Power Factor Correction

1.0 Introduction

The effects of a low power factor in an installation are well known. These include:-

i) A penalty charge in the electricity bill
ii) Extra losses in the feeder cable
iii) A significant voltage drop in the cables
iv) A reduction of the effective capacity of the cables
v) A reduction in the power available at the transformer
vi) A significant voltage drop at the secondary of the transformer
vii) Significant losses in the transformer

There are basically two types of equipment for improving the power factor of an installation:-

a) By rotary phase advancers, synchronous condensers or synchronous motors
b) Static capacitors.

For normal installations, the capital cost of rotating machinery, both synchronous and phase advancing, makes its use uneconomical and, in addition, the wear and tear inherent in all rotary machine involves additional expenses for upkeep and maintenance.

Capacitors, on the other hand, have a very low initial cost, have minimal upkeep costs and can be used with high efficiencies on all sizes of installations. They are compact, reliable and convenient to install and thus is the more satisfactory equipment for power factor improvement.

The siting of the capacitors in an installation depends on whether each piece of equipment, example a motor, is being individually corrected or the plant/installation as a whole is being corrected as a block (bulk or central correction).

As a rule of thumb, switchboards exceeding 200A shall be installed with power factor correction board.

2.0 Individual Correction

This is used in small installations on motors constantly in operation or, in the case of kVA maximum demand tariffs, on certain motors known to be in operation at the time of maximum demand. It should not be applied where the motors are used for haulage, cranes, and colliery winders of where “inching” or “plugging” and direct reversal takes place. Individual correction of tandem (or two seed motors) should be avoided. If correction is necessary, the capacitors should never be connected directly to the low speed component but a contactor arrangement installed using one capacitor for both windings.

In general, this method is not profitable for motors less than 10 kW.

i) **Advantages of Individual Correction**

This method reduces the current loading on the distribution system with consequent improvement in the voltage regulation. Also no additional switchgear is required as the capacitor is connected directly across the motor terminals and, therefore, switched with the load by the motor starter.

ii) **Disadvantages of Individual Correction**

Several small capacitors installed at various individual loads may cost more than a single capacitor of total equivalent rating centrally installed. Also the capacitors have a low utilization factor as the capacitor operates only when the particular load is used.

iii) **General Considerations**

a. One size of capacitor will give constant value of power factor over the normal low range since variations in motor kVAr are comparatively small.

b. Since connection of the capacitor directly across the motor results in a lower load current, the overload setting on the starter should be reduced in order to obtain the same degree of protection.

c. When star delta starting is used, a standard three terminal, delta connected capacitor should be employed, which gives maximum power factor correction at the start when the power factor of the motor is low.

d. To prevent auto-excitation (i.e. Self excitation of the motor by the stored capacitor charge – when the motor supply is switched off); ensure that the capacitor current is equal to or smaller than the motor magnetizing current. A commonly used value is 90% of the motor no load current.

e. The capacitor rating required is calculated as follows:-

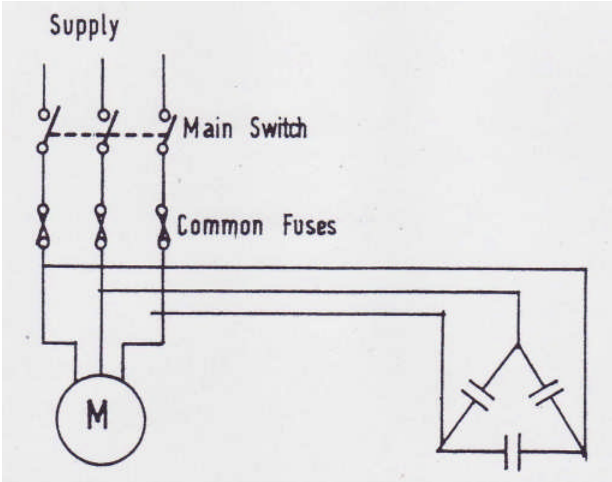
$$\text{kVAr} = \frac{\text{Hp} \times 0.746 \times \%\text{ of full load} \times (\tan\cos^{-1} ø_1 - \tan\cos^{-1} ø_2)}{\text{efficiency (at the above \% of full load)}}$$

where: $\cos ø_1$ is the original power factor
$\cos ø_2$ is the required power factor.

f. Motors are usually corrected to a power factor of 0.98 at 75% load.

g. Welding equipment generally have a power factor of about 0.35 lagging but since welding loads are intermittent and consequently have a low load factor, they are usually corrected to about 0.6 to 0.8 based on its continuous kVA rating.

h. The diagram below shows the method of connection for individual power factor correction of motors.



