which may be between 75 to 100% of the contract demand or actual recorded demand whichever is higher

1.3 Electrical Load Management and Maximum Demand Control

Need for Electrical Load Management

In a macro perspective, the growth in the electricity use and diversity of end use segments in time of use has led to shortfalls in capacity to meet demand. As capacity addition is costly and only a long time prospect, better load management at user end helps to minimize peak demands on the utility infrastructure as well as better utilization of power plant capacities.

The utilities (Distribution companies) use power tariff structure to influence end user in better load management through measures like time of use tariffs, penalties on exceeding allowed maximum demand, night tariff concessions etc. Load management is a powerful means of efficiency improvement both for end user as well as utility.

As the demand charges constitute a considerable portion of the electricity bill, from user angle too there is a need for integrated load management to effectively control the maximum demand.

Step By Step Approach for Maximum Demand Control

1. Load Curve Generation

Presenting the load demand of a consumer against time of the day is known as a 'load curve'. If it is plotted for the 24 hours of a single day, it is known as an 'hourly load curve' and if daily demands plotted over a month, it is called 'daily load curve'. A

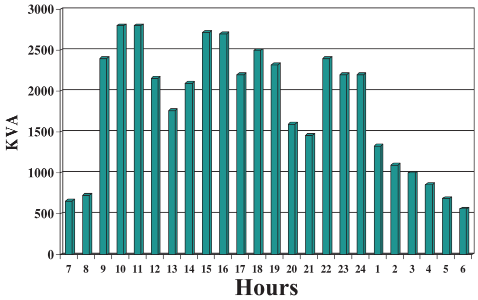

Figure 1.7 Maximum Demand (Daily Load Curve, Hourly kVA)

typical hourly load curve for an engineering industry is shown in Figure 1.7. These types of curves are useful in predicting patterns of drawl, peaks and valleys and energy use trend in a section or in an industry or in a distribution network as the case may be.

2. Rescheduling of Loads

Rescheduling of large electric loads and equipment operations, in different shifts can be planned and implemented to minimize the simultaneous maximum demand. For this purpose, it is advisable to prepare an operation flow chart and a process chart. Analyzing these charts and with an integrated approach, it would be possible to reschedule the operations and running equipment in such a way as to improve the load factor which in turn reduces the maximum demand.

3. Storage of Products/in process material/ process utilities like refrigeration

It is possible to reduce the maximum demand by building up storage capacity of products/ materials, water, chilled water / hot water, using electricity during off peak periods. Off peak hour operations also help to save energy due to favorable conditions such as lower ambient temperature etc.

Example: Ice bank system is used in milk & dairy industry. Ice is made in lean period and used in peak load period and thus maximum demand is reduced.

4. Shedding of Non-Essential Loads

When the maximum demand tends to reach preset limit, shedding some of non-essential loads temporarily can help to reduce it. It is possible to install direct demand monitoring and control systems (Figure 1.8), which will switch off non-essential loads when a preset demand is reached. Simple systems give an alarm, and the loads are shed manually. Sophisticated microprocessor controlled systems are also available, which provide a wide variety of control options like:

- Accurate prediction of demand
- Graphical display of present load, available load, demand limit
- Visual and audible alarm
- Automatic load shedding in a predetermined sequence
- Automatic restoration of load
- Recording and metering

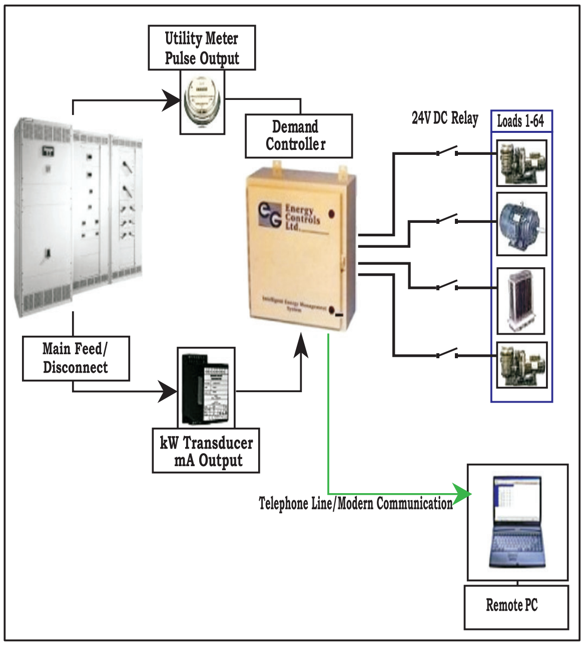

Figure 1.8 Maximum Demand Controller

5. Operation of Captive Generation and Diesel Generation Sets

When diesel generation sets are used to supplement the power supplied by the electric utilities, it is advisable to connect the D.G. sets for durations when demand reaches the peak value. This would reduce the load demand to a considerable extent and minimize the demand charges.

6. Reactive Power Compensation

The maximum demand can also be reduced at the plant level by using capacitor banks and maintaining the optimum power factor. Capacitor banks are available with microprocessor based control systems. These systems switch on and off the capacitor banks to maintain the desired Power factor of system and optimize maximum demand thereby.

1.4 Power Factor Improvement and Benefits

Power factor Basics

In all industrial electrical distribution systems, the major loads are resistive and inductive. Resistive loads are incandescent lighting and resistance heating. In case of pure resistive loads, the voltage (V),current (I), resistance (R) relations are linearly related, i.e.

$$V = I \times R \text{ and Power (kW)} = V \times I$$

Typical inductive loads are A.C. Motors, induction furnaces, transformers and ballast-type lighting. Inductive loads require two kinds of power: a) active (or working) power to perform the work and b) reactive power to create and maintain electro-magnetic fields.

Active power is measured in kW (Kilo Watts). Reactive power is measured in kVAr (kilo Volt-Amperes Reactive).

The vector sum of the active power and reactive power make up the total (or apparent) power used. This is the power generated by the SEBs for the user to perform a given amount of work. Total Power is measured in kVA (kilo Volts-Amperes) (See Figure 1.9).

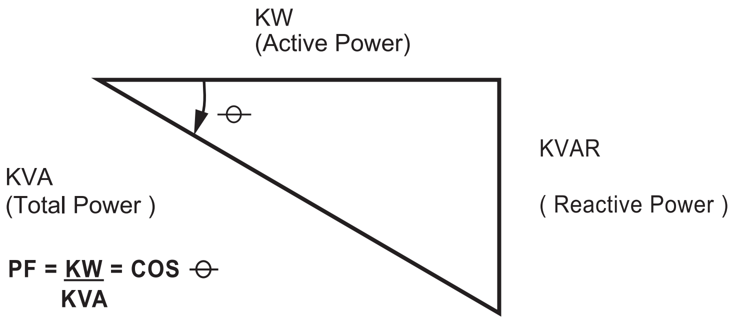

Figure 1.9 kW, kVAr and kVA Vector

The active power (shaft power required or true power required) in kW and the reactive power required (kVAr) are 90^0 apart vectorically in a pure inductive circuit i.e., reactive power kVAr lagging the active kW. The vector sum of the two is called the apparent power or kVA, as illustrated above and the kVA reflects the actual electrical load on distribution system.

The ratio of kW to kVA is called the power factor, which is always less than or equal to unity. Theoretically, when electric utilities supply power, if all loads have unity power factor, maximum power can be transferred for the same distribution system capacity. However, as the loads are inductive in nature, with the power factor ranging from 0.2 to 0.9, the electrical distribution network is stressed for capacity at low power factors.

Improving Power Factor

The solution to improve the power factor is to add power factor correction capacitors (see Figure 1.10) to the plant power distribution system. They act as reactive power generators, and provide the needed reactive power to accomplish kW of work. This reduces the amount of reactive power, and thus total power, generated by the utilities.

Figure 1.10 Capacitors

Example:

A chemical industry had installed a 1500 kVA transformer. The initial demand of the plant was 1160 kVA with power factor of 0.70. The % loading of transformer was about 78% (1160/1500 = 77.3%). To improve the power factor and to avoid the penalty, the unit had added about 410 kVAr in motor load end. This improved the power factor to 0.89, and reduced the required kVA to 913, which is the vector sum of kW and kVAr (see Figure 1.11).

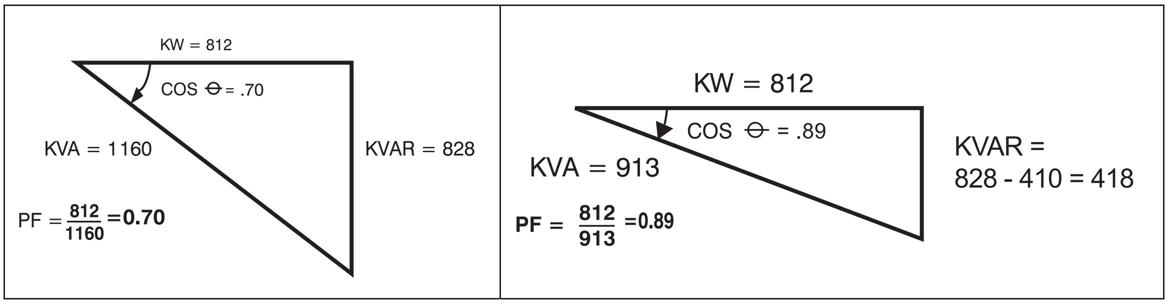

Figure 1.11 Power factor before and after Improvement

After improvement the plant has avoided penalty and the 1500 kVA transformer is now loaded only to 60% of capacity. This will allow the addition of more loads in the future to be supplied by the transformer.

The advantages of PF improvement by capacitor addition

a) Reactive component of the network is reduced and so also the total current in the system from the source end.

b) I^2R power losses are reduced in the system because of reduction in current.

c) Voltage level at the load end is increased.

d) kVA loading on the source generators as also on the transformers and lines up to the capacitors reduces giving capacity relief. A high power factor can help in utilizing the full capacity of the electrical system.

Cost benefits of PF improvement

While costs of PF improvement are in terms of investment needs for capacitor addition the benefits to be quantified for feasibility analysis are:

a) Reduced kVA (Maximum demand) charges in utility bill

b) Reduced distribution losses (KWH) within the plant network

c) Better voltage at motor terminals and improved performance of motors

d) A high power factor eliminates penalty charges imposed when operating with a low power factor

e) Investment on system facilities such as transformers, cables, switchgears etc for delivering load is reduced.

Automatic Power Factor Controllers

Many of the industries desire to maintain the power factor near unity with the objective of minimizing the maximum demand as well as availing the PF incentives offered by DISCOM's. When the loads in the industries are fluctuating it becomes difficult to maintain near unity PF with fixed capacitor banks. At low loads there is a possibility of PF going into leading side which can create high voltages at the motor terminals. In such cases the maximum demand will also rise. To overcome this situation automatic power factor controllers are deployed.

Power factor controllers are typically panel mount and used like a panel mount meter, indicating the power factor at the point of supply (Figure 1.12). Power factor controllers are programmable and range from quite simple to very complex.

Figure 1.12 Automatice Power Factor Control Relay

A simple power factor controller monitors the displacement power factor. The controller displays the power factor on a digital display and compares the measured power factor with the desired power factor. If the power factor is less than the desired power factor, another bank of capacitors is switched on via a relay output on the controller. If the power factor is leading, or is above a threshold point, a bank of capacitors is switched OFF.

The controller has a number of relay outputs for controlling contactors switching capacitors. Typically, the number of outputs will range from 6 to 14 relays. The number and size of the banks being switched is dependent on the type of load, the range of control required and the designated power factor range. Some controllers expect that equal stages will be used, and others are quite flexible. The top end controllers measure the size of each step and calculate which step combinations will give the best results. In this case, it is possible to use a combination of step sizes. A good configuration is to use at least two small steps and at least four large steps. For large installations, up to 14 stages can be used. The number of times that a bank can be switched is limited with delay ON and delay OFF times that are programmable. Some controllers keep the numbers of operations equal across all banks. There are a number of other options that can be included such as harmonic current alarms and low current thresholds to prevent capacitors being connected under very light load.

Selection and location of capacitors

The capacitors can be selected based on the following relation

$$\text{kVAr Rating} = \text{kW} [\tan \phi 1 - \tan \phi 2]$$

Where, kVAr rating is the size of the capacitor needed, kW is the average power drawn, tan $\phi 1$ is the trigonometric ratio for the present power factor, and tan ϕ_2 is the trigonometric ratio for the desired PF.

$$\phi_1 = \text{Existing } (\text{Cos}^{-1} \text{ PF}_1) \text{ and } \quad \phi_2 = \text{Improved } (\text{Cos}^{-1} \text{ PF}_2)$$

Alternatively the Table 1.2 can be used for capacitor sizing.

The figures given in table are the multiplication factors which are to be multiplied with the input power (kW) to give the kVAr of capacitance required to improve present power factor to a new desired power factor.

Example:

The utility bill shows an average power factor of 0.72 with an average KW of 627. How much kVAr is required to improve the power factor to 0.95 ?

Using formula

$$\mathbf{Cos}\ \Phi 1 = 0.72 \ , \tan \Phi 1 = 0.963$$

$$\mathbf{Cos}\ \Phi 2 = 0.95 \ , \tan \Phi 2 = 0.329$$

kVAr required = P ($\tan\phi 1$ - $\tan\phi 2$) = 627 (0.964 – 0.329)
= 398 kVAr

Using table (see Table 1.2)

1) Locate 0.72 (original power factor) in column (1).
2) Read across desired power factor to 0.95 column. We find 0.635 multiplier
3) Multiply 627 (average kW) by 0.635 = 398 kVAr.
4) Install 400 kVAr to improve power factor to 95%.

Table 1.2 Multipliers to Determine Capacitor kVAr Requirements for Power Factor Correction

