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 (State Electricity Boards) 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 curves. A typical hourly load curve for an engineering industry is shown in Figure 1.5. 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.

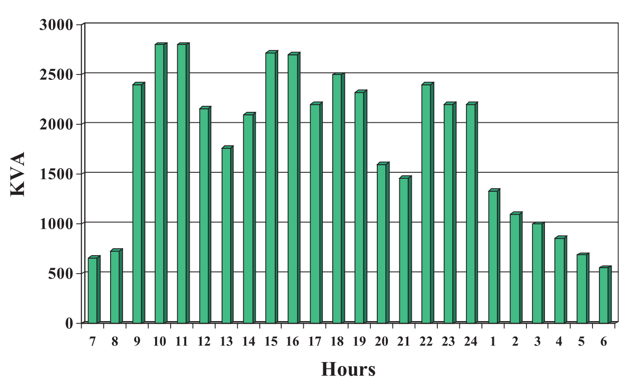


Figure 1.5 Maximum Demand (Daily Load Curve, Hourly kVA)

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 systems, 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

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 1.6).

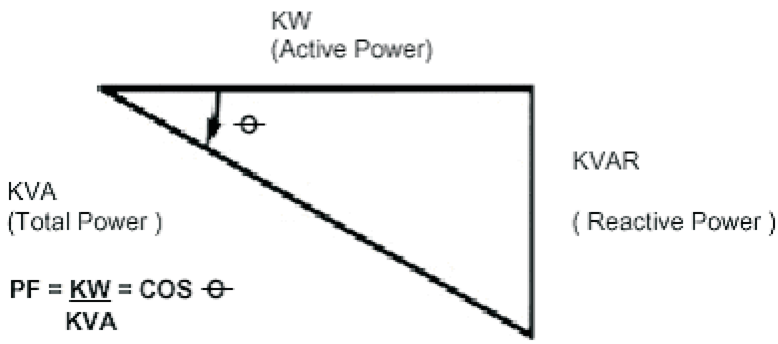


Figure 1.6 kW, kVAr and kVA Vector

The active power (shaft power required or true power required) in kW and the reactive power required (kVAr) are 90° 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 1.7) 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 1.7 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 1.8).

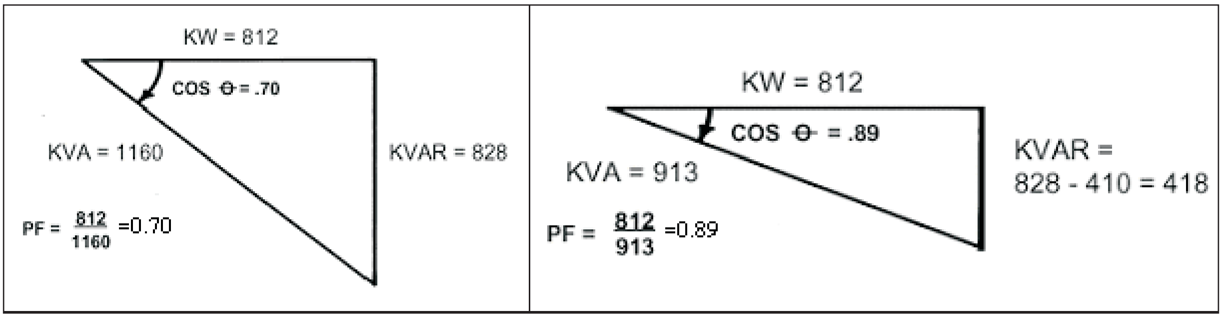


Figure 1.8 Power factor before and after Improvement

After improvement the plant had avoided penalty and the 1500 kVA transformer now loaded only to 60% of capacity. This will allow the addition of more load 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 upto the capacitors reduces giving capacity relief. A high power factor can help in utilising the full capacity of your 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.

Selection and location of capacitors

Direct relation for capacitor sizing.

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

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 .95 ?

Using formula

$$Cos\ \Phi 1 = 0.72\ ,\ tan\ \Phi 1 = 0.963$$
$$Cos\ \Phi 2 = 0.95\ ,\ tan\ \Phi 2 = 0.329$$

$$\textbf{kVAr required} = P\ (\tan\phi_1 - \tan\phi_2) = 627\ (0.964 - 0.329)$$
$$= 398\ kVAr$$

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%.