Capacitor Bank with Discharge Resistors

Diagram 1: Connections for individual motor power factor correction

Category	Typical uncompensated PF
Hospitals	0.7,..0.8
Machinery- big sized	0.5,..0.6
Machinery-small sized	0.4,..0.5
Office Building-General	0.7,..0.8
Water pumps	0.8,..0.85
Compressor	0.7,..0.8
Vocational School (Welding Transformer)	0.5,..0.7
School (normal Laboratory)	07,..0.8
Factory (Steel)	0.6,..0.7
Breweries / sawmill / factory	0.6,..0.7

Table 1 : Typical uncompensated PF for building/plant

3.0 Bulk or Central Correction

The method is used when the total reactive load varies during the day, but is too small to be compensated individually because of cost reasons. Also, it may sometimes be impossible to connect capacitors at the individual load locations due to uncertainty of loads, high ambient temperatures, restricted space or presence of explosive gases.

i) **Advantages of Central Correction**

This is ideal method of obtaining the full electrical and financial benefits of a capacitor installation. The central location makes supervision easier and with automatic control, the resulting economics and convenience may outweigh the initial cost.

ii) **Disadvantages of Central Correction**

Here the loads in the distribution lines are not lightened. The capacitors must also be provided with protective and isolating gear. This was previously done manually but manual switching requires surveillance which may not be convenient to provide. Therefore it is now to be done automatically (but at a higher cost).

iii) **General Considerations for central automatic power factor correction**

a) The equipment consists of a capacitor bank subdivided into two or more steps, each step or capacitor being controlled by a contactor.

b) In turn the contactors are controlled by a reactive relay. The reactive relay consists of a potential coil connected across 2 phases of the supply load and a current coil taken from a current transformer on the third phase – so as to obtain a 90^{o} phase displacement at unity power factor. The utilization category of contactor for the switching of capacitor banks is AC-6b.

c) The number of stages installed is usually a compromise between the technical requirement and cost. The aim is to have each contactor switching its maximum rated capacitance and, at the same time, have the capacitor bank divided into the most economic subsections, so that all variations in load can be corrected.

d) To determine the rating of the capacitor needed, the following formula is used:-

$Q = P(\tan ø_1 - \tan ø_2)$

Where:
Q is the rating of the capacitor required in kVAr
P is the installation load in kW
Cos $ø_1$ is the initial power factor, and
Cos $ø_2$ is the required power factor.

The above formula is derived from the following Diagram 2 which shows the effect of correction.

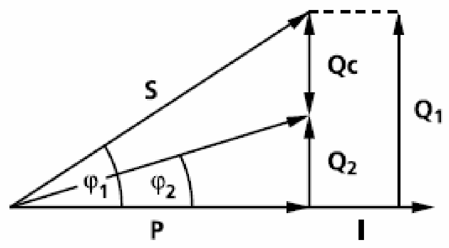


Fig. 5: Power triangle showing the effect of correction

The reactive power Q_C corrected by the capacitor is given by the difference between the inductive reactive power **Q1** before correction and the reactive power **Q2** after correction, i.e. $Q_C = Q1 - Q2$.

$$Q_c = P \cdot (\tan \varphi_1 - \tan \varphi_2)$$
[VAr] [W]

Alternatively, the required rating can be obtained from tables which give the required values of ($\tan ø_1 - \tan ø_2$). This is given by 'k Value' in Table-2.