Original Power Factor	Desired Power Factor																				
	0.80	0.81	0.82	0.83	0.84	0.85	0.86	0.87	0.88	0.89	0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1.0
0.50	0.982	1.008	1.034	1.060	1.086	1.112	1.139	1.165	1.192	1.220	1.248	1.276	1.306	1.337	1.369	1.403	1.440	1.481	1.529	1.589	1.732
0.51	0.937	0.962	0.989	1.015	1.041	1.067	1.094	1.120	1.147	1.175	1.203	1.231	1.261	1.292	1.324	1.358	1.395	1.436	1.484	1.544	1.687
0.52	0.893	0.919	0.945	0.971	0.997	1.023	1.050	1.076	1.103	1.131	1.159	1.187	1.217	1.248	1.280	1.314	1.351	1.392	1.440	1.500	1.643
0.53	0.850	0.876	0.902	0.928	0.954	0.980	1.007	1.033	1.060	1.088	1.116	1.144	1.174	1.205	1.237	1.271	1.308	1.349	1.397	1.457	1.600
0.54	0.809	0.835	0.861	0.887	0.913	0.939	0.968	0.992	1.019	1.047	1.075	1.103	1.133	1.164	1.196	1.230	1.267	1.308	1.356	1.416	1.559
0.55	0.769	0.795	0.821	0.847	0.873	0.899	0.926	0.952	0.979	1.007	1.035	1.063	1.093	1.124	1.156	1.190	1.227	1.268	1.316	1.376	1.519
0.56	0.730	0.756	0.782	0.808	0.834	0.860	0.887	0.913	0.940	0.968	0.996	1.024	1.054	1.085	1.117	1.151	1.188	1.229	1.277	1.337	1.480
0.57	0.692	0.718	0.744	0.770	0.796	0.822	0.849	0.875	0.902	0.930	0.958	0.986	1.016	1.047	1.079	1.113	1.150	1.191	1.239	1.299	1.442
0.58	0.655	0.681	0.707	0.733	0.759	0.785	0.812	0.838	0.865	0.893	0.921	0.949	0.979	1.010	1.042	1.076	1.113	1.154	1.202	1.262	1.405
0.59	0.619	0.645	0.671	0.697	0.723	0.749	0.776	0.802	0.829	0.857	0.885	0.913	0.943	0.974	1.006	1.040	1.077	1.118	1.166	1.226	1.369
0.60	0.583	0.609	0.635	0.661	0.687	0.713	0.740	0.766	0.793	0.821	0.849	0.877	0.907	0.938	0.970	1.004	1.041	1.082	1.130	1.190	1.333
0.61	0.549	0.575	0.601	0.627	0.653	0.679	0.706	0.732	0.759	0.787	0.815	0.843	0.873	0.904	0.936	0.970	1.007	1.048	1.096	1.156	1.299
0.62	0.516	0.542	0.568	0.594	0.620	0.646	0.673	0.699	0.726	0.754	0.782	0.810	0.840	0.871	0.903	0.937	0.974	1.015	1.063	1.123	1.266
0.63	0.483	0.509	0.535	0.561	0.587	0.613	0.640	0.666	0.693	0.721	0.749	0.777	0.807	0.838	0.870	0.904	0.941	0.982	1.030	1.090	1.233
0.64	0.451	0.474	0.503	0.529	0.555	0.581	0.608	0.634	0.661	0.689	0.717	0.745	0.775	0.806	0.838	0.872	0.909	0.950	0.998	1.068	1.201
0.65	0.419	0.445	0.471	0.497	0.523	0.549	0.576	0.602	0.629	0.657	0.685	0.713	0.743	0.774	0.806	0.840	0.877	0.918	0.966	1.026	1.169
0.66	0.388	0.414	0.440	0.466	0.492	0.518	0.545	0.571	0.598	0.626	0.654	0.682	0.712	0.743	0.775	0.809	0.846	0.887	0.935	0.995	1.138
0.67	0.358	0.384	0.410	0.436	0.462	0.488	0.515	0.541	0.568	0.596	0.624	0.652	0.682	0.713	0.745	0.779	0.816	0.857	0.905	0.965	1.108
0.68	0.328	0.354	0.380	0.406	0.432	0.458	0.485	0.511	0.538	0.566	0.594	0.622	0.652	0.683	0.715	0.749	0.786	0.827	0.875	0.935	1.078
0.69	0.299	0.325	0.351	0.377	0.403	0.429	0.456	0.482	0.509	0.537	0.565	0.593	0.623	0.654	0.686	0.720	0.757	0.798	0.846	0.906	1.049
0.70	0.270	0.296	0.322	0.348	0.374	0.400	0.427	0.453	0.480	0.508	0.536	0.564	0.594	0.625	0.657	0.691	0.728	0.769	0.817	0.877	1.020
0.71	0.242	0.268	0.294	0.320	0.346	0.372	0.399	0.425	0.452	0.480	0.508	0.536	0.566	0.597	0.629	0.663	0.700	0.741	0.789	0.849	0.992
0.72	0.214	0.240	0.266	0.292	0.318	0.344	0.371	0.397	0.424	0.452	0.480	0.508	0.538	0.569	0.601	0.635	0.672	0.713	0.761	0.821	0.964
0.73	0.186	0.212	0.238	0.264	0.290	0.316	0.343	0.369	0.396	0.424	0.452	0.480	0.510	0.541	0.573	0.607	0.644	0.685	0.733	0.793	0.936
0.74	0.159	0.185	0.211	0.237	0.253	0.289	0.316	0.342	0.369	0.397	0.425	0.453	0.483	0.514	0.546	0.580	0.617	0.658	0.706	0.766	0.909
0.75	0.132	0.158	0.184	0.210	0.236	0.262	0.289	0.315	0.342	0.370	0.398	0.426	0.456	0.487	0.519	0.553	0.590	0.631	0.679	0.739	0.882
0.76	0.105	0.131	0.157	0.183	0.209	0.235	0.262	0.288	0.315	0.343	0.371	0.399	0.429	0.460	0.492	0.526	0.563	0.604	0.652	0.712	0.855
0.77	0.079	0.105	0.131	0.157	0.183	0.209	0.236	0.262	0.289	0.317	0.345	0.373	0.403	0.434	0.486	0.500	0.537	0.578	0.626	0.685	0.829
0.78	0.052	0.078	0.104	0.130	0.156	0.182	0.209	0.235	0.262	0.290	0.318	0.346	0.376	0.407	0.439	0.473	0.510	0.551	0.599	0.659	0.802
0.79	0.026	0.052	0.078	0.104	0.130	0.156	0.183	0.209	0.236	0.264	0.292	0.320	0.350	0.381	0.413	0.447	0.484	0.525	0.573	0.633	0.776
0.80	0.000	0.026	0.052	0.078	0.104	0.130	0.157	0.183	0.210	0.238	0.266	0.294	0.324	0.355	0.387	0.421	0.458	0.499	0.547	0.609	0.750
0.81		0.000	0.026	0.052	0.078	0.104	0.131	0.157	0.184	0.212	0.240	0.268	0.298	0.329	0.361	0.395	0.432	0.473	0.521	0.581	0.724
0.82			0.000	0.026	0.052	0.078	0.105	0.131	0.158	0.186	0.214	0.242	0.272	0.303	0.335	0.369	0.406	0.447	0.495	0.555	0.698
0.83				0.000	0.026	0.052	0.079	0.105	0.132	0.160	0.188	0.216	0.246	0.277	0.309	0.343	0.380	0.421	0.469	0.529	0.672
0.84					0.000	0.026	0.053	0.079	0.106	0.134	0.162	0.190	0.220	0.251	0.283	0.317	0.354	0.395	0.443	0.503	0.646
0.85						0.000	0.027	0.053	0.080	0.108	0.136	0.164	0.194	0.225	0.257	0.291	0.328	0.369	0.417	0.477	0.620
0.86							0.000	0.026	0.053	0.081	0.109	0.137	0.167	0.198	0.230	0.264	0.301	0.342	0.390	0.450	0.593
0.87								0.000	0.027	0.055	0.083	0.111	0.141	0.172	0.204	0.238	0.275	0.316	0.364	0.424	0.567
0.88									0.000	0.028	0.056	0.084	0.114	0.145	0.177	0.211	0.248	0.289	0.337	0.397	0.540
0.89										0.000	0.028	0.056	0.086	0.117	0.149	0.183	0.220	0.261	0.309	0.369	0.512
0.90											0.000	0.028	0.058	0.089	0.121	0.155	0.192	0.233	0.281	0.341	0.484
0.91												0.000	0.030	0.061	0.093	0.127	0.164	0.205	0.253	0.313	0.456
0.92													0.000	0.031	0.063	0.097	0.134	0.175	0.223	0.283	0.426
0.93														0.000	0.032	0.066	0.103	0.144	0.192	0.252	0.395
0.94															0.000	0.034	0.071	0.112	0.160	0.220	0.363
0.95																0.000	0.037	0.079	0.026	0.186	0.329
0.96																	0.000	0.041	0.089	0.149	0.292
0.97																		0.000	0.048	0.108	0.251
0.98																			0.000	0.060	0.203
0.99																				0.000	0.143
																					0.000

Location of Capacitors

The primary purpose of capacitors is to reduce the maximum demand. Additional benefits are derived by capacitor location. The Figure 1.13 indicates typical capacitor locations. Maximum benefit of capacitors is derived by locating them as close as possible to the load. At this location, its kilovars are confined to the smallest possible segment, decreasing the load current. This, in turn, will reduce power losses of the system substantially. Power losses are proportional to the square of the current. When power losses are reduced, voltage at the motor increases; thus, motor performance also increases.

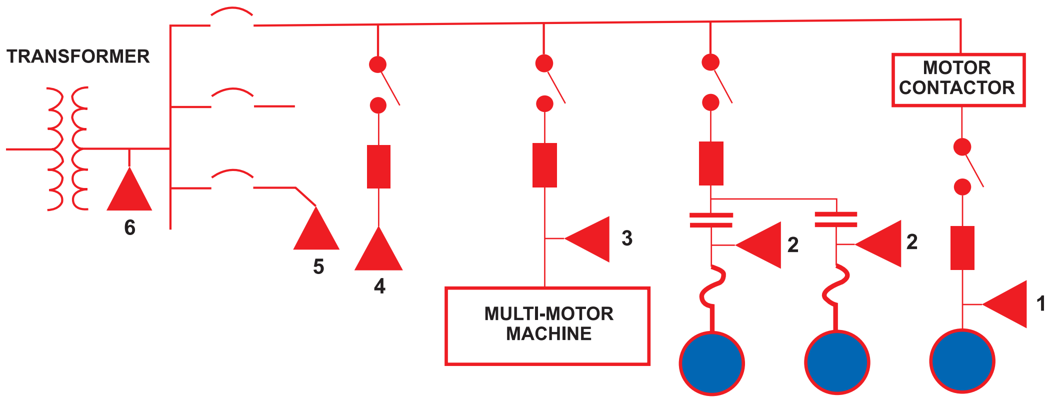

Figure 1.13 Power Distribution Diagram Illustrating Capacitor Locations

Where to correct power factor?

Capacitor correction is relatively inexpensive both in material and installation costs. Capacitors can be installed at any point in the electrical system, and will improve the power factor between the point of application and the power source. However, the power factor between the utilization equipment and the capacitor will remain unchanged. Capacitors are usually added at each piece of offending equipment, ahead of groups of small motors (ahead of motor control centers or distribution panels) or at main services.

The advantages and disadvantages of each type of capacitor installation are listed below:

Capacitor on each piece of equipment (1,2)

Advantages

- Increases load capabilities of distribution system.
- Can be switched with equipment; no additional switching is required.
- Better voltage regulation because capacitor use follows load.
- Capacitor sizing is simplified.
- Capacitors are coupled with equipment and move with equipment if rearrangements are instituted.

Disadvantages

- Small capacitors cost more per kVAr than larger units (economic break point for individual correction is generally at 10 HP).

It should be noted that the rating of the capacitor should not be greater than the no-load magnetizing kVAr of the motor. If this condition exists, damaging over voltage or transient torques can occur. This is why most motor manufacturers specify maximum capacitor ratings to be applied to specific motors.

Capacitor with equipment group (3)

Advantages

- Increased load capabilities of the service
- Reduced material costs relative to individual correction
- Reduced installation costs relative to individual correction

Disadvantages

- Switching means may be required to control amount of capacitance used.

The advantage of locating capacitors at power centers or feeders is that they can be grouped together. When several motors are running intermittently, the capacitors are permitted to be on line all the time, reducing the kVA demand regardless of load.

Capacitor at main service (4,5, & 6)

Advantages

- Low material installation costs.

Disadvantages

- Switching will usually be required to control the amount of capacitance used.
- Does not improve the load capabilities of the distribution system.

From energy efficiency point of view, capacitor location at receiving substation only helps the utility in loss reduction. Locating capacitors at tail end will help to reduce loss reduction within the plants distribution network as well and directly benefit the user by reduced consumption. Reduction in the distribution loss% in kWh when tail end power factor is raised from PF_1 to a new power factor PF_2, will be proportional to

$$\left\lfloor 1-(PF_1/PF_2)^2 \right\rfloor \times 100$$

Other Considerations

Where the loads contributing to power factor are relatively constant, and system load capabilities are not a factor, correcting at the main service could provide a cost advantage. When the low power factor is derived from a few selected pieces of equipment, individual equipment correction would be cost effective.

The growing use of ASDs (nonlinear loads) has increased the complexity of system power factor and its corrections. The application of PF correction capacitors without a thorough analysis of the system can aggravate rather than correct the problem, particularly if the fifth and seventh harmonics are present.

Capacitors for Other Loads

The other types of load requiring capacitor application include induction furnaces, induction heaters and arc welding transformers etc. The capacitors are normally supplied with control gear for the application of induction furnaces and induction heating furnaces. The PF of arc furnaces experiences a wide variation over melting cycle as it changes from 0.7 at starting to 0.9 at the end of the cycle. Power factor for welding transformers is corrected by connecting capacitors across the primary winding of the transformers, as the normal PF would be in the range of 0.35.

Performance Assessment of Power Factor Capacitors

Voltage effects: Ideally capacitor voltage rating is to match the supply voltage. If the supply voltage is lower, the reactive kVAr produced will be the ratio V_1^2 / V_2^2 where V_1 is the actual supply voltage, V_2 is the rated voltage.

On the other hand, if the supply voltage exceeds rated voltage, the life of the capacitor is adversely affected.

Material of capacitors: Power factor capacitors are available in various types by dielectric material used as; paper/ polypropylene etc. The watt loss per kVAr as well as life vary with respect to the choice of the dielectric material and hence is a factor to be considered while selection.

Connections: Shunt capacitor connections are adopted for almost all industry/ end user applications, while series capacitors are adopted for voltage boosting in distribution networks.

Operational performance of capacitors: This can be made by monitoring capacitor charging current vis- a- vis the rated charging current. Capacity of fused elements can be replenished as per requirements. Portable analyzers can be used for measuring kVAr delivered as well as charging current. Capacitors consume 0.2 to 6.0 Watt per kVAr, which is negligible in comparison to benefits.

Some checks that need to be adopted in use of capacitors are:

i. Nameplates can be misleading with respect to ratings. It is good to check by charging currents.

ii. Capacitor boxes may contain only insulated compound and insulated terminals with no capacitor elements inside.

iii. Capacitors for single phase motor starting and those used for lighting circuits for voltage boost, are not power factor capacitor units and these cannot withstand power system conditions.

1.5 Transformers

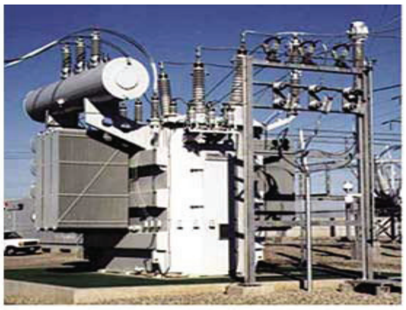

Figure 1.14 View of a Transformer

A transformer can accept energy at one voltage and deliver it at another voltage. This permits electrical energy to be generated at relatively low voltages and transmitted at high voltages and low currents, thus reducing line losses and voltage drop (see Figure 1.14).

Transformers consist of two or more coils that are electrically insulated, but magnetically linked. The primary coil is connected to the power source and the secondary coil connects to the load. The turn's ratio is the ratio between the numbers of turns on the secondary to the turns on the primary (See Figure 1.15).

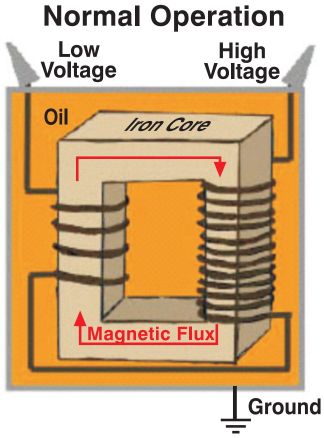

Figure 1.15 View of a Transformer Coil

The secondary voltage is equal to the primary voltage times the turn's ratio. Ampere-turns are calculated by multiplying the current in the coil times the number of turns. Primary ampere-turns are equal to secondary ampere-turns. Voltage regulation of a transformer is the percent increase in voltage from full load to no load.

Types of Transformers

Transformers are classified as two categories: power transformers and distribution transformers.

Power transformers are used in transmission network of higher voltages, deployed for step-up and step down transformer application (400 kV, 200 kV, 110 kV, 66 kV, 33kV)

Distribution transformers are used for lower voltage distribution networks as a means to end user connectivity. (11kV, 6.6 kV, 3.3 kV, 440V, 230V)

Rating of Transformer

Rating of the transformer is calculated based on the connected load and applying the diversity factor on the connected load, applicable to the particular industry and arrive at the kVA rating of the Transformer. Diversity factor is defined as the ratio of overall maximum demand of the plant to the sum of individual maximum demand of various equipment. Diversity factor varies from industry to industry and depends on various factors such as individual loads, load factor and future expansion needs of the plant. Diversity factor will always be less than one.

Location of Transformer

Location of the transformer is very important as far as distribution loss is concerned. Transformer receives HT voltage from the grid and steps it down to the required voltage. Transformers should be placed close to the load centre, considering other features like optimization needs for centralized control, operational flexibility etc. This will bring down the distribution loss in cables.

Transformer Losses and Efficiency

The efficiency varies anywhere between 96 to 99 percent. The efficiency of the transformers not only depends on the design, but also, on the effective operating load.

Transformer losses consist of two parts: No-load loss and Load loss

1. No-load loss (also called core loss) is the power consumed to sustain the magnetic field in the transformer's steel core. Core loss occurs whenever the transformer is energized; core loss does not vary with load. Core losses are caused by two factors: hysteresis and eddy current losses. Hysteresis loss is that energy lost by reversing the magnetic field in the core as the magnetizing AC rises and falls and reverses direction. Eddy current loss is a result of induced currents circulating in the core.
2. Load loss (also called copper loss) is associated with full-load current flow in the transformer windings. Copper loss is power lost in the primary and secondary windings of a transformer due to the ohmic resistance of the windings. Copper loss varies with the square of the load current. ($P=I^2R$). Typical 3 Phase Transformer losses of various capacities is given in Table1.3.

Transformer losses as a percentage of load is given in the Figure 1.16.