Location of Capacitors

The primary purpose of capacitors is to reduce the maximum demand. Additional benefits are derived by capacitor location. The Figure 1.9 indicates typical capacitor locations. Maximum benefit of capacitors is derived by locating them as close as possible to the load. At this location, its kVAr 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.

Locations C1A, C1B and C1C of Figure 1.9 indicate three different arrangements at the load. Note that in all three locations extra switches are not required, since the capacitor is either switched with the motor starter or the breaker before the starter. Case C1A is recommended for new installation, since the maximum benefit is derived and the size of the motor thermal protector is reduced. In Case C1B, as in Case C1A, the capacitor is energized only when the motor is in opera-

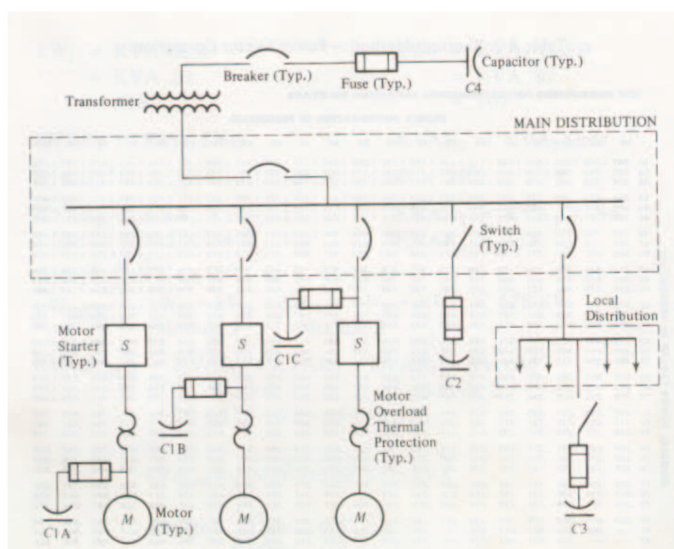


Figure 1.9: Power Distribution Diagram Illustrating Capacitor Locations

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	0.966	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	0.263	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	0.466	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	0.126	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

tion. Case C1B is recommended in cases where the installation already exists and the thermal protector does not need to be re-sized. In position C1C, the capacitor is permanently connected to the circuit but does not require a separate switch, since capacitor can be disconnected by the breaker before the starter.

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.

The next preference for capacitor locations as illustrated by Figure 1.9 is at locations C2 and C3. In these locations, a breaker or switch will be required. Location C4 requires a high voltage breaker. The advantage of locating capacitors at power centres 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 total power regardless of load.

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 PF1 to a new power factor PF2, will be proportional to

$$\left[1 - \left(PF_1 / PF_2\right)^2\right] x100$$

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

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 1.10).

Figure 1.10 View of a Transformer

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 number of turns on the secondary to the turns on the primary (See Figure 1.11).

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)

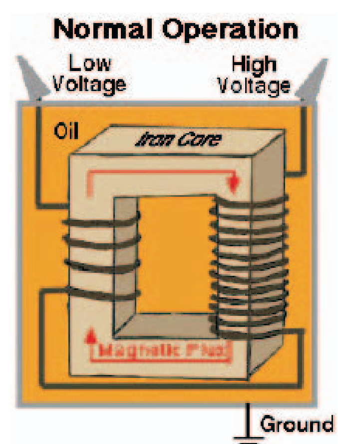


Figure 1.11 Transformer Coil

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

1.7 Harmonics

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.

However in real life situation, various devices like diodes, silicon controlled rectifiers, PWM systems, thyristors, voltage & current chopping saturated core reactors, induction & arc furnaces are also deployed for various requirements and due to their varying impedance characteristic, these NON LINEAR devices cause distortion in voltage and current waveforms which is of increasing concern in recent times. Harmonics occurs as spikes at intervals which are multiples of the mains (supply) frequency and these distort the pure sine wave form of the supply voltage & current.