Power Factor of load before applying Capacitors	(k Value) Size of Capacitor in kVA per kW of Load for Raising the Power Factor												
	0.80	0.85	0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	Unity
0.40	1.537	1.668	1.805	1.832	1.861	1.895	1.924	1.959	1.998	2.037	2.085	2.144	2.288
0.41	1.474	1.605	1.742	1.769	1.798	1.831	1.860	1.896	1.935	1.973	2.021	2.082	2.225
0.42	1.413	1.544	1.681	1.709	1.738	1.771	1.800	1.836	1.874	1.913	1.961	2.022	2.164
0.43	1.356	1.487	1.624	1.651	1.680	1.713	1.742	1.778	1.816	1.855	1.903	1.964	2.107
0.44	1.290	1.421	1.558	1.585	1.614	1.647	1.677	1.712	1.751	1.790	1.837	1.899	2.048
0.45	1.230	1.360	1.501	1.522	1.561	1.592	1.626	1.659	1.698	1.737	1.784	1.846	1.988
0.46	1.179	1.309	1.446	1.473	1.502	1.533	1.567	1.600	1.636	1.677	1.725	1.786	1.929
0.47	1.130	1.260	1.397	1.425	1.454	1.485	1.518	1.552	1.588	1.629	1.677	1.758	1.881
0.48	1.076	1.206	1.343	1.370	1.400	1.430	1.464	1.497	1.534	1.575	1.623	1.684	1.826
0.49	1.030	1.160	1.297	1.326	1.355	1.386	1.428	1.453	1.489	1.530	1.578	1.639	1.782
0.50	0.982	1.112	1.248	1.276	1.303	1.327	1.368	1.403	1.441	1.481	1.528	1.598	1.752
0.51	0.936	1.066	1.202	1.230	1.257	1.291	1.323	1.357	1.395	1.435	1.483	1.544	1.686
0.52	0.894	1.024	1.160	1.188	1.213	1.249	1.281	1.315	1.353	1.393	1.441	1.502	1.644
0.53	0.850	0.980	1.116	1.144	1.171	1.205	1.237	1.271	1.309	1.349	1.397	1.458	1.600
0.54	0.809	0.939	1.075	1.103	1.130	1.164	1.196	1.230	1.268	1.308	1.356	1.417	1.559
0.55	0.769	0.899	1.835	1.863	1.080	1.124	1.156	1.190	1.228	1.268	1.316	1.377	1.519
0.56	0.730	0.860	0.996	1.024	1.051	1.085	1.117	1.151	1.189	1.229	1.277	1.338	1.400
0.57	0.692	0.822	0.958	0.986	1.013	1.047	1.079	1.113	1.151	1.191	1.239	1.300	1.442
0.58	0.655	0.785	0.921	0.949	0.976	1.010	1.042	1.076	1.114	1.154	1.202	1.263	1.405
0.59	0.618	0.748	0.884	0.912	0.939	0.973	1.005	1.039	1.077	1.117	1.165	1.226	1.368
0.60	0.584	0.714	0.848	0.878	0.905	0.939	0.971	1.005	1.043	1.083	1.131	1.192	1.334
0.61	0.549	0.679	0.815	0.843	0.870	0.904	0.936	0.970	1.008	1.018	1.096	1.157	1.299
0.62	0.515	0.645	0.785	0.809	0.836	0.870	0.902	0.936	0.974	1.014	1.062	1.123	1.265
0.63	0.483	0.613	0.749	0.777	0.804	0.838	0.870	0.904	0.942	0.982	1.830	1.091	1.233
0.64	0.450	0.580	0.716	0.744	0.771	0.805	0.837	0.871	0.909	0.949	0.997	1.058	1.200
0.65	0.419	0.549	0.685	0.713	0.748	0.774	0.806	0.848	0.876	0.918	0.966	1.027	1.169
0.66	0.388	0.518	0.654	0.682	0.709	0.743	0.775	0.809	0.847	0.887	0.935	0.996	1.138
0.67	0.358	0.488	0.624	0.652	0.679	0.713	0.745	0.779	0.817	0.857	0.905	0.966	1.108
0.68	0.329	0.459	0.595	0.623	0.650	0.684	0.716	0.750	0.788	0.828	0.876	0.937	1.079
0.69	0.299	0.429	0.565	0.593	0.620	0.654	0.686	0.28	0.758	0.798	0.848	0.907	1.049
0.70	0.270	0.400	0.534	0.544	0.591	0.625	0.657	0.691	0.729	0.769	0.811	0.878	1.028