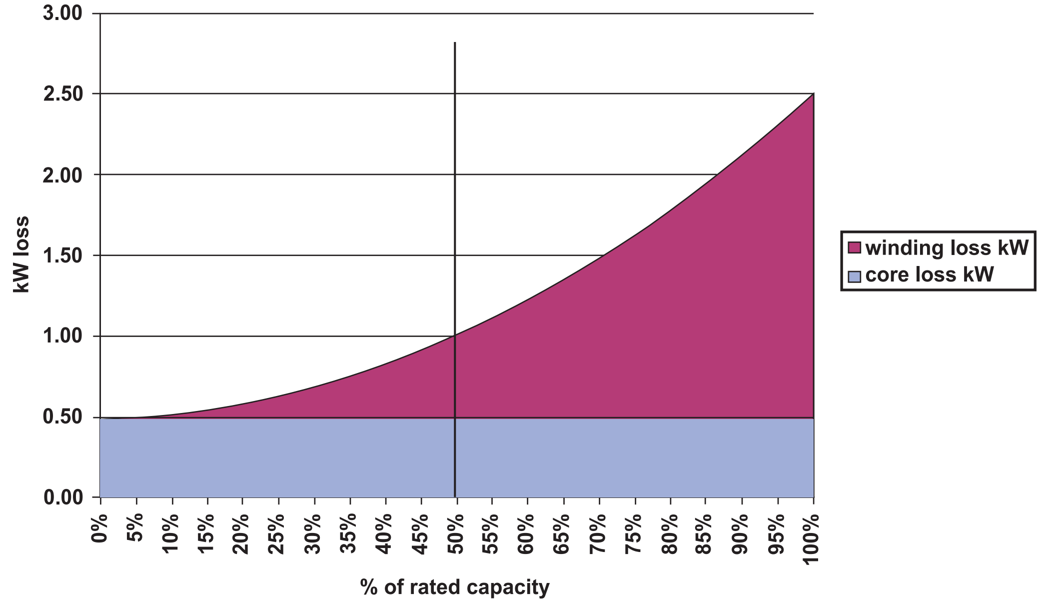

Figure 1.16 Transformer loss vs %Load

For a given transformer, the manufacturer can supply values for no-load loss, $P_{NO\text{-}LOAD}$, and load loss, P_{LOAD}. The total transformer loss, P_{TOTAL}, at any load level can then be calculated from:

$$\mathbf{P_{TOTAL} = P_{NO\text{-}LOAD} + (\%\ Load/100)^2 \times P_{LOAD}}$$

Where transformer loading is known, the actual transformers loss at given load can be computed as:

$$= \text{No load loss} + \left(\frac{\text{kVA load}}{\text{Rated kVA}}\right)^2 \text{x (Full load loss)}$$

Table 1.3 – Typical 3 Phase Transformer losses of various capacities (for CRGO Core Transformers)		
Rating (KVA)	**No Load Loss (W)**	**Load Loss (W)**
100	320	1950
160	455	2800
250	640	4450
500	900	6450
630	1260	9300
1000	1800	13300
1600	2600	19800
2000	3200	21000
3150	4600	28000
5000	6500	38000
6300	7700	45000
10000	11000	63000
12500	13000	77000
20000	18000	107000
31500	25000	150000
40000	30000	180000

Source: Siemens Electrical Engineers Hand Book

Voltage Fluctuation Control

A control of voltage in a transformer is important due to frequent changes in supply voltage level. Whenever the supply voltage is less than the optimal value, there is a chance of nuisance tripping of voltage sensitive devices. The voltage regulation in transformers is done by altering the voltage transformation ratio with the help of tapping.

There are two methods of tap changing facility available: ***Off-circuit tap changer and On-load tap changer.***

Off-circuit tap changer

It is a device fitted in the transformer, which is used to vary the voltage transformation ratio. Here the voltage levels can be varied only after isolating the primary voltage of the transformer.

On load tap changer (OLTC)

The voltage levels can be varied without isolating the connected load to the transformer. To minimize the magnetization losses and to reduce the nuisance tripping of the plant, the main transformer (the transformer that receives supply from the grid) should be provided with On Load Tap Changing facility at design stage. The downstream distribution transformers can be provided with off-circuit tap changer.

The On-load gear can be put in auto mode or manually depending on the requirement. OLTC can be arranged for transformers of size 250 kVA onwards. However, the necessity of OLTC below 1000 kVA can be considered after calculating the cost economics.

Parallel Operation of Transformers

The design of Power Control Centre (PCC) and Motor Control Centre (MCC) of any new plant should have the provision of operating two or more transformers in parallel. Additional switchgears and bus couplers should be provided at design stage.

Whenever two transformers are operating in parallel, both should be technically identical in all aspects and more importantly should have the same impedance level. This will minimize the circulating current between transformers.

Where the load is fluctuating in nature, it is preferable to have more than one transformer running in parallel, so that the load can be optimized by sharing the load between transformers. The transformers can be operated close to the maximum efficiency range by this operation.

For operating transformers in parallel, the transformers should have the following principal characteristics.

- The same phase angle difference between the primary and secondary terminals.
- Same voltage ratio
- Same percentage impedance
- Same polarity
- Same phase sequence

Energy Efficient Transformers

Most energy loss in dry-type transformers occurs through heat or vibration from the core. The new high-efficiency transformers minimize these losses. The conventional transformer is made up of a silicon alloyed iron (grain oriented) core. The iron loss of any transformer depends on the type of core used in the transformer. However the latest technology is to use amorphous material – a metallic glass alloy for the core (see Figure 1.17). The expected reduction in core loss over conventional (Si Fe core) transformers is roughly around 70%, which is quite significant. By using an amorphous core– with unique physical and magnetic properties- these new types of transformers have increased efficiency even at low loads - 98.5% efficiency at 35% load.

Electrical distribution transformers made with amorphous metal cores provide excellent opportunity to conserve energy right from the installation. Though these transformers are a little costlier than conventional iron core transformers, the overall benefit towards energy savings will compensate for the higher initial investment.

Figure 1.17 1600 kVA Amorphous Core Transformer

Standards & Labeling Programme for Distribution Transformers

The Bureau of Energy Efficiency has included Distribution transformers under Standards & Labeling Programme as large number of Distribution transformers are used by Electricity supply companies and also by different users for supplying power to their load centers. This provision has been made mandatory with effect from 7th January 2010.

The existing efficiency or the loss standards are specified in IS 1180 (part 1). This standard defines load losses and no load losses separately. For the BEE labeling programme total losses at 50% and 100% load have been defined. The highest loss segment is defined as star 1 and lowest loss segment is defined as star 5. The existing IS 1180 (part 1) specification losses are the base case with star 1.

The details of Star Rating plan for Distribution transformers and corresponding losses are given in Table 1.4. More details can be obtained from www.beestarlabel.com.

Table 1.4 Total Transformer Losses at 50% and 100% Loading

	1 star		2 star		3 star		4 star		5 star	
Rating kVA	Max Losses at 50% (Watts)	Max Losses at 100% (Watts)	Max Losses at 50% (Watts)	Max Losses at 100% (Watts)	Max Losses at 50% (Watts)	Max Losses at 100% (Watts)	Max Losses at 50% (Watts)	Max Losses at 100% (Watts)	Max Losses at 50% (Watts)	Max Losses at 100% (Watts)
16	200	555	165	520	150	480	135	440	120	400
25	190	785	235	740	210	695	190	635	175	595
63	490	1415	430	1335	380	1250	340	1140	300	1050
100	700	2020	610	1910	520	1800	475	1650	435	1500
160	1000	2800	880	2550	770	2200	670	1950	570	1700
200	1130	3300	1010	3000	890	2700	780	2300	670	2100

1.6 Distribution Losses in Industrial System

In an electrical system often the constant no load losses and the variable load losses are to be assessed, over long reference duration, for energy loss estimation.

Identifying and calculating the sum of the individual contributing loss components is a challenging one, requiring extensive experience and knowledge of all the factors impacting the operating efficiencies of each of these components.

For example the cable losses in any industrial plant will be up to 6 percent depending on the size and complexity of the distribution system. All of these are current dependent, and can be readily mitigated by any technique that reduces facility current load. The various losses in different distribution equipments are given in Table1.5.

In system distribution loss optimization, the various options available include:

- Relocating transformers and sub-stations near to load centers
- Re-routing and re-conducting such feeders and lines where the losses / voltage drops are higher.

- Power factor improvement by incorporating capacitors at load end.
- Optimum loading of transformers in the system.
- Opting for lower resistance All Aluminum Alloy Conductors (AAAC) in place of conventional Aluminum Cored Steel Reinforced (ACSR) lines
- Minimizing losses due to weak links in distribution network such as jumpers, loose contacts, and old brittle conductors.

Table 1.5 Losses in Electrical Distribution Equipment

S.No	Equipment	% Energy Loss at Full Load Variations	
		Min	Max
1.	Outdoor circuit breaker (15 to 230 KV)	0.002	0.015
2.	Generators	0.019	3.5
3.	Medium voltage switchgears (5 to 15 KV)	0.005	0.02
4.	Current limiting reactors	0.09	0.30
5.	Transformers	0.40	1.90
6.	Load break switches	0.003	0.025
7.	Medium voltage starters	0.02	0.15
8.	Bus ways less than 430 V	0.05	0.50
9.	Low voltage switchgear	0.13	0.34
10.	Motor control centers	0.01	0.40
11.	Cables	1.00	4.00
12.	Large rectifiers	3.0	9.0
13.	Static variable speed drives	6.0	15.0
14.	Capacitors (Watts / kVAr)	0.50	6.0

1.7 Assessment of Transmission and Distribution (T&D) Losses in Power Systems

For an electric utility (DISCOMs) the distribution losses which are more predominant, can be categorized as

i) Technical Losses

ii) Commercial Losses

Technical Losses:

The technical losses primarily take place due to the following factors

- Transformation Losses (at various transformation levels)
- High I^2R losses in distribution lines due to inherent resistance and poor power factor in the electrical network

Normative Technical loss limits in Indian Transmission and Distribution network are shown in Table 1.6.

Table 1.6 Normative Technical loss limits in Transmission and Distribution network in Indian Context

System Component	Loss Limit % Min	Loss Limit % Max
STEP-UP Transformers & EHV Transmission System	0.5	1.0
Transmission to intermediate voltage level, transmission system & Step-down to sub transmission Voltage level	1.5	3.0
Sub transmission System & step down to distribution voltage level	2.0	4.5
Distribution lines and Service connections	3.0	7.0
Total Losses	**7.0**	**15.5**

1.8 Estimation of Technical Losses in Distribution System

The first and important step in reduction of energy losses is to carry out energy audit of power distribution system. There are two methods of determining the energy losses namely direct method and indirect method.

The **Direct method** involves placement of energy meters at all locations starting from the input point of the feeder to the individual consumers. The difference between input energy and sum of all consumers over a specific duration is accounted as distribution loss of the network. This calls for elaborate and accurate metering and collection of simultaneous data.

The **Indirect method** essentially involves:

- Energy metering at critical locations in the system such as substation and feeders.
- Compiling the network information, such as length of the line/feeders, conductor size, DTR details, capacitor details etc.
- Conducting load flow studies (all electrical parameters) on peak load durations as well as normal load durations.
- Application of suitable software to assess the system losses.

This software can also be used for system simulation, identifying improvements and network optimization.

Causes of technical losses in distribution system

The factors contributing to the increase in the distribution losses are

1. Lengthy distribution lines:

In practice, 11 KV and 415 volts lines, in rural areas are extended radially over long distances to feed loads scattered over large areas. This results in high line resistance and therefore high I^2R losses in the line.

2. Inadequate Size of Conductors:

On account of load growth, many distribution feeders end up being under sized for the loads to be catered to the consumers. The size of the conductors should be selected/upgraded/transformers to be relocated on the basis of KVA Kilometer capacity of standard conductor to maintain voltage regulation within limits.

Voltage Regulation:

The voltage regulation is usually expressed as a percentage drop with reference to the receiving end voltage.

Percentage regulation = 100 (Es - Er) / Er

Where, Es = Sending end voltage
Er = Receiving end voltage

3. Distribution Transformers (DTR) not located at load center on the Secondary Distribution System:

Often, DTs are not located centrally with respect to consumer loads. Consequently, the farthest consumers receive low voltage even though a good voltage level is maintained at the transformer's secondary. This again leads to high line loss. Therefore in order to reduce the voltage drop in the line to the farthest consumers, the distribution transformer should be located near to consumer load to keep voltage drop within permissible limits.

4. Low Power Factor:

A low PF contributes towards high distribution losses. For a given load, if the PF is low, the current drawn is high. Consequently, the losses which are proportional to square of the current will be more.

Therefore, line losses owing to the poor PF can be reduced by improving the PF. This can be done by application of shunt capacitors.

Shunt capacitors can be connected in the following locations:

- On the secondary side (11 KV side) of the 33/11 KV power transformers in substation.
- On the secondary side of distribution transformers

The following example shows how the improvement in power factor in 11 KV lines results in considerable reduction in losses:

Reduction of Line Losses with improvement in Power Factor

Load (kW)	PF	kVA	Current (A)	Line Loss (kW)	Remarks
300	0.7	428	38.9	27.2	Before
300	1.0	300	27.2	13.4	After

Measures to reduce technical losses

Some of the measures to reduce technical losses in distribution system include,

- **High Voltage Distribution System (HVDS):-** Distribution Companies (Discoms) have started implementing distribution systems at high voltage. The L.T. distributions are reduced and eliminated wherever feasible. A typical LT System consists of LT 3 Phase 415V Distribution System with lengthy LT Lines serving the consumers, contributing to more losses in the System. Reduction in these losses is done through restructuring of the existing LVDS network to HVDS network by installation of three phase 11 kV/400V 25 KVA & 16KVA pole mounted transformers at the load centers to serve different consumers.

- **Amorphous Core Transformers:** Recently Distribution Transformers DTRs with amorphous core have been manufactured with just about 30% of no-load losses compared to the Conventional Transformers. Some of the Discoms have installed these transformers to reduce the distribution loess in the network.

Commercial Losses

Any illegal consumption of electrical energy, which is not correctly metered, billed and revenue collected, causes commercial losses to the utilities. The commercial losses are primarily attributable to discrepancies in:

Meter Reading: Commercial losses occur due to discrepancy in meter reading. Meter reading problems are manifested in the form of zero consumption in meter reading books which may be due to premises found locked, untraceable consumers, stopped/defective meters, temporarily disconnected consumers continuing in billing solution etc. Collusion with consumers is also a source of commercial loss to utilities which are primarily due to incorrect meter reading.

Metering: Most utilities use either electro-mechanical or electronic meters for consumer metering. Commercial losses through metering can be in the form of meter tampering in various forms.

Collection efficiency: Typically in a billing cycle, a distribution utility issues bills against metered energy and assessed (generally in case of agricultural loads and temporary connections) energy. The ratio of amount collected to total amount billed is termed as collection efficiency.

The above losses are collectively categorized as AT & C (Aggregate Technical & Commercial) losses. The estimation of AT & C losses for a sample area is shown in Table 1.7.

Computation of AT & C Losses

The aggregate technical and commercial losses can be measured using the formula mentioned below.

AT & C Losses = {1- (Billing Efficiency x Collection Efficiency)} x 100

Where,

$$\text{Billing Efficiency, \%} = \frac{\text{Total units sold, } MU}{\text{Total input, } MU} \times 100$$

$$\text{Collection Efficiency, \%} = \frac{\text{Re } venue\ Collected,\ Rs.}{Amount\ billed,\ Rs.} \times 100$$

MU = Million Units

Table 1.7 Estimation of AT & C Losses			
Sl. No.	**Description**		**Annual data**
1	Input Energy = (Import-Export), MU	Ei	10
2a	Energy Billed (Metered), MU	E1	6
2b	Energy Billed (Un-Metered), MU	E2	1
2c	Total Energy Billed (E1 + E2)	Eb	7
3	Amount Billed (Rs. lakhs)	Ab	400
4a	Gross Amount Collected (Rs. lakhs)	AG	410
4b	Arrears Collected (Rs. lakhs)	Ar	40
4c	Amount Collected without Arrears (Rs. lakhs)	Ac=AG-Ar	370
5	Billing Efficiency (BE)	= Eb/Ei *100%	70%
6	Collection Efficiency(CE)	=Ac/Ab *100%	93%
7	AT& C Loss	{1- (BE *CE) *100%	35%

BE = Billing Efficiency, CE = Collection Efficiency, Note: If A_r is not known, assume $A_r = A_G - A_b$

Measures to Reduce Commercial Losses

Some of the measures to reduce commercial losses in distribution system include:

- Accurate Metering (A metering plan for installing meters with sustained accuracy).
- Appropriate range of meter with reference to connected load.
- Installation of Electronic meters with (TOD, tamper proof, data and remote reading facility).
- Intensive inspections.
- Compulsory metering/average billing
- Use of energy audit as a tool to pinpoint areas of high losses.
- Eradication of theft.