Harmonics are multiples of the fundamental frequency of an electrical power system. If, for example, the fundamental frequency is 50 Hz, then the 5th harmonic is five times that frequency, or 250 Hz. Likewise, the 7th harmonic is seven times the fundamental or 350 Hz, and so on for higher order harmonics.

Harmonics can be discussed in terms of current or voltage. 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…

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

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.

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

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

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

Major Causes Of Harmonics

Devices that draw non-sinusoidal currents when a sinusoidal voltage is applied create harmonics. Frequently these are devices that convert AC to DC. Some of these devices are listed below:

Electronic Switching Power Converters

- Computers, Uninterruptible power supplies (UPS), Solid-state rectifiers
- Electronic process control equipment, PLC's, etc
- Electronic lighting ballasts, including light dimmer
- Reduced voltage motor controllers

Arcing Devices

- Discharge lighting, e.g. Fluorescent, Sodium and Mercury vapor
- Arc furnaces, Welding equipment, Electrical traction system

Ferromagnetic Devices

- Transformers operating near saturation level
- Magnetic ballasts (Saturated Iron core)
- Induction heating equipment, Chokes, Motors

Appliances

- TV sets, air conditioners, washing machines, microwave ovens
- Fax machines, photocopiers, printers

These devices use power electronics like SCRs, diodes, and thyristors, which are a growing percentage of the load in industrial power systems. The majority use a 6-pulse converter. Most loads which produce harmonics, do so as a steady-state phenomenon. A snapshot reading of an operating load that is suspected to be non-linear can determine if it is producing harmonics. Normally each load would manifest a specific harmonic spectrum.

Many problems can arise from harmonic currents in a power system. Some problems are easy to detect; others exist and persist because harmonics are not suspected. Higher RMS current and voltage in the system are caused by harmonic currents, which can result in any of the problems listed below:

1. Blinking of Incandescent Lights - Transformer Saturation
2. Capacitor Failure - Harmonic Resonance
3. Circuit Breakers Tripping - Inductive Heating and Overload
4. Conductor Failure - Inductive Heating
5. Electronic Equipment Shutting down - Voltage Distortion
6. Flickering of Fluorescent Lights - Transformer Saturation
7. Fuses Blowing for No Apparent Reason - Inductive Heating and Overload
8. Motor Failures (overheating) - Voltage Drop
9. Neutral Conductor and Terminal Failures - Additive Triplen Currents
10. Electromagnetic Load Failures - Inductive Heating
11. Overheating of Metal Enclosures - Inductive Heating
12. Power Interference on Voice Communication - Harmonic Noise
13. Transformer Failures - Inductive Heating

Overcoming Harmonics

Tuned Harmonic filters consisting of a capacitor bank and reactor in series are designed and adopted for suppressing harmonics, by providing low impedance path for harmonic component.

The Harmonic filters connected suitably near the equipment generating harmonics help to reduce THD to acceptable limits. In present Indian context where no Electro Magnetic Compatibility regulations exist as a application of Harmonic filters is very relevant for industries having diesel power generation sets and co-generation units.

1.8 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 1.4).

TABLE 1.4 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 waste.	Reduce the load by conservation load 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 counteract 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.

QUESTIONS	
1.	Name different types of power generation sources.
2.	The temperatures encountered in power plant boilers is of the order of a) 8500C b) 3200°C c) 1300°C d) 1000°C
3.	What do you understand by the term "Heat Rate"?
4.	Explain why power is generated at lower voltage and transmitted at higher voltages.
5.	The efficiency of steam based power plant is of the order of a) 28-35% b) 50-60% c) 70-75% d) 90-95%
6.	The technical T & D loss in India is estimated to be a) 50% b) 25% c) 17% d) 10%
7.	What are the typical billing components of the two-part tariff structure of industrial utility?
8.	Define contract demand and billing demand.
9.	What are the areas to be looked into for maximum demand reduction in industry?
10.	A trivector-meter with half-hour cycle has the following inputs during the maximum demand period: MD Drawn kVA — Duration in Minutes 100 — 10 200 — 5 50 — 10 150 — 5 What is the maximum demand during the half-hour interval?
11.	Power factor is the ratio of a) kW/kVA b) kVA/kW c) kVAr/kW d) kVAr/kVA
12.	A 3-phase, 415 V, 100 kW induction motor is drawing 50 kW at a 0.75 PF Calculate the capacitor rating requirements at motor terminals for improving PF to 0.95. Also calculate the reduction in current drawn and kVA reduction, from the point of installation back to the generated side due to the improved PF.
13.	A process plant consumes of 12500 kWh per month at 0.9 Power Factor (PF). What is the percentage reduction in distribution losses per month if PF is improved up to 0.96 at load end?
14.	What is the % loss reduction, if an 11 kV supply line is converted into 33 kV supply system for the same length and electrical load application?
15.	The efficiency at various stages from power plant to end-use is given below. Efficiency of power generation in a power plant is 30 %. The T & D losses are 23 %. The distribution loss of the plant is 6 %. Equipment end use efficiency is 65 %. What is the overall system efficiency from generation to end-use?