1.9 Demand Side Management (DSM)

DSM refers to "Actions taken on the customer's side of the meter to change the amount (kWh) or timing (kVA) of energy consumption. Electricity DSM strategies have the goal of maximizing end use efficiency to avoid or postpone the construction of new generating plants".

The ever increasing demand growth of electricity can be met either by matching increase in capacity, i.e. Supply side capacity addition or adopting demand side management and end use efficiency improvement strategies, which are much more cost effective and resource efficient.

Utilities are driven by supply side and customer side concerns such as capacity (peak demand) short falls, energy shortfalls, need for optimization of generation and network utilization, Regulatory issues, environmental mandates and customer demand for uninterrupted supply at competitive tariffs. Demand side management offers itself as a powerful tool to distribution companies, to analyze, develop and implement customized DSM programs, cost effectively, to enable meeting the supply side concern of the utilities.

DSM Objectives

The key objectives of DSM include the following.

- Improve the efficiency of energy systems.
- Reduce financial needs to build new energy facilities (generation).
- Minimize adverse environmental impacts.
- Lower the cost of delivered energy to consumers.
- Reduce power shortages and power cuts.
- Improve the reliability and quality of power supply.

DSM methodology

Step 1: Load Research

This stage in the DSM implementation will typically assess the customer base, tariff, load profile on an hourly basis and will identify the sectors contributing to the load shape. This step will also identify peak load contributors.

Step 2: Define load-shape objectives

Based on the results of the load research in the utility, the load shape objectives for the current situation are defined. Various load-shape objectives are represented in Figure 1.18 below.

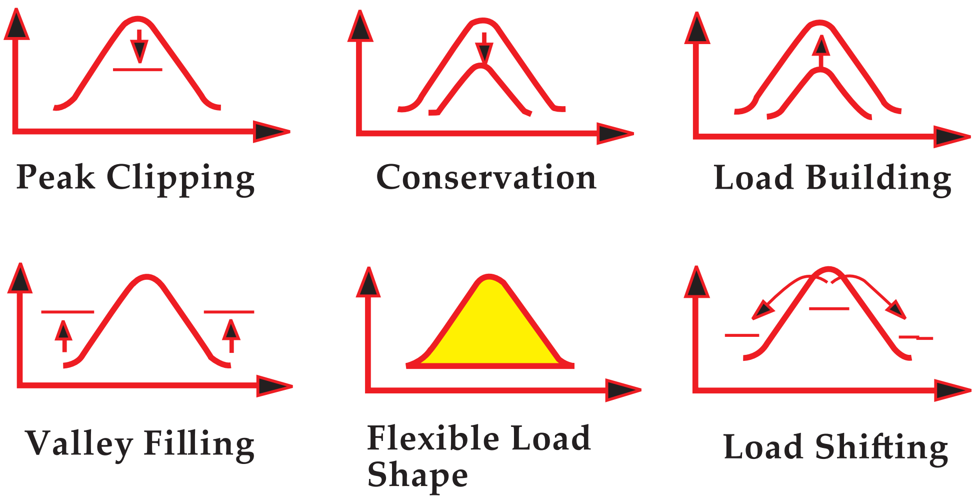

Figure 1.18 Load Shape Profiles and Objectives

Meaning of load-shape objective

Peak Clipping: the reduction of utility load primarily during periods of peak demand.

Valley-Filling: the improvement of system load factor by building load in off-peak periods.

Load Shifting: the reduction of utility loads during periods of peak demand, while at the same time building load in off-peak periods. Load shifting typically does not substantially alter total electricity sales.

Conservation: the reduction of utility loads, more or less equally, during all or most hours of the day.

Load Building: the increase of utility loads, more or less equally, during all or most hours of the day.

Flexible Utility Load Shape: refers to programs that set up utility options to alter customer energy consumption on an as-needed basis, as in interruptible/ curtailable agreements.

Step 3: Assess program implementation strategies

This step will identify the end-use applications that can be potentially targeted to reduce peak demand, specifically in sectors contributing to system peak. This step will also carry out a detailed cost *benefit analysis* for the end-users and the utilities, including analysis of societal as well as environmental benefits.

Step 4: Implementation

Implementation stage includes program design for specific end-use applications, promotes the program to the target audience through marketing approaches such as advertising, bills and inserts, and focused group meetings (specifically in case of commercial and industrial sector).

Step 5: Monitoring and Evaluation

This step tracks the program design and implementation and compares the same with proposed DSM goal set by the utility. A detailed benefit-cost analysis in this case includes identifying the avoided supply cost for the utility vis-à-vis the total program cost for the utilities and benefits to the participants including the reduced bills or incentives to the end-users.

Types of DSM Measures

Broadly the types of DSM measures can be classified as follows.

a) Energy reduction programmes - reducing demand through more efficient processes, buildings or equipment, for example:

Efficient Lighting (CFLs, Using natural light), Appliance Labelling, Building regulations, Efficient and alternative energy use, Efficient use of electric motors and motor driven systems, Preventative maintenance, Energy management and audit.

b) Load management programmes - changing the load pattern and encouraging less demand at peak times and peak rates, for example:

Load Levelling (Peak clipping, Valley filling and load shifting), Load growth, Tariff Incentives or Penalties (Time-of-Use & real time pricing, power factor penalties)

Benefits of DSM

Benefits of the DSM initiatives are manifold, some of which are described in Table 1.8 below.

Table 1.8 Benefits of DSM

Customer benefits	Societal benefits	Utility benefits
Satisfy electricity demands Reduce / stabilize costs (bills) Improve value of service Maintain/improve lifestyle and productivity	Reduce environmental degradation Conserve resources Protect global environment Maximize customer welfare	Lower cost of service Improve operating efficiency, flexibility Reduce capital needs Improve customer service

1.10 Harmonics

A harmonic is a component frequency of the signal that is an integer multiple of the fundamental frequency. Harmonic voltages and currents in an electric power system are a result of non-linear electric loads. **The Harmonic current represents energy that cannot be used by any devices on the network. It will be therefore converted to heat and is wasted.** For instance, the fundamental frequency is 50 Hz, and then the 5th harmonic is five times that frequency, or 250 Hz (Figure 1.19).

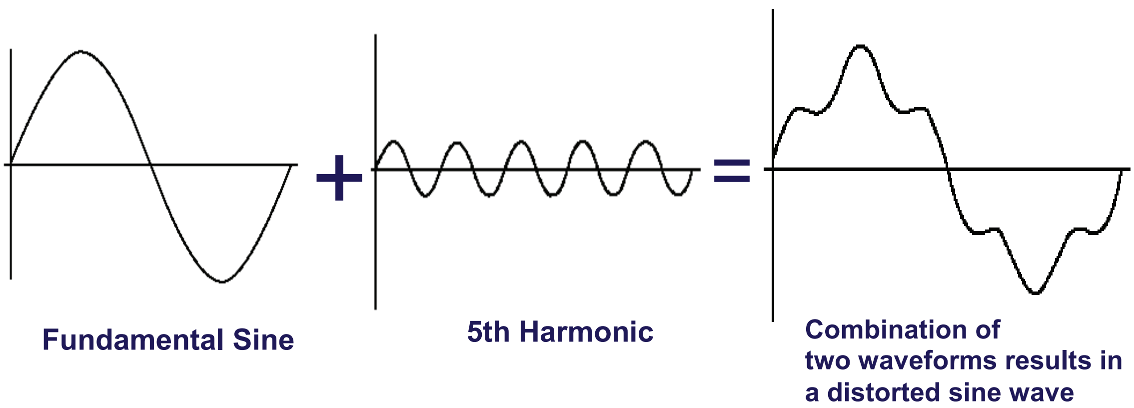

Figure 1.19 Harmonic wave pattern

Linear System

In any alternating current network, flow of current depends upon the voltage applied and the impedance (resistance to AC) provided by elements like resistances, reactances of inductive and capacitive nature. As the value of impedance in above devices is constant, they are called linear whereby the voltage and current relation is of linear nature.

e.g. Incandescent lamps, heaters and, to a great extent, motors are linear systems

Non-linear System

Non-Linear systems are one with varying impedance characteristics, These NON LINEAR devices cause distortion in voltage and current waveforms which is of increasing concern in recent times.

e.g. Variable frequency drives (VFDs), electronic ballasts, UPS and Computers, induction and arc furnaces

Current Distortion:

Current Harmonics could cause transformer heating or nuisance tripping by fuses, circuit breakers and other protective devices since they are typically not rated for harmonically rich waveforms.

$$THD_{current} = \sqrt{\sum_{n=2}^{n=n}\left(\frac{I_n}{I_1}\right)^2} \times 100$$

A 5th harmonic current is simply a current flowing at 250 Hz on a 50 Hz system. The 5th harmonic current flowing through the system impedance creates a 5th harmonic voltage. Total Harmonic Distortion (THD) expresses the amount of harmonics. The following is the formula for calculating the THD for current:

$$THD_{current} = \sqrt{\sum_{n=2}^{n=n}\left(\frac{I_n}{I_1}\right)^2} \times 100$$

Then…

$$I_{THD} = \sqrt{\left[\left(\frac{50}{250}\right)^2 + \left(\frac{35}{250}\right)^2\right]} x100 \;=\; 24\%$$

Current at fundamental frequency I_1 = Base Current = 250 amps
Third Harmonic current = 50 amps
Fifth Harmonic current = 35 amps

When harmonic currents flow in a power system, they are known as "poor power quality" or "dirty power". Other causes of poor power quality include transients such as voltage spikes, surges, sags, and ringing. Because they repeat every cycle, harmonics are regarded as a steady-state cause of poor power quality. The distortion travels back into the power source and can affect other equipment connected to the same source.

Voltage Distortion:

A distorted current has higher peak values that cause non-sinusoidal voltage drops across the distribution system. The resulting voltage drops add or subtract from the sinusoidal voltage supplied by the utility. Other utility customers could get distorted voltage on the downstream side of the power distribution circuit.

When expressed as a percentage of fundamental voltage THD is given by,

$$\mathrm{THD}_{\mathrm{voltage}} = \sqrt{\sum_{n=2}^{n=n}\left(\frac{V_n}{V_1}\right)^2} \times 100$$

Where, V_1 is the fundamental frequency voltage and V_n is n^{th} harmonic voltage component.

Causes of Harmonics

Harmonic currents and voltages are created by non- linear loads connected to the power distribution system. All power electronic converters used in different types of electronic systems can increase harmonic disturbances by injecting harmonic currents directly into the supply network. Common non-linear loads include variable speed drives (AC as well as DC), induction furnaces, LED based and CFL lamps, certain types of UPS & computer power supplies.

Effects of Harmonics

- Blinking of Incandescent Lights - Transformer Saturation
- Capacitor Failure - Harmonic Resonance
- Circuit Breakers Tripping - Inductive Heating and Overload
- Conductor Failure - Inductive Heating
- Electronic Equipment Shutting down - Voltage Distortion
- Flickering of Fluorescent Lights - Transformer Saturation
- Fuses Blowing for No Apparent Reason - Inductive Heating and Overload
- Motor Failures (overheating) - Voltage Drop
- Neutral Conductor and Terminal Failures - Additive Triplen Currents
- Electromagnetic Load Failures - Inductive Heating
- Overheating of Metal Enclosures - Inductive Heating
- Power Interference on Voice Communication - Harmonic Noise
- Transformer Failures - Inductive Heating

Overcoming Harmonics in Power systems

Passive Filters: Built-up by combinations of capacitors, inductors (reactors) and resistors. It is the most common and available for all voltage levels

Active Power Filter APF: Inserting negative phase compensating harmonics into the AC-Network, thus eliminating the undesirable harmonics on the AC power network.

Special Transformers: There are several special types of transformer connections which can cancel harmonics. Additional special winding connections can be used to cancel other harmonics on balanced loads. These systems also use more copper. Harmonic canceling transformers are also known as phase-shifting transformers. It is a relatively new power quality product for mitigating harmonic problems.

Since VFD is emerging as a major energy saving application and results in harmonic generation, harmonic mitigation in VFD is discussed here.

The Harmonic Mitigation solutions currently in use in the industry broadly fall into the following categories:

1. Passive Harmonic Filter (PHF)
2. Advance Active Filters (AAF)
3. Active Front End based VFDs (AFE)

They are briefly described in the sections below:

Passive filter is the most common method for the cancellation of harmonic current in the distributed system. These filters are basically designed on principle either single tuned/double tuned or band pass filter technology. Passive filters (Figure 1.20) offer very low impedance in the network at the tuned frequency to divert all the harmonic current at the tuned frequency.

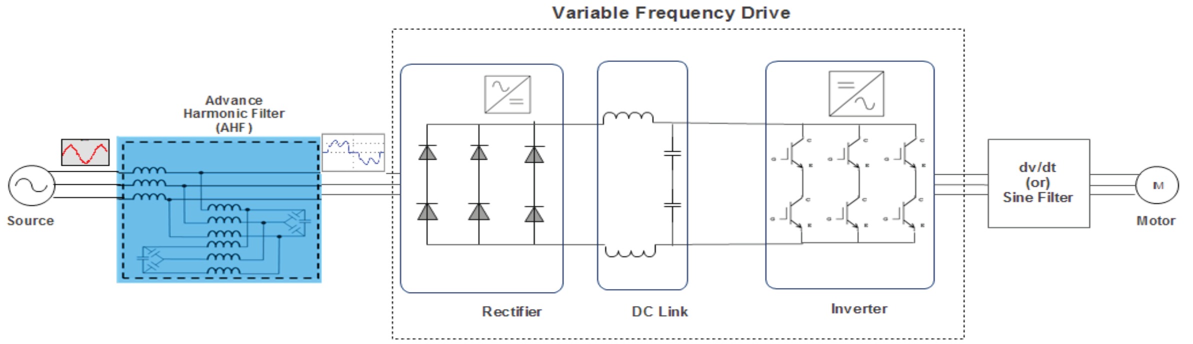

Figure 1.20 Power schematic of Series passive filter

Active filter is connected parallel with the distribution system. Distribution system consists of a wide percentage of harmonics produced by non- linear loads. Active filters (Figure 1.21) compensate current harmonics by injecting equal magnitude but opposite phase harmonic compensating current.

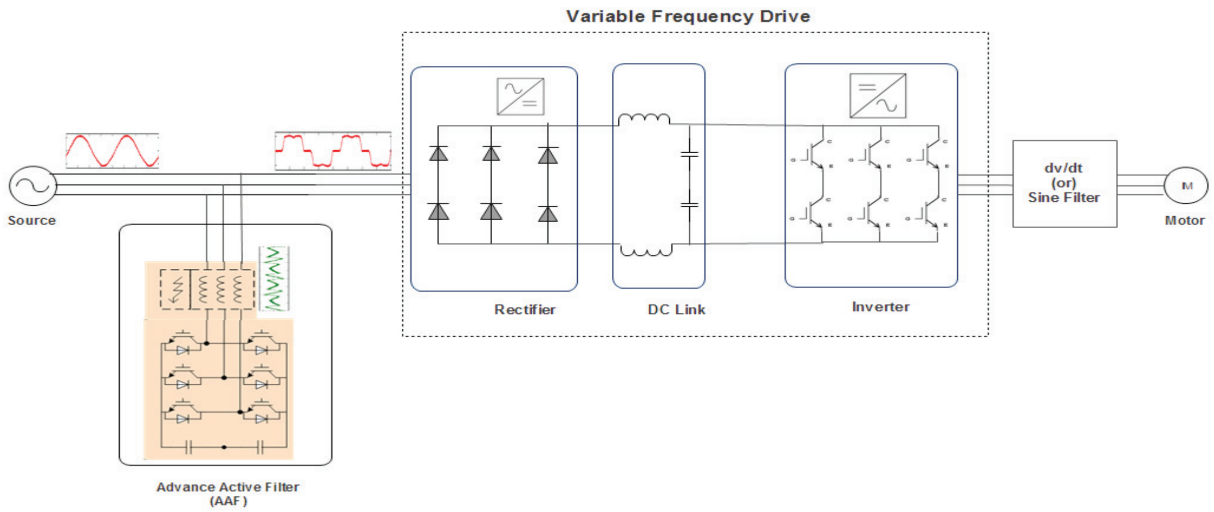

Figure 1.21 Power schematic of shunt active filter

Active Front end Rectifiers used in VFDs has the major advantage of mitigation of harmonics without using external filter, to maintain unity power factor at the point of common coupling, Bidirectional power flow makes recovery of energy to the mains by saving it, Clean power to the grid which in turn does not affect the other loads connected to it, maintaining the DC voltage irrespective of the supply variations.

LCL Filter is connected at Point of Common Coupling (PCC) between Grid and active Front End Rectifier (AFE) (Figure 1.22). Due to High switching frequency operation of AFE IGBTs there will be harmonics in the Sinusoidal waveform at that particular High frequency. The LCL (Inductance and Capacitance Combination) is introduced to bypass those Switching frequencies which will in turn have approximately sinusoidal supply at the Grid.

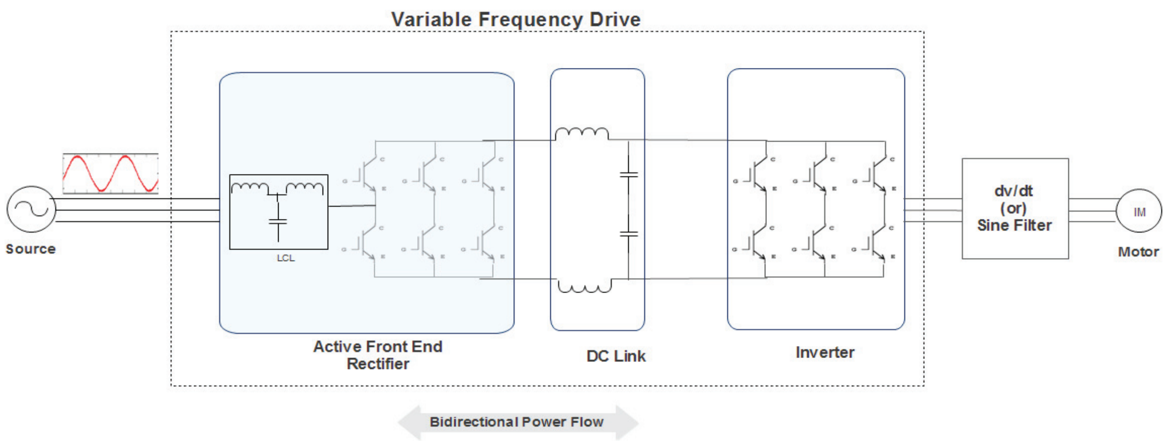

Figure 1.22 Power schematic of Active front end (AFE) drive

Harmonics Limits:

The permissible harmonic limit for different current (Isc / IL) as per IEEE standard is given in Table 1.9 and for different bus voltage are given in Table 1.10

Current Distortion Limits for General Distribution System's end-User limits (120 Volts To 69,000 Volts)

Table 1.9 Maximum Harmonic Current Distortion in % of IL

Individual Harmonic Order (Odd Harmonics)						
Isc/IL	**<11**	**11 ≤ h < 17**	**17 ≤ h < 23**	**23 ≤ h < 35**	**35 ≤ h**	**TDD**
< 20*	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

Even harmonics are limited to 25% of the odd current harmonic limits above.
Current distortions that result in a direct current offset, e.g. half wave converters are not allowed.
*All power generation equipment is limited to these values of current distortion, regardless of actual Isc/IL.
Where, Isc = Maximum short circuit current at PCC. I_L = Maximum Demand Load Current (fundamental frequency component) at PCC. TDD = Total demand distortion (RSS), harmonic current distortion in % of maximum demand load current (15 or 30 min demand).

Table 1.10 Total Harmonic Distribution for Different Voltage Levels in %

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69 kV and below	3.0	5.0
69.001 kV Thru 161 kV	1.5	2.5
161 kV and above	1.0	1.5

Note:

High voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.

Two very important points must be made in reference to the above.

1. The customer is responsible for maintaining current distortion to within acceptable levels, while the utility is responsible for limiting voltage distortion.

2. The limits are only applicable at the point of common coupling (PCC) between the utility and the customer. The PCC, while not explicitly defined, is usually regarded as the point at which the utility equipment ownership meets the customer’s or the metering point.

Therefore, the above limits cannot be meaningfully applied to distribution panels or individual equipment within a plant. The entire plant must be considered complying with these limits.

1.11 Analysis of Electrical Power Systems

An analysis of an electrical power system may uncover energy waste, fire hazards, and equipment failure. Facility /energy managers increasingly find that reliability-centered maintenance can save money, energy, and downtime (see Table 1.11).

Table 1.11 Trouble shooting of Electrical Power Systems

System Problem	Common Causes	Possible Effects	Solutions
Voltage imbalances among the three phases	Improper transformer tap settings, Single-phase loads not balanced among phases, poor connections, bad conductors, transformer grounds or faults.	Motor vibration, premature motor failure A 5% imbalance causes a 40% increase in motor losses.	Balance loads among phases.
Voltage deviations from rated voltages (too low or high)	Improper transformer settings, Incorrect selection of motors.	Over-voltages in motors reduce efficiency, power factor and equipment life Increased temperature	Correct transformer settings, motor ratings and motor input voltages
Poor connections in distribution or at connected loads.	Loose bus bar connections, loose cable connections, corroded connections, poor crimps, loose or worn contactors	Produces heat, causes failure at connection site, leads to voltage drops and voltage imbalances	Use Infra Red camera to locate hot-spots and correct.
Undersized conductors.	Facilities expanding beyond original designs, poor power factors	Voltage drop and energy wastage.	Reduce the load by conservation scheduling.
Insulation leakage	Degradation over time due to extreme temperatures, abrasion, moisture, chemicals	May leak to ground or to another phase. Variable energy waste.	Replace conductors, insulators
Low Power Factor	Inductive loads such as motors, transformers, and lighting ballasts Non-linear loads, such as most electronic loads.	Reduces current-carrying capacity of wiring, voltage regulation effectiveness, and equipment life.	Add capacitors to counter reactive loads.
Harmonics (non-sinusoidal voltage and/or current wave forms)	Office-electronics, UPSs, variable frequency drives, high intensity discharge lighting, and electronic and core-coil ballasts.	Over-heating of neutral conductors, motors, transformers, switch gear. Voltage drop, low power factors, reduced capacity.	Take care with equipment selection and isolate sensitive electronics from noisy circuits.

<u>Solved Example:</u>

An energy audit of electricity bills of a process plant was conducted. The plant has a contract demand of 5000 kVA with the power supply company. The average maximum demand of the plant is 3850 kVA/month at a power factor of 0.95. The maximum demand is billed at the rate of Rs.600/kVA/month. The minimum billable maximum demand is 75 % of the contract demand. An incentive of 0.5 % reduction in energy charges component of electricity bill are provided for every 0.01 increase in power factor over and above 0.95. The average energy charge component of the electricity bill per month for the plant is Rs.18 lakhs.

The plant decides to improve the power factor to unity. Determine the power factor capacitor kVAr required, annual reduction in maximum demand charges and energy charge component. What will be the simple payback period if the cost of power factor capacitors is Rs.900/kVAr.

Ans:

kW drawn	3850 x 0.95 = 3657.5 kW
kVAr required to improve power factor from 0.95 to 1	kW (tan θ_1 – tan θ_2)
	kW (tan ($\cos^{-}\theta_1$) – tan ($\cos^{-}\theta_2$)
	3657.5 (tan ($\cos^{-}0.95$) – tan ($\cos^{-}1$)
	3657.5(0.329 - 0)
	1203 x 900 kVAr
Cost of capacitors @Rs.900/kVAr	Rs.10,82,700
Maximum demand at unity power factor	3657.5/1 = 3657.5 kVA
75 % of contract demand	5000x0.75=3750 kVA
Reduction in Demand charges	3850-3750= 100 kVA, as the plant has to pay MD charges on minimum billable demand of 3750, and not on the improved MD of 3657.5 kVA in this case
	100kVA/month x 12 months x Rs.600 kVA/ month= Rs.7,20,000
Percentage reduction in energy charge from 0.95 to 1 @ 0.5 % for every 0.01 increase	2.5 %
Monthly energy cost component of the bill	Rs.18,00,000
Reduction in energy cost component	18,00,000 x (2.5/100)
	Rs.45,000/month
Annual reduction	Rs.45,000 x 12
	Rs.5,40,000
Savings in electricity bill	Rs.7,20,000+ 5,40,000= 12,60,000
Investment	Rs.10,82,700
Payback period	10,82,700/12,60,000
	0.859 years or 10.31months

2. ELECTRIC MOTORS

Types, Squirrel cage and slip ring and their characteristics, Losses in induction motors, motor efficiency, Factors affecting motor performance, Rewinding versus replacement of motor, Energy saving opportunities, Motor history sheet, Star operation of motors, Energy efficient motors, Variable speed drives, Soft starters with energy saver, Electrical characteristics. S & L programme on energy efficient motors.

2.1 Introduction

Motors convert electrical energy into mechanical energy by the interaction between the magnetic fields set up in the stator and rotor windings. Industrial electric motors can be broadly classified as induction motors, direct current motors or synchronous motors. All motor types have the same four operating components: stator (stationary windings), rotor (rotating windings), bearings, and frame (enclosure).

2.2 Motor Types

Induction Motors

An AC induction motor (Figure 2.1) has a fixed outer portion, called the stator and a rotor that spins inside with a carefully engineered air gap between the two.

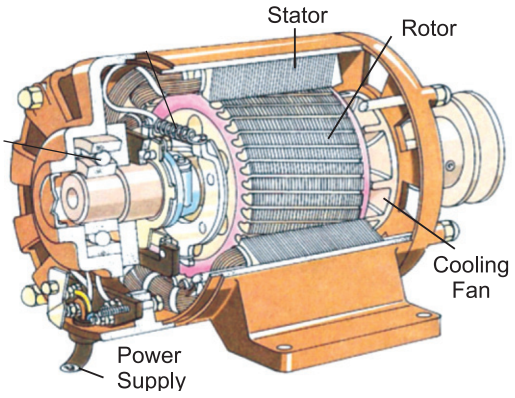

Figure 2.1 Induction Motor

If a 3-phase supply is fed to the stator windings of a 3-phase motor, *a magnetic flux of constant magnitude, rotating at synchronous speed is set up*. At this point, the rotor is stationary. The rotating magnetic flux passes through the air gap between the stator & rotor and sweeps past the stationary rotor conductors. *This rotating flux, as it sweeps, cuts the rotor conductors, thus causing an e.m.f to be induced in the rotor conductors*. As per the *Faraday's law of electromagnetic induction*, it is this relative motion between the rotating magnetic flux and the stationary rotor conductors, which induces an e.m.f on the rotor conductors. Since the rotor conductors are shorted and form a closed circuit, the induced e.m.f produces a rotor current whose direction is given by *Lenz's Law*, is such as to oppose the cause producing it. In this case, the cause which produces the rotor current is the relative motion between the rotating magnetic flux and the stationary rotor conductors. Thus to reduce the relative speed, the rotor starts to rotate in the same direction as that of the rotating flux on the stator windings, trying to catch it up. The frequency of the induced e.m.f is same as the supply frequency.

The magnetic field produced in the rotor because of the induced voltage is alternating in nature. To reduce the relative speed, with respect to the stator, the rotor starts running in the same direction as that of the stator flux and tries to catch up with the rotating flux. However, in practice, the rotor never succeeds in "catching up" to the stator field. The rotor runs slower than the speed of the stator field.

The windings on the rotor of a squirrel cage motor is comprised of aluminum (or sometimes copper) bars embedded in the steel laminations of the rotor. The ends of the rotor bars are shorted together by rings at each end of the rotor. There is no external electrical connection to the rotor. The bar and ring structure looks like an exercise wheel for a pet squirrel.

Slip-ring motor

The slip-ring motor or wound-rotor motor is a variation of the squirrel cage induction motor. While the stator is the same as that of the squirrel cage motor, the rotor of a slip-ring motor is wound with wire coils. The ends of the windings are connected to slip rings so that resistors or other circuitry can be inserted in series with the rotor coils through carbon brushes that slide on the slip-rings allowing an electrical connection with the rotating coils. This basically is the difference in construction between a squirrel cage and slip-ring motors. These are helpful in adding external resistors and contactors. The slip necessary to generate the maximum torque (pull-out torque) is directly proportional to the rotor resistance. In the slip-ring motor, the effective rotor resistance is increased by adding external resistance through the slip rings. Thus, it is possible to get higher slip and hence, the pull-out torque at a lower speed. A particularly high resistance can result in the pull-out torque occurring at almost zero speed, providing a very high pull-out torque at a low starting current. As the motor accelerates, the value of the resistance can be reduced, altering the motor characteristic to suit the load requirement. Once the motor reaches the base speed, external resistors are removed from the rotor. This means that now the motor is working as the standard induction motor.

This motor type is ideal for very high inertia loads, where it is required to generate the pull-out torque at almost zero speed and accelerate to full speed in the minimum time with minimum current draw.

Modifying the speed torque curve by altering the rotor resistors, the speed at which the motor will drive a particular load can be altered. At full load the speed can be reduced effectively to about 50% of the motor synchronous speed, particularly when driving variable torque/variable speed loads, such as printing presses, compressors, conveyer belts, hoists and elevators. Reducing the speed below 50%, results in very low efficiency due to higher power dissipation in the rotor resistances. This type of motor is used in applications for driving variable torque/ variable speed loads.

Direct-Current Motors

Direct-Current motors, as the name implies, use direct-unidirectional, current. Direct current motors are used in special applications- where high torque starting or where smooth acceleration over a broad speed range is required.

Synchronous Motors

AC power is fed to the stator of the synchronous motor. The rotor is fed by DC from a separate source. The rotor magnetic field locks onto the stator rotating magnetic field and rotates at the same speed. The speed of the rotor is a function of the supply frequency and the number of magnetic poles in the stator. While induction motors rotate with a slip, i.e., rpm is less than the synchronous speed, the synchronous motor rotate with no slip, i.e., the RPM is same as the synchronous speed governed by supply frequency and number of poles. The slip energy is provided by the D.C. excitation power.

Permanent Magnet Synchronous Motor (PMSM)

The permanent magnet synchronous motor (PMSM) is an alternative for AC induction motors due to various advantages such as power density, better cooling, smaller size, better efficiency and so on. These PMSM's have rotor structures similar to brushless DC motors which contain permanent magnets. However, their stator structure is similar to Induction Motor wherein the windings are assembled such that they produce a sinusoidal flux density in the air gap of the motor. As a result, these motors perform best when driven by sinusoidal waveforms.

Synchronous Reluctance Motors

A synchronous reluctance motor has the same structure as that of a salient pole synchronous motor except that it does not have a field winding on the rotor. These motors are becoming popular due its superior performance and capable of achieving IE4 efficiency class. Synchronous reluctance Motors Stator is similar to induction motors and permanent magnet synchronous motors (PMSMs) and its rotor is built with simple magnetic materials to take advantage of the reluctance principle. The Synchronous reluctance motor rotor runs at synchronous speed and there are no magnets or current-conducting parts in the rotor. Hence rotor losses are very small compared to those of an induction motor.

2.3 Motor Characteristics

Motor Speed

The speed of a motor is the number of revolutions in a given time frame, typically revolutions per minute (RPM). 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. The synchronous speed in RPM is given by the following equation, where the frequency is in hertz or cycles per second:

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

Indian motors have synchronous speeds like 3000 / 1500 / 1000 / 750 / 600 / 500 / 375 RPM corresponding to no. of poles being 2, 4, 6, 8, 10, 12, 16 (always even) and given the mains frequency of 50 cycles / sec.

The actual speed, with which the motor operates, will be less than the synchronous speed. The difference between synchronous and full load speed is called slip and is measured in percent. It is calculated using this equation:

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

As per relation stated above, the speed of an AC motor is determined by the number of motor poles and by the input frequency. It can also be seen that theoretically speed of an AC motor can be varied infinitely by changing the frequency. Manufacturer's guidelines should be referred for practical limits to speed variation. With the addition of a Variable Frequency Drive (VFD), the speed of the motor can be decreased as well as increased.

Power Factor

The power factor of the motor is given as: Power Factor = Cos $\phi = \frac{kW}{kVA}$

As the load on the motor comes down, the magnitude of the **active current** reduces. However, there is no corresponding reduction in the **magnetizing current,** which is proportional to supply voltage with the result that the motor power factor reduces, with a reduction in applied load. Induction motors, especially those operating below their rated capacity, are the main reason for low power factor in electric systems.

2.4 Motor Efficiency

Two important attributes relating to efficiency of electricity use by A.C. Induction motors are efficiency (η), defined as the ratio of the mechanical energy delivered at the rotating shaft to the electrical energy input at its terminals, and power factor (PF). Motors, like other inductive loads, are characterized by power factors less than one. As a result, the total current draw needed to deliver the same real power is higher than for a load characterized by a higher PF. An important effect of operating with a PF less than one is that resistance losses in wiring upstream of the motor will be higher, since these are proportional to the square of the current. Thus, both a high value for η and a PF close to unity are desired for efficient overall operation in a plant.