16.	A unit has a 2 identical 500 kVA transformers each with a no load loss of 840 W and full load copper loss of 5700 watt. The plant load is 400 kVA. Compare the transformer losses when single transformer is operation and when both transformers are in parallel operation.
17.	Explain how fluctuations in plant voltage can be overcome.
18.	What are Total Harmonic Distortion and its effects on electrical system?
19.	What are the equipments / devices contributing to the harmonics?
20.	Select the location of installing capacitor bank, which will provide the maximum energy efficiency. a) Main sub-station b) Motor terminals c) Motor control centers d) Distribution board
21.	The designed power transformers efficiency is in the range of a) 80 to 90.5 % b) 90 to 95.5 % c) 95 to 99.5 % d) 92.5 to 93.5 %
22.	The power factor indicated in the electricity bill is a) Peak day power factor b) Power factor during night c) Average power factor d) Instantaneous power factor

REFERENCES

1. Technology Menu on Energy Efficiency – NPC
2. NPC In-house Case Studies
3. Electrical energy conservation modules of AIP-NPC, Chennai

Energy audit Instrument list:

We use the following portable instruments for relevant operating parameters measurements during the field energy audit. Accurate measurements are very important to understand operations and estimate energy efficiency values.

S.No	Energy audit Instrument	Purpose of Measurement
1	Power Quality Manger/Three & single phase power Analyser for Balanced / Un-Balanced Load	To measure, record real time Power Consumption, analysis of electrical load, demand control, harmonics and transient. It is done without interrupting the connections.
2	Lux meter	To measure illumination level
3	Digital Multimeter	To measure voltage, Current and resistance.
4	Digital Tachometer&Stroboscope	To measure speed of rotation equipment.
5	Thermo-hygrometer	To measure air velocity & humidity
6	Anemometer	To measure air flow and velocity
7	Digital Temperature & Humidity monitor	To measure temperature and humidity
8	Digital Ultrasonic Flow Meter	To measure flow of water and other liquids through pipelines.
9	Portable Flue Gas Analyser	To measure oxygen and CO in ppm and temperature in flue gas of boilers, furnaces etc..
10	Temperature Indicators	To measure temperatures of gases/air, liquids etc.
11	Thermal Imager	To measure loss of energy from hot/cold insulated surfaces.
12	Digital Pressure Meter	To measure differential pressure.
13	Digital Infrared Thermometer	To measure surface temperature from distance
14	Surface Temp Meter	To measure radiation loss from hot/cold insulated surfaces.
15	Digital TDS meter	To measuretotal dissolved solids in water

LUX meter:

Light or illuminance meters provide a simple and effective method for determining actual delivered light levels. It is useful to compare actual levels with suggested or recommended levels for specific activities or areas.

An illuminance meter typically utilizes a sensor corrected for:

- light colour – light sources vary in colour
- angle of incidence – the cosine law is used to correct for reduced apparent illumination at small angles to the horizontal

A basic meter is shown in Figure 1. It is battery-powered, can measure from 0 to 50 000 lux and has a separate light sensor with a flexible cord.

Sample Specifications

- Measures 0–50 000 lux in three ranges (0–2000/0–20 000/0–50 000)
- Accuracy to 5% q Automatic zero adjustment
- Sensor housed in a separate unit from display with flexible cord connection
- Battery-operated
- LCD display

Useful Features

- Analogue output function for recording

Compact Data Loggers

With compact data loggers, the energy auditor can quickly and easily collect data from a wide variety of sensors and other instruments. These devices range from self-contained temperature and humidity loggers to general-purpose multi-channel loggers with standard analogue and digital inputs.