Squirrel cage motors are normally more efficient than slip-ring motors, and higher-speed motors are normally more efficient than lower-speed motors. Efficiency is also a function of motor temperature. Totally-enclosed, fan-cooled (TEFC) motors are more efficient than screen-protected, drip-proof (SPDP) motors. Also, as with most equipment, motor efficiency increases with the rated capacity.

The efficiency of a motor is determined by intrinsic losses that can be reduced only by changes in motor design. Intrinsic losses are of two types: **fixed losses**- independent of motor load, and **variable losses** - dependent on load.

Fixed losses consist of magnetic core losses and friction and windage losses. Magnetic core losses (sometimes called iron losses) consist of eddy current and hysteresis losses in the stator. They vary with the core material and geometry and with input voltage.

Friction and windage losses are caused by friction in the bearings of the motor and aerodynamic losses associated with the ventilation fan and other rotating parts.

Variable losses consist of resistance losses in the stator and in the rotor and miscellaneous stray losses. Resistance to current flow in the stator and rotor result in heat generation, that is proportional to the resistance of the material and the square of the current (I^2R). Stray losses arise from a variety of sources and are difficult to either measure directly or to calculate, but are generally proportional to the square of the rotor current.

Part-load performance characteristics of a motor also depend on its design. Both the η and PF fall to very low levels at low loads. The Figures 2.2 shows the effect of load on power factor and efficiency. It can be seen that power factor drops sharply at part loads. The Figure 2.3 shows the effect of speed on power factor.

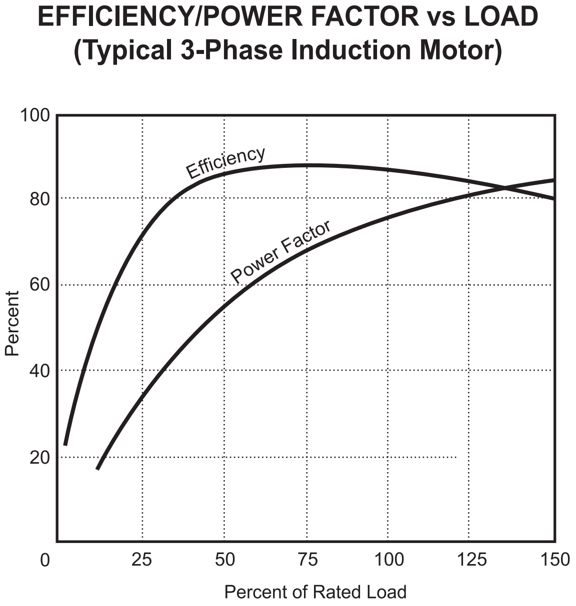

Figure 2.2 % Load vs. Power factor, Efficiency

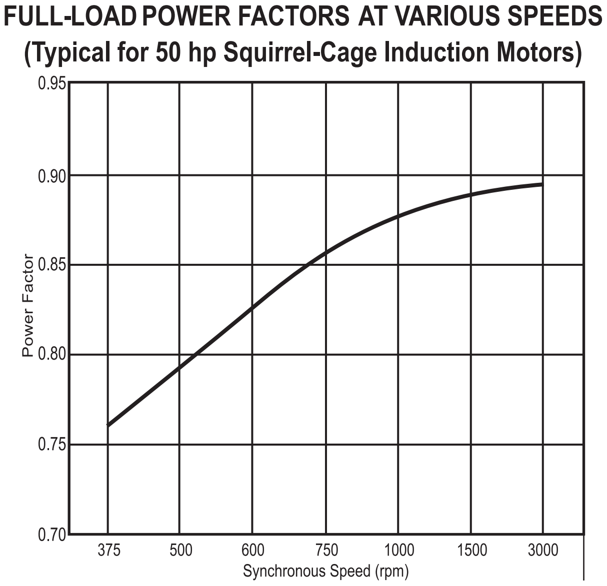

Figure 2.3 Speed vs. Power factor

Field Tests for Determining 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

The various losses in the motor are determined as follows:

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 useful to plot no-load input kW versus Voltage; the intercept is Friction & Windage kW loss component.

F&W and core losses = No load power (Watts) – (No load current)^2 × 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 100^0C to 120^0C and necessary correction should be made. Correction to 75^0C 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, ^oC & t_2 = operating temperature, ^oC.

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

Rotor I^2R losses = Slip × (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 input. The actual value of stray losses is likely to be more. IEEE – 112 specifies values from 0.9 % to 1.8 % (see Table 2.1.)

Table 2.1 Motor Rating Vs. Stray Losses - IEEE

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

Pointers 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 %. In view of this, for selecting high efficiency motors, the following can be done:

a. When purchasing large number of small motors or a large motor, ask for a detailed test certificate. If possible, try to remain present during the tests; this will add cost.

b. See that efficiency values are specified without any tolerance

c. Check the actual input current and kW, if replacement is done

d. For new motors, keep a record of no load input power and current

e. Use values of efficiency for comparison and for confirming; rely on measured inputs for all calculations.

Estimation of efficiency in the field can be done 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:

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 30^0C	=	0.264 Ohms
No load power, P_{nl}	=	1063.74 Watts

a. Calculate iron plus friction and windage losses

b. Calculate stator resistance at 120^0C

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

c. Calculate stator copper losses at operating temperature of resistance at 120^0C

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-30^0C (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 120^0C,

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

$= 0.354$ ohms per phase

c) Stator copper losses at full load, Pst.cu 120^0C

$= 3 \times (57 / \sqrt{3})^2 \times 0.354$
$= 1150.1$ Watts

d) Full load slip

$S = (1500 - 1475) / 1500$
$= 0.0167$

Rotor input, Pr $= P_{output} / (1\text{-}S)$
$= 34000 / (1\text{-}0.0167)$
$= 34577.4$ Watts

e) Motor full load input power, P input

$= P_r + Pst.cu\ 120^0C + (P_i + fw) + P_{stray}$
$= 34577.4 + 1150.1 + 995.3 + (0.005^* \times 34000)$
$= 36892.8$ Watts

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

f) Motor efficiency at full load

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

$$= \frac{34000}{36892.8} \times 100 = 92.2\ \%$$

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

$$= \frac{36892.8}{\sqrt{3} \times 415 \times 57} = 0.90$$

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.

2.5 Motor Selection

The primary technical consideration defining the motor choice for any particular application is the torque required by the load, especially the relationship between the maximum torque generated by the motor (break-down torque) and the torque requirements for start-up (locked rotor torque) and during acceleration periods.

The duty / load cycle determines the thermal loading on the motor. One consideration with totally enclosed fan cooled (TEFC) motors is that the cooling may be insufficient when the motor is operated at speeds below its rated value.

Ambient operating conditions affect motor choice; special motor designs are available for corrosive or dusty atmospheres, high temperatures, restricted physical space, etc.

An estimate of the switching frequency (usually dictated by the process), whether automatic or manually controlled, can help in selecting the appropriate motor for the duty cycle.

The demand a motor will place on the balance of the plant electrical system is another consideration - if the load variations are large, for example as a result of frequent starts and stops of large components like compressors, the resulting large voltage drops could be detrimental to other equipment.

Reliability is of prime importance - in many cases, however, designers and process engineers seeking reliability will grossly oversize equipment, leading to sub-optimal energy performance. Good knowledge of process parameters and a better understanding of the plant power system can aid in reducing over sizing with no loss of reliability.

Inventory is another consideration - Many large industries use standard equipment, which can be easily serviced or replaced, thereby reducing the stock of spare parts that must be maintained and minimizing shut-down time. This practice affects the choice of motors that might provide better energy performance in specific applications. Shorter lead times for securing individual motors from suppliers would help reduce the need for this practice.

Price is another issue - Many users are first-cost sensitive, leading to the purchase of less expensive motors that may be more costly on a lifecycle basis because of lower efficiency. For example, energy efficient motors or other specially designed motors typically save within a few years an amount of money equal to several times the incremental cost for an energy efficient motor, over a standard-efficiency motor. Few of salient selection issues are given below:

- In the selection process, the power drawn at 75 % of loading can be a meaningful indicator of energy efficiency.
- Reactive power drawn (kVAr) by the motor.
- Indian Standard 325 for standard motors allows 15 % tolerance on efficiency for motors upto 50 kW rating and 10 % for motors over 50 kW rating.
- The Indian Standard IS 8789 addresses technical performance of Standard Motors while IS 12615 addresses the efficiency criteria of High Efficiency Motors. Both follow IEC 34-2 test methodology wherein, stray losses are assumed as 0.5 % of input power. By the IEC test method, the losses are understated and if one goes by IEEE test methodology, the motor efficiency values would be further lowered.
- It would be prudent for buyers to procure motors based on test certificates rather than labeled values.
- The energy savings by motor replacement can be worked out by the simple relation : kW savings = kW output × [$1/\eta_{old}$ - $1/\eta_{new}$] where η_{old} and η_{new} are the existing and proposed motor efficiency values.
- The cost benefits can be worked out on the basis of premium required for high efficiency vs. worth of annual savings.

2.6 Energy Efficient Motors

Energy-efficient motors (EEM), are the ones in which, design improvements are incorporated specifically to increase operating efficiency over motors of standard design (see figure 2.4). Design improvements focus on reducing intrinsic motor losses. Improvements include the use of lower-loss silicon steel, a longer core (to increase active material), thicker wires (to reduce resistance), thinner laminations, smaller air gap between stator and rotor, copper instead of aluminum bars in the rotor, superior bearings and a smaller fan, etc.

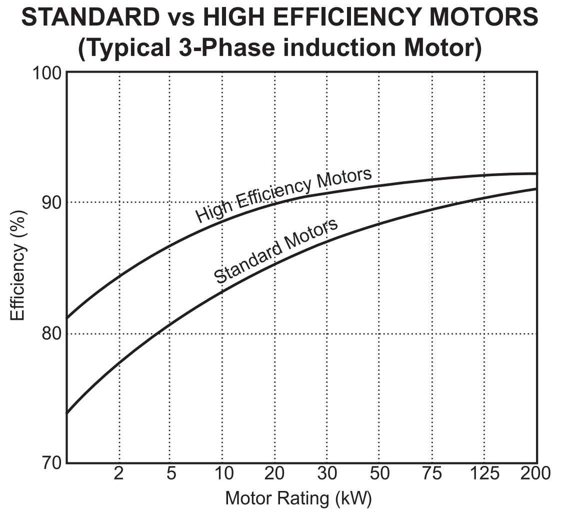

Figure 2.4 Standard vs High Efficiency Motors

Energy-efficient motors now available in India operate with efficiencies that are typically 3 to 4 percentage points higher than standard motors. In keeping with the stipulations of the BIS, energy-efficient motors are designed to operate without loss in efficiency at loads between 75 % and 100 % of rated capacity. This may result in major benefits in varying load applications. The power factor is about the same or may be higher than for standard motors. Furthermore, energy-efficient motors have lower operating temperatures and noise levels, greater ability to accelerate higher-inertia loads, and are less affected by supply voltage fluctuations.

Minimising Watts Loss in Motors

Improvements in motor efficiency can be achieved without compromising motor performance - at higher cost - within the limits of existing design and manufacturing technology.

From the Table 2.2, it can be seen that any improvement in motor efficiency must result from reducing the Watts losses. In terms of the existing state of electric motor technology, a reduction in watts losses can be achieved in various ways.

Table 2.2 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.

Stator and Rotor I^2R Losses

These losses are major losses and typically account for 55% to 60% of the total losses. I^2R losses are heating losses resulting from current passing through stator and rotor conductors. I^2R losses are the function of a conductor resistance, the square of current. Resistance of conductor is a function of conductor material, length and cross sectional area. The suitable selection of copper conductor size will reduce the resistance. Reducing the motor current is most readily accomplished by decreasing the magnetizing component of current. This involves lowering the operating flux density and possible shortening of air gap. Rotor I^2R losses are a function of the rotor conductors (usually aluminium) and the rotor slip. Utilisation of copper conductors will reduce the winding resistance. Motor operation closer to synchronous speed will also reduce rotor I^2R losses.

Core Losses

Core losses are those found in the stator-rotor magnetic steel and are due to hysterisis effect and eddy current effect during 50 Hz magnetization of the core material. These losses are independent of load and account for 20 – 25 % of the total losses.

The hysteresis losses which are a function of flux density, are be reduced by utilizing low-loss grade of silicon steel laminations. The reduction of flux density is achieved by suitable increase in the core length of stator and rotor. Eddy current losses are generated by circulating current within the core steel laminations. These are reduced by using thinner laminations.

Friction and Windage Losses

Friction and windage losses results from bearing friction, windage and circulating air through the motor and account for 8 – 12 % of total losses. These losses are independent of load. The reduction in heat generated by stator and rotor losses permits the use of smaller fan. The windage losses also reduce with the diameter of fan leading to reduction in windage losses.

Stray Load-Losses

These losses vary according to square of the load current and are caused by leakage flux induced by load currents in the laminations and account for 4 to 5 % of total losses. These losses are reduced by careful selection of slot numbers, tooth/slot geometry and air gap.

Energy efficient motors cover a wide range of ratings and the full load efficiencies are higher by 3 to 7 %. The mounting dimensions are also maintained as per IS1231 to enable easy replacement.

As a result of the modifications to improve performance, the costs of energy-efficient motors are higher than those of standard motors. The higher cost will often be paid back rapidly in saved operating costs, particularly in new applications or end-of-life motor replacements. In cases where existing motors have not reached the end of their useful life, the economics will be less clearly positive.

Because the favourable economics of energy-efficient motors are based on savings in operating costs, there may be certain cases which are generally economically ill-suited to energy-efficient motors. These include highly intermittent duty or special torque applications such as hoists and cranes, traction drives, punch presses, machine tools, and centrifuges. In addition, energy, efficient designs of multi-speed motors are generally not available. Furthermore, energy-efficient motors are not yet available for many special applications, e.g. for flame-proof operation in oil-field or fire pumps or for very low speed applications (below 750 rpm). Also, most energy-efficient motors produced today are designed only for continuous duty cycle operation.

Given the tendency of over sizing on the one hand and ground realities like; voltage, frequency variations, efficacy of rewinding in case of a burnout, on the other hand, benefits of EEM's can be achieved only by careful selection, implementation, operation and maintenance efforts of energy managers.

Technical aspects of Energy Efficient Motors

Energy-efficient motors last longer, and may require less maintenance. At lower temperatures, bearing grease lasts longer; required time between re-greasing increases. Lower temperatures translate to long lasting insulation. Generally, motor life doubles for each 10°C reduction in operating temperature.

Select energy-efficient motors with a 1.15 service factor, and design for operation at 85% of the rated motor load.

Electrical power problems, especially poor incoming power quality can affect the operation of energy-efficient motors.

Speed control is crucial in some applications. In polyphase induction motors, slip is a measure of motor winding losses. Lower the slip, higher the efficiency. Less slippage in energy efficient motors results in speeds about 1% faster than in standard counterparts.

Starting torque for efficient motors may be lower than for standard motors. Facility managers should be careful when applying efficient motors to high torque applications.

2.7 Factors Affecting Energy Efficiency & Minimising Motor Losses in Operation

Power Supply Quality

Motor performance is affected considerably by the quality of input power that is the actual volts and frequency available at motor terminals vis-à-vis rated values as well as voltage and frequency variations and voltage unbalance across the three phases. Motors in India must comply with standards set by the Bureau of Indian Standards (BIS) for tolerance to variations in input power 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 %. Fluctuations much larger than these are quite common in utility-supplied electricity in India. Voltage fluctuations can have detrimental impacts on motor performance. The general effects of voltage and frequency variation on motor performance are presented in Table 2.3:

Table 2.3 General Effects of Voltage and Frequency Variation on Induction Motor Characteristics

	Percen-tage	Starting and Max. Running Torque	Syn-chronous Speed %	% Slip	Full-load Speed %	Efficiency			Power Factor			Full-load Current %	Starting Current %	Max. Overload Capacity %
						100 % Load	75 % Load	50 % Load	100 % Load	75 % Load	50 % Load			
Voltage	120	↑ 44	None	↓ 30	↑ 1.5	Small incr.	↓ 5 to 2 pts.	↓ 7 to 20 pts	↓ 5 to 15 pts	↓ 10 to 30 pts	↓ 15 to 40 pts	↓ 11	↑ 25	↑ 44
	110	↑ 21	None	↓ 17	↑ 1	↑ .5 to 1 pt.	Almost none	↓ 1 to 2 pts	↓ 3 pts	↓ 4 pts	↓ 5 to 6 pts	↓ 7	↑ 10 to 12	↑ 21
	90	↓ 19	None	↑ 23	↓ 1.5	↓ 2 pts.	Almost none	↑ 1 to 2 pts	↑ 1 pt	↑ 2 to 3 pts	↑ 4 to 5 pts	↑11	↓ 10 to 12	↓ 19
	Function of	$(volt)^2$	Const.	$(volt)^2$	(Synch. speed slip)								(volt.)	$(volt.)^2$
Frequency	105	↓ 10	↑ 5	Almost none	↑ 5	------------ slight increase each load ------------						Slight	↓ 5 to 6	Slight ↓
	95	↑ 11	↓ 5	Almost non	↓ 5	------------ slight decrease each load ------------						Slight ↑	↑ 5 to 6	Slight ↑
	Function of	$(freq.)^2$	(freq.)		(synch. Speed slip)								$(freq.)^{-1}$	

Note : pts. Indicate the change in value and not as percentage, for example, 2 pts reduction from 75% efficiency means the new efficiency will be 73% .

The options available for an energy manager to ensure near to rated voltage at motor terminals include:

i) Load end power factor improvement by providing matching PF capacitors
ii) Minimizing line / cable voltage drops from sub-station to motor terminals
iii) Transformer tap changing as required in case of consistent and continuous low voltage situations.

Voltage Unbalance

Voltage unbalance, the condition where the voltages in the three phases are not equal, can be still more detrimental to motor performance and motor life. Unbalance typically occurs as a result of supplying single-phase loads disproportionately from one of the phases. It can also result from the use of different sizes of cables in the distribution system. An example of the effect of voltage unbalance on motor performance is shown in Table 2.4.

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 (National Electrical Manufacturers Association of USA) standard definition of voltage unbalance is given by the following equation:

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

As an example, consider a three-phase supply system (in volts):

The line-line voltages are:

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

% 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%.

Common Causes of Voltage Unbalance

It is recommended that the voltage unbalance at the motor terminals not exceed 1% , anything above this will lead to derating of the motor. The common causes of voltage unbalance are

Some of the more common causes of unbalanced voltages are:

- Unbalanced incoming utility supply
- Unequal transformer tap settings
- Large single phase distribution transformer on the system
- Open phase on the primary of a 3 phase transformer on the distribution system
- Faults or grounds in the power transformer

- Open delta connected transformer banks
- A blown fuse on a 3 phase bank of power factor improvement capacitors
- Unequal impedance in conductors of power supply wiring
- Unbalanced distribution of single phase loads such as lighting
- Heavy reactive single phase loads such as welders

Voltage unbalance is probably the leading power factor problem that results in motor over heating and premature motor failure.

Voltage unbalance causes extremely high current imbalance. The magnitude of current imbalance may be 6 to 10 times as large as the voltage imbalance. A motor will run hotter when operating on a power supply with voltage unbalance. The additional temperature rise is estimated with the following equation

$$\text{Additional temperature rise} = 2 \text{ x } (\% \text{ Voltage unbalance})^2$$

For example, if the voltage unbalance is 2% for a motor operating at 100 ^{o}C, the additional temperature rise will be 8 ^{o}C. The winding insulation life is reduced by one half for each 10 ^{o}C increase in operating temperature.

Motor Loading

Measuring Load

% Loading of the motor can be estimated by the following relation:

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

(or)

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

- Never assume power factor
- Loading should not be estimated as the ratio of currents.

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

Motor Load Survey: Methodology

Large industries have a massive population of LT motors. Load survey of LT motors can be taken-up methodically to identify improvement options as illustrated in following case study.

i) Sampling Criteria

Towards the objective of selecting representative LT motor drives among the motor population, for analysis, the criteria considered are:

- Utilization factor i.e., hours of operation with preference given to continuously operated drive motors.
- Sample representative basis, where one drive motor analysis can be reasoned as representative for the population. Ex : Cooling Tower Fans, Air Washer Units, etc.
- Conservation potential basis, where drive motors with inefficient capacity controls on the machine side, fluctuating load drive systems, etc., are looked into.

ii) Measurements

Studies on selected LT motors involve measurement of electrical load parameters namely volts, amperes, power factor, kW drawn.

Observations on machine side parameters such as speed, load, pressure, temperature, etc., (as relevant) are also taken. Availability of online instruments for routine measurements, availability of tail-end capacitors for PF correction, energy meters for monitoring is also looked into for each case.

iii) Analysis

Analysis of observations on representative LT motors and connected drives is carried out towards following outputs:

- Motor load on kW basis and estimated energy consumption.
- Scope for improving monitoring systems to enable sustenance of a regular in-house Energy Audit function.
- Scope areas for energy conservation with related cost benefits and source information.

The observations are to 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.

The findings / recommendations may include:

- Identified motors with less than 50 % loading, 50 – 75 % loading, 75 – 100 % loading, over 100 % loading.
- Identified motors with low voltage / power factor / voltage imbalance for needed improvement measures.
- Identified motors with machine side losses / inefficiencies like idle operations, throttling / damper operations for avenues like automatic controls / interlocks, variable speed drives, etc.

Motor load survey is aimed not only as a measure to identify motor efficiency areas but equally importantly, as a means to check combined efficiency of the motor, driven machine and controller if any. The margins in motor efficiency may be less than 10 % of consumption often, but the load survey would help to bring out savings in driven machines / systems, which can give 30 – 40 % energy savings.

Reducing Under-loading

Probably the most common practice contributing to sub-optimal motor efficiency is that of under-loading. Under-loading results in lower efficiency and power factor, and higher-than-necessary first cost for the motor and related control equipment. Under-loading is common for several reasons. Original equipment manufacturers tend to use a large safety factor in motors they select. Under-loading of the motor may also occur from under-utilisation of the equipment. For example, machine tool equipment manufacturers provide for a motor rated for the full capacity load of the equipment ex. depth of cut in a lathe machine. The user may need this full capacity rarely, resulting in under-loaded operation most of the time. Another common reason for under-loading is selection of a larger motor to enable the output to be maintained at the desired level even when input voltages are abnormally low. Finally, under-loading also results from selecting a large motor for an application requiring high starting torque where a special motor, designed for high torque, would have been suitable.

A careful evaluation of the load would determine the capacity of the motor that should be selected. Another aspect to consider is the incremental gain in efficiency achievable by changing the motor. Larger motors have inherently higher rated efficiencies than smaller motors. Therefore, the replacement of motors operating at 60 – 70 % of capacity or higher is generally not recommended. However, there are no rigid rules governing motor selection; the savings potential needs to be evaluated on a case-to-case basis. When downsizing, it may be preferable to select an energy-efficient motor, the efficiency of which may be higher than that of a standard motor of higher capacity.

Improving the Motor Loading by Operating in Star Mode

For motors, which consistently operate at loads below 40 % of rated capacity, an inexpensive and effective measure might be to operate in star mode. A change from the standard delta operation to permanent star operation involves re-configuring the wiring at terminal box and resetting of the over current relay.

Operating in the star mode leads to a voltage reduction by a factor of '$\sqrt{3}$'. Motor is electrically downsized by 1/3rd in star mode operation, but performance characteristics as a function of load remain unchanged. For example if a motor is rated for 15 kW in delta mode, its derated capacity is 5kW in star mode. Thus, full-load operation in star mode gives higher efficiency and power factor than partial load operation in the delta mode. However, motor operation in the star mode is possible only for applications where the torque-to-speed requirement is lower at reduced load.

As speed of the motor reduces in star mode this option may be avoided in case the motor is connected to a production facility whose output is related to the motor speed. Further in star mode the motor loading should not be allowed to cross derated capacity. For example in above case of 15 kW delta connected electric motor, should not be loaded above 5 kW when delta to star switchover takes place.

For applications with high initial torque and low running torque needs, automatic Star-Del-Star converters are also available, which help in load following de-rating of electric motors after initial start-up.

Sizing to Variable Load

Industrial motors frequently operate under varying load conditions due to process requirements. A common practice in cases where such variable-loads are found is to select a motor based on the highest anticipated load. In many instances, an alternative approach is typically less costly, more efficient, and provides equally satisfactory operation. With this approach, the optimum rating for the motor is selected on the basis of the load duration curve for the particular application. Thus, rather than selecting a motor of high rating that would operate at full capacity for only a short period, a motor would be selected with a rating slightly lower than the peak anticipated load and would operate at overload for a short period of time. Since operating within the thermal capacity of the motor insulation is of greatest concern in a motor operating at higher than its rated load, the motor rating is selected as that which would result in the same temperature rise under continuous full-load operation as the weighted average temperature rise over the actual operating cycle. Under extreme load changes, e.g. frequent starts / stops, or high inertial loads, this method of calculating the motor rating is unsuitable since it would underestimate the heating that would occur.

Where loads vary substantially with time, in addition to proper motor sizing, the control strategy employed can have a significant impact on motor electricity use. Traditionally, mechanical means (e.g. throttle valves in piping systems) have been used when lower output is required. More efficient speed control mechanisms include multi-speed motors, eddy-current couplings, fluid couplings, and solid-state electronic variable speed drives.

Power Factor Correction

As noted earlier, induction motors are characterized by power factors less than unity, leading to lower overall efficiency (and higher overall operating cost) associated with a plant's electrical system. Capacitors connected in parallel (shunted) with the motor are typically used to improve the power factor. The impacts of PF correction include reduced kVA demand (and hence reduced utility demand charges), reduced I^2R losses in cables upstream of the capacitor (and hence reduced energy charges), reduced voltage drop in the cables (leading to improved voltage regulation), and an increase in the overall efficiency of the plant electrical system.

It should be noted that PF capacitor improves power factor from the point of installation back to the generating side. It means that, if a PF capacitor is installed at the starter terminals of the motor, it won't improve the operating PF of the motor, but the PF from starter terminals to the power generating side will improve, i.e., the benefits of PF would be only on upstream side.

The size of capacitor required for a particular motor depends upon the no-load reactive kVA (kVAR) drawn by the motor, which can be determined only from no-load testing of the motor. In general, the capacitor is then selected to not exceed 90 % of the no-load kVAR of the motor. (Higher capacitors could result in over-voltages and motor burn-outs). Alternatively, typical power factors of standard motors can provide the basis for conservative estimates of capacitor ratings to use for different size motors. The capacitor rating for power connection by direct connection to induction motors is shown in Table 2.5.

Table 2.5 Capacitor Ratings for Power Factor Correction by Direct Connection to Induction Motors						
Motor Rating (HP)	Capacitor rating (kVAr) for Motor Speed					
	3000	1500	1000	750	600	500
5	2	2	2	3	3	3
7.5	2	2	3	3	4	4
10	3	3	4	5	5	6
15	3	4	5	7	7	7
20	5	6	7	8	9	10
25	6	7	8	9	9	12
30	7	8	9	10	10	15
40	9	10	12	15	16	20
50	10	12	15	18	20	22
60	12	14	15	20	22	25
75	15	16	20	22	25	30
100	20	22	25	26	32	35
125	25	26	30	32	35	40
150	30	32	35	40	45	50
200	40	45	45	50	55	60
250	45	50	50	60	65	70

From the above table, it may be noted that required capacitive kVAr increases with decrease in speed of the motor, as the magnetizing current requirement of a low speed motor is more in comparison to the high speed motor for the same HP of the motor. Since a reductions in line current, and associated energy efficiency gains, are reflected backwards from the point of application of the capacitor, the maximum improvement in overall system efficiency is achieved when the capacitor is connected across the motor terminals, as compared to somewhere further upstream in the plant's electrical system. However, economies of scale associated with the cost of capacitors and the labor required to install them will place an economic limit on the lowest desirable capacitor size.

Maintenance

Inadequate maintenance of motors can significantly increase losses and lead to unreliable operation. For example, improper lubrication can cause increased friction in both the motor and associated drive transmission equipment. Resistance losses in the motor, which rise with temperature, would increase. Providing adequate ventilation and keeping motor cooling ducts clean can help dissipate heat to reduce excessive losses. The life of the insulation in the motor would also be longer : for every 10^0C increase in motor operating temperature over the recommended peak, the time before rewinding would be needed is estimated to be halved.

A checklist of good maintenance practices to help insure proper motor operation would include:

- Inspecting motors regularly for wear in bearings and housings (to reduce frictional losses) and for dirt/dust in motor ventilating ducts (to ensure proper heat dissipation).

- Checking load conditions to ensure that the motor is not over or under loaded. A change in motor load from the last test indicates a change in the driven load, the cause of which should be understood.
- Lubricating appropriately. Manufacturers generally give recommendations for how and when to lubricate their motors. Inadequate lubrication can cause problems, as noted above. Over-lubrication can also create problems, e.g. excess oil or grease from the motor bearings can enter the motor and saturate the motor insulation, causing premature failure or creating a fire risk.
- Checking periodically for proper alignment of the motor and the driven equipment. Improper alignment can cause shafts and bearings to wear quickly, resulting in damage to both the motor and the driven equipment.
- Ensuring that supply wiring and terminal box are properly sized and installed. Inspect regularly the connections at the motor and starter to be sure that they are clean and tight.

Age

Most motor cores in India are manufactured from silicon steel or de-carbonized cold-rolled steel, the electrical properties of which do not change measurably with age. However, poor maintenance (inadequate lubrication of bearings, insufficient cleaning of air cooling passages, etc.) can cause a deterioration in motor efficiency over time. Ambient conditions can also have a detrimental effect on motor performance. For example, excessively high temperatures, high dust loading, corrosive atmosphere, and humidity can impair insulation properties; mechanical stresses due to load cycling can lead to misalignment. However, with adequate care, motor performance can be maintained.

2.8 Rewinding Effects on Energy Efficiency

It is common practice in industry to rewind burnt-out motors. The population of rewound motors in some industries exceeds 50 % of the total population. Careful rewinding can sometimes maintain motor efficiency at previous levels, but in most cases, losses in efficiency result. Rewinding can affect a number of factors that contribute to deteriorated motor efficiency: winding and slot design, winding material, insulation performance, and operating temperature. For example, a common problem occurs when heat is applied to strip old windings: the insulation between laminations can be damaged, thereby increasing eddy current losses. A change in the air gap may affect power factor and output torque.

However, if proper measures are taken, motor efficiency can be maintained, and in some cases increased, after rewinding. Efficiency can be improved by changing the winding design, though the power factor could be affected in the process. Using wires of greater cross section, slot size permitting, would reduce stator losses thereby increasing efficiency. However, it is generally recommended that the original design of the motor be preserved during the rewind, unless there are specific, load-related reasons for redesign.

The impact of rewinding on motor efficiency and power factor can be easily assessed if the no-load losses of a motor are known before and after rewinding. Maintaining documentation of no-load losses and no-load speed from the time of purchase of each motor can facilitate assessing this impact. For example, comparison 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 can be one of the indicators to assess the efficacy of rewinding.

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.

The monitoring format for rewound motor is given Table 2.6 below:

Table 2.6 Monitoring Format for Rewound Motors

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

2.9 Speed Control of Motors

Traditionally, DC motors have been employed when variable speed capability was desired. By controlling the armature (rotor) voltage and field current of a separately excited DC motor, a wide range of output speeds can be obtained. DC motors are available in a wide range of sizes, but their use is generally restricted to a few low speed, low-to-medium power applications like machine tools and rolling mills because of problems with mechanical commutation at large sizes. Also, they are restricted for use only in clean, non-hazardous areas because of the risk of sparking at the brushes. DC motors are also expensive relative to AC motors.

Because of the limitations of DC systems, AC motors are increasingly the focus for variable speed applications. Both AC synchronous and induction motors are suitable for variable speed control. Induction motors are generally more popular, however, because of their ruggedness and lower maintenance requirements. AC induction motors are inexpensive (half or less of the cost of a DC motor) and also provide a high power to weight ratio (about twice that of a DC motor).

An induction motor is an asynchronous motor, the speed of which can be varied by changing the supply frequency. The control strategy to be adopted in any particular case will depend on a number of factors including investment cost, load reliability and any special control requirements. Thus, for any particular application, a detailed review of the load characteristics, historical data on process flows, the features required of the speed control system, the electricity tariffs and the investment costs would be a prerequisite to the selection of a speed control system.

The characteristics of the load are particularly important. Load refers essentially to the torque output and corresponding speed required. Loads can be broadly classified as either constant power or constant torque. Constant torque loads are those for which the output power requirement may vary with the speed of operation but the torque does not vary. Conveyors, rotary kilns, and constant-displacement pumps are typical examples of constant torque loads. Variable torque loads are those for which the torque required varies with the speed of operation. Centrifugal pumps and fans are typical examples of variable torque loads (torque varies as the square of the speed). Constant power loads are those for which the torque requirements typically change inversely with speed. Machine tools are a typical example of a constant power load.

The largest potential for electricity savings with variable speed drives is generally in variable torque applications, for example centrifugal pumps and fans, where the power requirement changes as the cube of speed. Constant torque loads are also suitable for VSD application.