Description A data logger is an electronic instrument that records measurements of temperature, relative humidity, light intensity, on/off and open/closed state changes, voltage and events over extended periods of time. Typically, data loggers are small, stand-alone, batterypowered devices equipped with a microprocessor, memory for data storage and sensor or group of sensors. Sensors may be internal or external.

Data loggers have some form of interface with a PC and come with software for configuration and retrieval of data collected. Configuration enables the user to set operating parameters for the logger including

✓ external sensor types connected

✓ sampling intervals

✓ survey start and stop times (if not immediate)

✓ real-time clock

Typically, the memory installed in these loggers is sufficient for the collection of 10 000 or more data records, which could span many hours or days depending on the measurement interval selected. Measurement intervals may be as frequent as one second or as long as one hour or more. Once a data survey is completed, the data must be downloaded from the logger for viewing or analysis with the software provided or exported to a spreadsheet for further analysis.

Applications

✓ Temperature and humidity and illumination level logging with internal sensors

✓ Logging of other analogue signals such as pressure and CO2 sensors or any sensor with a standard current or voltage interface

✓ Event logging such as motor, lights or heater on/off events

✓ Logging of signals from other instruments such as light meters, digital thermometers, airflow meters and electric current clamp meters

Power Analyzer

A power analyzer is used to measure the flow of power (w) in an electrical system. This refers to the rate of electrical transferral between a power source and a sink, hence the alternative expression of power as energy per second (J/s). Measuring power flow is a critical yet rudimentary process that can be carried out with consummate ease using a standard power analyzer. More advanced systems acquire electrical signals and carry out integrated calculations for additional, complex analysis.

The Working Principles of Power Analyzers

Power analyzers can be used to measure the flow of energy in either alternating current (AC) or direct current (DC) systems – with distinct considerations for measuring AC circuits.

The determination of an electrical signal's True RMS time period underlines each of the subsequent calculations performed by the measuring instrument. This is complicated by AC measurements, where root mean square is typically expressed as an equivalent DC value. To accurately determine the True RMS of an AC waveform, an average must be calculated across the cycle of the AC frequency. This is defined as the fundamental frequency of the circuit. Power analyzers can digitally detect frequency cycles to provide reliable RMS periods during power conversion.

A power analyzer must also detect the voltage and current of the system. Typical systems directly acquire individual voltages using voltage dividers, while a transformer is usually required to measure the current. This may comprise a coil that measures the electrical field of a wire carrying a current, or a flux gate current transducer.

Once the power analyzer has determined each of these values, calculating power is a matter of simple mathematics.

Advanced Power Analysis

As mentioned, innovative power analyzers provide more than just power measurements. They are often required to measure various values of mechanical energy such as torque and speed, which are critical factors for test bench and manufacturing applications. This provides reliable data for comprehensive investigations into the performance and efficiency of electromechanical systems. Some of the additional calculations and analytical methods performed using advanced power analyzers include:

- Efficiency mapping;
- Fast Fourier Transform (FFT) and harmonic analysis;
- Fundamental power and root mean square (RMS) values;
- Polar diagrams and symmetrical components;
- Space vectors and DQ-currents.

Optical pyrometer(Disappearing filament Type)