Motor Speed Control Systems

Multi-speed motors

Motors can be wound such that two speeds, in the ratio of 2:1, can be obtained. Motors can also be wound with two separate windings, each giving 2 operating speeds, for a total of four speeds. Multi-speed motors can be designed for applications involving constant torque, variable torque, or for constant output power. Multi-speed motors are suitable for applications, which require limited speed control (two or four fixed speeds instead of continuously variable speed), in which cases they tend to be very economical. They have lower efficiency than single-speed motors

Direct Current Drives (DC)

The DC drive technology is the oldest form of electrical speed control. The drive system consists of a DC motor and a controller. The motor is constructed with armature and field windings. Both of these windings require a DC excitation for motor operation. Usually the field winding is excited with a constant level voltage from the controller.

Then, applying a DC voltage from the controller to the armature of the motor will operate the motor. The armature connections are made through a brush and commutator assembly. The speed of the motor is directly proportional to the applied voltage.

The controller is a phase controlled bridge rectifier with logic circuits to control the DC voltage delivered to the motor armature. Speed control is achieved by regulating the armature voltage to the motor. Often a tachogenerator is included to achieve good speed regulation. The tachogenerator would be mounted on the motor and produces a speed feedback signal that is used within the controller.

Wound Rotor AC Motor Drives (Slip Ring Induction Motors)

Wound rotor motor drives use a specially constructed motor to accomplish speed control. The motor rotor is constructed with windings which are brought out of the motor through slip rings on the motor shaft. These windings are connected to a controller which places variable resistors in series with the windings. The torque performance of the motor can be controlled using these variable resistors. Wound rotor motors are most common in the range of 300 HP and above.

Slip Power Recovery Systems

Slip power recovery is a more efficient alternative speed control mechanism for use with slip-ring motors. In essence, a slip power recovery system varies the rotor voltage to control speed, but instead of dissipating power through resistors, the excess power is collected from the slip rings and returned as mechanical power to the shaft or as electrical power back to the supply line. Because of the relatively sophisticated equipment needed, slip power recovery tends to be economical only in relatively high power applications and where the motor speed range is 1:5 or less.

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.

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.

Need for VFD

Earlier motors tended to be over designed to drive a specific load over its entire range. This resulted in a highly inefficient driving system, as a significant part of the input power was not doing any useful work. Most of the time, the generated motor torque was more than the required load torque.

In many applications, the input power is a function of the speed like fan, blower, pump and so on. In these types of loads, the torque is proportional to the square of the speed and the power is proportional to the cube of speed. Variable speed, depending upon the load requirement, provides significant energy saving. A reduction of 20% in the operating speed of the motor from its rated speed will result in an almost 50% reduction in the input power to the motor. This is not possible in a system where the motor is directly connected to the supply line. In many flow control applications, a mechanical throttling device is used to limit the flow. Although this is an effective means of control, it wastes energy because of the high losses and reduces the life of the motor valve due to generated heat.

Principles of VFD's

The VFD is a system made up of active/passive power electronics devices (IGBT, MOSFET, etc.), a high speed central controlling unit and optional sensing devices, depending upon the application requirement. A typical modern-age intelligent VFD for the three phase induction motor is shown in Figure 2.5.

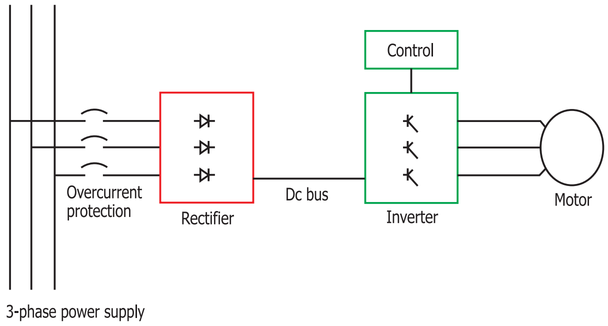

Figure 2.5 Components of a Variable Speed Drive

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. The inverter, under the control of the microcontroller, synthesizes the DC into three-phase variable voltage, variable frequency AC.

The base speed of the motor is proportional to supply frequency and is inversely proportional to the number of stator poles. The number of poles cannot be changed once the motor is constructed. So, by changing the supply frequency, the motor speed can be changed. But when the supply frequency is reduced, the equivalent impedance of electric circuit reduces. This results in higher current drawn by the motor and a higher flux. If the supply voltage is not reduced, the magnetic field may reach the saturation level. Therefore, in order to keep the magnetic flux within working range, both the supply voltage and the frequency are changed in a constant ratio. Since the torque produced by the motor is proportional to the magnetic field in the air gap, the torque remains more or less constant throughout the operating range.

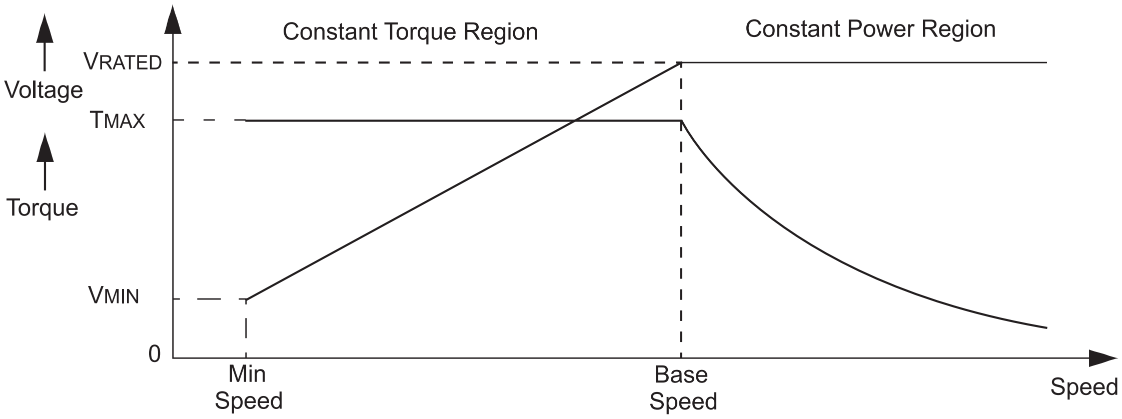

Figure 2. 6 V/f Control

As seen in Figure 2.6, the voltage and the frequency are varied at a constant ratio up to the base speed. The flux and the torque remain almost constant up to the base speed. Beyond the base speed, the supply voltage cannot be increased. Increasing the frequency beyond the base speed results in the field weakening and the torque reduces. Above the base speed, the torque governing factors become more nonlinear as the friction and windage losses increase significantly. Due to this, the torque curve becomes nonlinear. Based on the motor type, the field weakening can go up to twice the base speed. This control is the most popular in industries and is popularly known as the constant V/f control.

By selecting the proper V/f ratio for a motor, the starting current can be kept well under control. This avoids any sag in the supply line, as well as heating of the motor. The VFD also provides overcurrent protection. This feature is very useful while controlling the motor with higher inertia. Since almost constant rated torque is available over the entire operating range, the speed range of the motor becomes wider. User can set the speed as per the load requirement, thereby achieving higher energy efficiency (especially with the load where power is proportional to the cube speed). Continuous operation over almost the entire range is smooth, except at very low speed. This restriction comes mainly due to the inherent losses in the motor, like frictional, windage, iron, etc. These losses are almost constant over the entire speed. Therefore, to start the motor, sufficient power must be supplied to overcome these losses and the minimum torque has to be developed to overcome the load inertia.

A single VFD has the capability to control multiple motors. The VFD is adaptable to almost any operating condition.

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).

Driven Load Types and Characteristics

Mechanical load, which is the load on the motor shaft, can be of two types- Constant Torque (CT) or Variable Torque (VT). There is a basic difference between the two loads with respect to load torque variation at different speeds.

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

This means that the load torque remains approximately the same at all speeds. Examples of CT loads include material handling conveyers, reciprocating & screw compressors and certain types of blowers such as roots blower.

A VT load implies that the load torque seen at the motor shaft is dependent upon the motor speed.

Examples of VT loads include centrifugal fans & pumps and centrifugal compressors.

The graphs (Figures 2.7 & 2.8) below describe the torque requirements at various speeds.

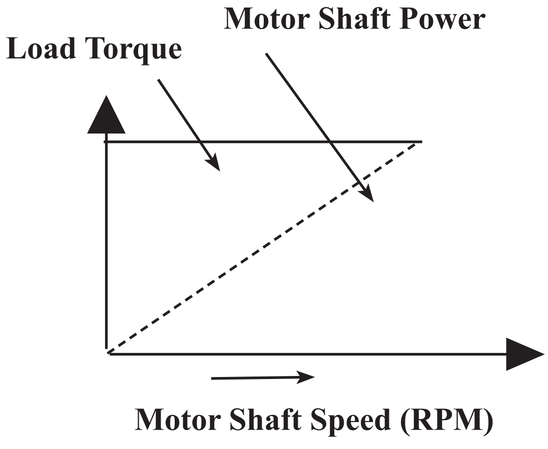

Figure 2.7 A CT load characteristic

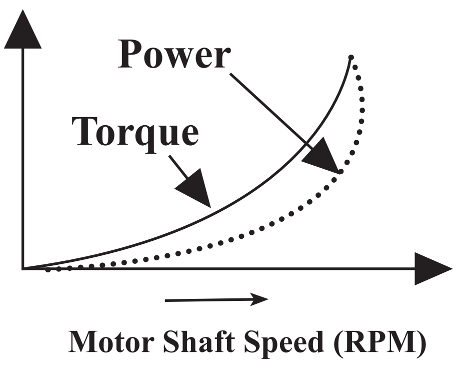

Figure 2.8 A VT load characteristic

Other methods of speed control of motors

In addition to DC drives, VFD and slip ring motors there are other methods used in industries to control the speed of the motors. Some of the common methods used in industries are discussed below:

Eddy Current Drives

This method employs an eddy-current clutch to vary the output speed. The clutch consists of a primary member coupled to the shaft of the motor and a freely revolving secondary member coupled to the load shaft. The secondary member is separately excited using a DC field winding. The motor starts with the load at rest and a DC excitation is provided to the secondary member, which induces eddy-currents in the primary member. The interaction of the fluxes produced by the two currents gives rise to a torque at the load shaft. By varying the DC excitation the output speed can be varied to match the load requirements. The major disadvantage of this system is relatively poor efficiency particularly at low speeds. (See Figure 2.9)

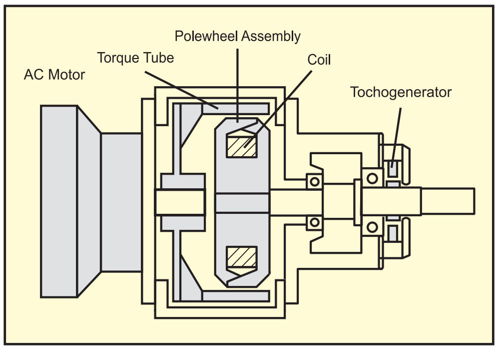

Figure 2.9 Eddy Current Drive

Fluid Coupling

Fluid coupling is one way of applying varying speeds to the driven equipment, without changing the speed of the motor.

Construction

Fluid couplings (see Figure 2.10) work on the hydrodynamic principle. Inside every fluid coupling are two basic elements – the impeller and the runner and together they constitute the working circuit. One can imagine the impeller as a centrifugal pump and the runner as a turbine. The impeller and the rotor are bowl shaped and have large number of radial vanes. They are suitably enclosed in a casing, facing each other with an air gap. The impeller is connected to the prime mover while the rotor has a shaft bolted to it. This shaft is further connected to the driven equipment through a suitable arrangement.

Thin mineral oil of low viscosity and good-lubricating qualities is filled in the fluid coupling from the filling plug provided on its body. A fusible plug is provided on the fluid coupling which blows off and drains out oil from the coupling in case of sustained overloading.

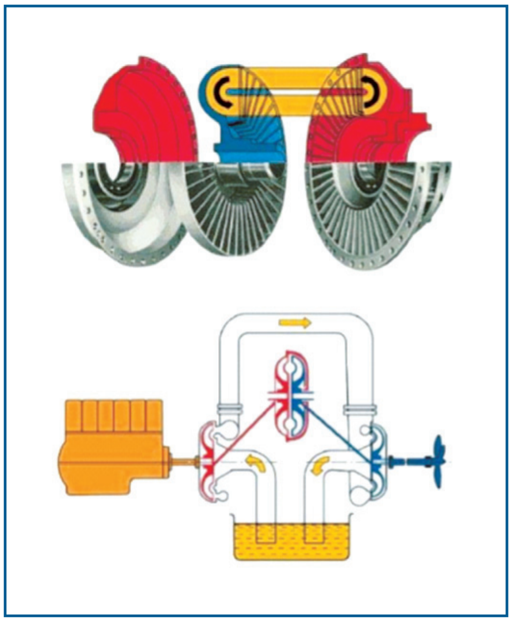

Figure 2.10 Fluid Coupling

Operating Principle

There is no mechanical inter-connection between the impeller and the rotor and the power is transmitted by virtue of the fluid filled in the coupling. When the impeller is rotated by the prime mover, the fluid flows out radially and then axially under the action of centrifugal force. It then crosses the air gap to the runner and is directed towards the bowl axis and back to the impeller. To enable the fluid to flow from impeller to rotor it is essential that there is difference in head between the two and thus it is essential that there is difference in RPM known as slip between the two. Slip is an important and inherent characteristic of a fluid coupling resulting in several desired advantages. As the slip increases, more and more fluid can be transferred. However when the rotor is at a stand still, maximum fluid is transmitted from impeller to rotor and maximum torque is transmitted from the coupling. This maximum torque is the limiting torque. The fluid coupling also acts as a torque limiter.

Characteristics

Fluid coupling has a centrifugal characteristic during starting thus enabling no-load start up of prime mover, which is of great importance. The slipping characteristic of fluid coupling provides a wide range of choice of power transmission characteristics. By varying the quantity of oil filled in the fluid coupling, the normal torque transmitting capacity can be varied. The maximum torque or limiting torque of the fluid coupling can also be set to a pre-determined safe value by adjusting the oil filling. The fluid coupling has the same characteristics in both directions of rotation.

Soft Starter

When starting, AC Induction motor develops more torque than is required at full speed. This stress is transferred to the mechanical transmission system resulting in excessive wear and premature failure of chains, belts, gears, mechanical seals, etc. Additionally, rapid acceleration also has a massive impact on electricity supply charges with high inrush currents drawing +600% of the normal run current.

Figure 2.11 Soft Starter

The use of Star Delta only provides a partial solution to the problem. Should the motor slow down during the transition period, the high peaks can be repeated and can even exceed direct on line current.

Soft starter (see Figure 2.11) provides a reliable and economical solution to these 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.

Soft Start & Soft Stop is built into 3 phase units, providing controlled starting and stopping with a selection of ramp times and current limit settings to suit all applications (see Figure 2.12).

Advantages of Soft Start

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

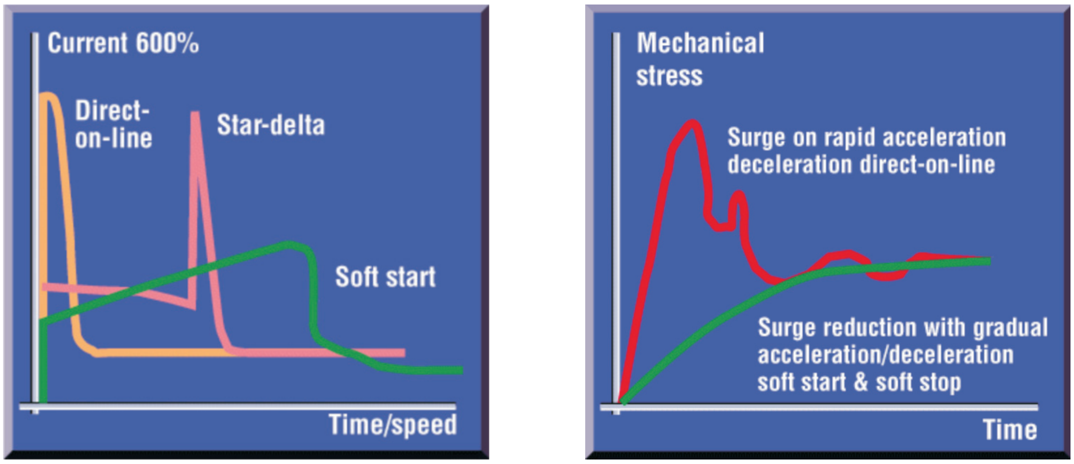

Figure 2.12 Soft Starter: Starting current, Stress profile during starting

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.

In particular, 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 (++))
3. Some of the requirements for energy label validity.
4. The performance criteria for energy labeling validity.
5. Test report format.
6. Label design and details to be incorporated on the label.