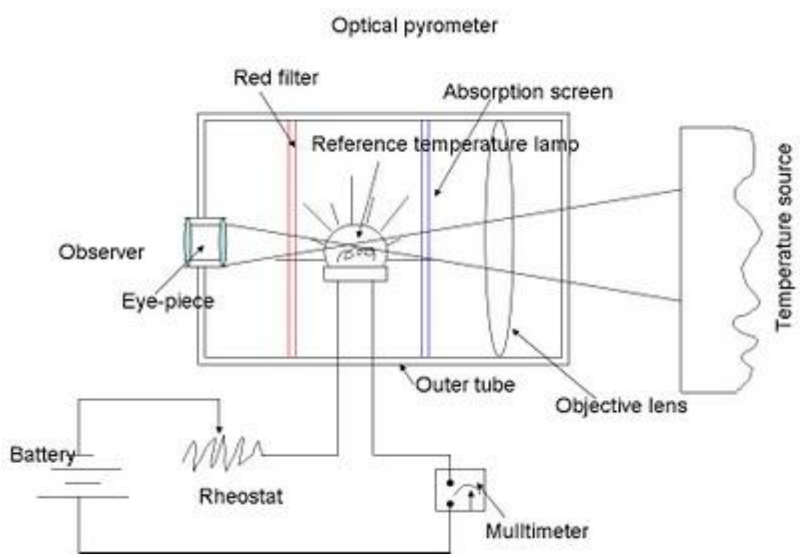
Basic Principle of optical pyrometer:

The principle of temperature measurement by brightness comparision is used in optical pyrometer. A colour variation with the growth in temperature is taken as an index of temperature.

This optical pyrometer compares the brightness of image produced by temperature source with that of reference temperature lamp. The current in the lamp is adjusted until the brightness of the lamp is equal to the brightness of the image produced by the temperature source. Since the intensity of light of any wave length depends on the temperature of the radiating object, the current passing through the lamp becomes a measure of the temperature of the temperature source when calibrated.

Construction of optical pyrometer:

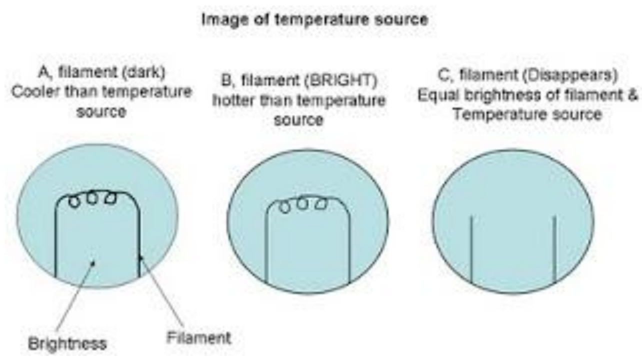
The main parts of an optical pyrometer are as follows:



An eye piece at one end and an objective lens at the other end.
A power source (battery), rheostat and millivoltmeter (to measure current) connected to a reference temperature bulb.
An absorption screen is placed in between the objective lens and reference temperature lamp. The absorption screen is used to increase the range of the temperature which can be measured by the instrument.
The red filter between the eye piece and the lamp allows only a narrow band of wavelength of around 0.65mui

Operation of optical pyrometer:

When a temperature source is to be measured , the radiation from the source are focused onto the filament of the reference temperature lamp using the objective lens. Now the eye piece is adjusted so that the filament of the reference temperature lamp is in sharp focus and the filament is seen super imposed on the image of the temperature source. Now the observer starts controlling the lamp current and the filament will appear dark as in figure (a) if the filament is cooler than the temperature source, the filament will appear bright as in figure (b) if the filament is hotter than the temperature source, the filament will not be seen as in figure (c) if the filament and temperature source are in the same temperature.



Hence the observer should control the lamp current until the filament and the temperature source have the same brightness which will be noticed when the filament disappears as in figure (c) in the superimposed image of the temperature source [that is the brightness of the lamp and the temperature source are same]. At the instance, the current flowing through the lamp which is indicated by the millivoltmeter connected to the lamp becomes a measure of the temperature of the temperature source when calibrated.

Applications of optical pyrometer:

Optical pyrometers are used to measure temperature of molten metals or heated materials.
Optical pyrometers are used to measure temperature of furnace and hot bodies.

Advantages of optical pyrometer:

Physical contact of the instrument is not required to measure temperature of the temperature source.
Accuracy is high + or – 5’C.
Provided a proper sized image of the temperature source is obtained in the instrument, the distance between the instrument and the temperature source doesnot matter.
The instrument is easy to operate.

Limitations of the Optical pyrometer:

Temperature of more than 700'C can only be measured since illumination of the temperature source is a must for measurement.
Since it is manually operated, it cannot be used for the continuous monitoring and controlling purpose.

Source:

http://instrumentationandcontrollers.blogspot.in/2010/09/optical-pyrometer-disappearing-filament.html