0.71	0.242	0.372	0.508	0.536	0.563	0.597	0.629	0.663	0.701	0.741	0.783	0.850	0.992
0.72	0.213	0.343	0.479	0.507	0.534	0.568	0.600	0.634	0.672	0.712	0.754	0.821	0.963
0.73	0.186	0.316	0.452	0.480	0.507	0.541	0.573	0.607	0.645	0.685	0.727	0.794	0.936
0.74	0.159	0.289	0.425	0.453	0.480	0.514	0.546	0.580	0.618	0.658	0.700	0.767	0.909
0.75	0.132	0.262	0.398	0.426	0.453	0.487	0.519	0.553	0.591	0.631	0.673	0.740	0.882
0.76	0.105	0.235	0.371	0.399	0.426	0.460	0.492	0.526	0.564	0.604	0.652	0.713	0.855
0.77	0.079	0.209	0.345	0.373	0.400	0.434	0.466	0.500	0.538	0.578	0.620	0.687	0.829
0.78	0.053	0.183	0.319	0.347	0.374	0.408	0.448	0.474	0.512	0.552	0.594	0.661	0.803
0.79	0.026	0.156	0.292	0.320	0.347	0.381	0.413	0.447	0.485	0.525	0.567	0.634	0.776
0.80	-	0.138	0.266	0.294	0.321	0.355	0.387	0.421	0.459	0.499	0.541	0.688	0.730
0.81	-	0.104	0.240	0.268	0.295	0.329	0.351	0.395	0.433	0.473	0.515	0.582	0.724
0.82	-	0.078	0.214	0.242	0.269	0.303	0.335	0.369	0.407	0.447	0.489	0.556	0.698
0.83	-	0.052	0.188	0.216	0.243	0.277	0.309	0.343	0.381	0.421	0.463	0.530	0.672
0.84	-	0.026	0.162	0.190	0.217	0.251	0.283	0.317	0.355	0.395	0.437	0.504	0.645
0.85	-	-	0.136	0.164	0.191	0.225	0.257	0.291	0.329	0.369	0.417	0.478	0.620
0.86	-	-	0.109	0.140	0.167	0.198	0.230	0.264	0.301	0.343	0.390	0.450	0.593
0.87	-	-	0.083	0.114	0.141	0.172	0.204	0.238	0.275	0.317	0.364	0.424	0.567
0.88	-	-	0.054	0.085	0.112	0.143	0.175	0.209	0.246	0.288	0.335	0.395	0.530
0.89	-	-	0.028	0.059	0.086	0.117	0.149	0.183	0.238	0.262	0.309	0.369	0.512
0.90	-	-	-	0.031	0.058	0.089	0.121	0.155	0.192	0.234	0.281	0.341	0.484
0.91	-	-	-	-	0.027	0.058	0.090	0.124	0.161	0.203	0.250	0.310	0.453
0.92	-	-	-	-	-	0.031	0.063	0.097	0.134	0.176	0.223	0.283	0.426
0.93	-	-	-	-	-	-	0.032	0.066	0.103	0.145	0.192	0.252	0.395
0.94	-	-	-	-	-	-	-	0.034	0.071	0.113	0.160	0.220	0.363
0.95	-	-	-	-	-	-	-	-	0.037	0.079	0.126	0.186	0.329
0.96	-	-	-	-	-	-	-	-	-	0.012	0.089	0.149	0.292
0.97	-	-	-	-	-	-	-	-	-	-	0.047	0.107	0.250
0.98	-	-	-	-	-	-	-	-	-	-	-	0.060	0.203
0.99	-	-	-	-	-	-	-	-	-		-	-	0.143

Table 2: k Value

e) It is necessary to set the relay to operate with the particular current transformer used. On most relays, this is usually achieved by means of a C/K setting, where

C = size of capacitor being switched (in kVAr), and
K = ratio of current transformer primary to secondary.

Example: For C=100 kVAr and K = 2000/5 = 400

C/K = 100/400=0.25

f) To prevent "hunting" i.e. continuous switching in and out of a capacitor step, the sensitivity limit of the regulator is set such that it is greater than the current of one capacitor step. In practice the regulator is usually set to react to changes corresponding to about 2/3 of the current of one capacitor step.

g) A typical connection of an automatic relay is as shown:-

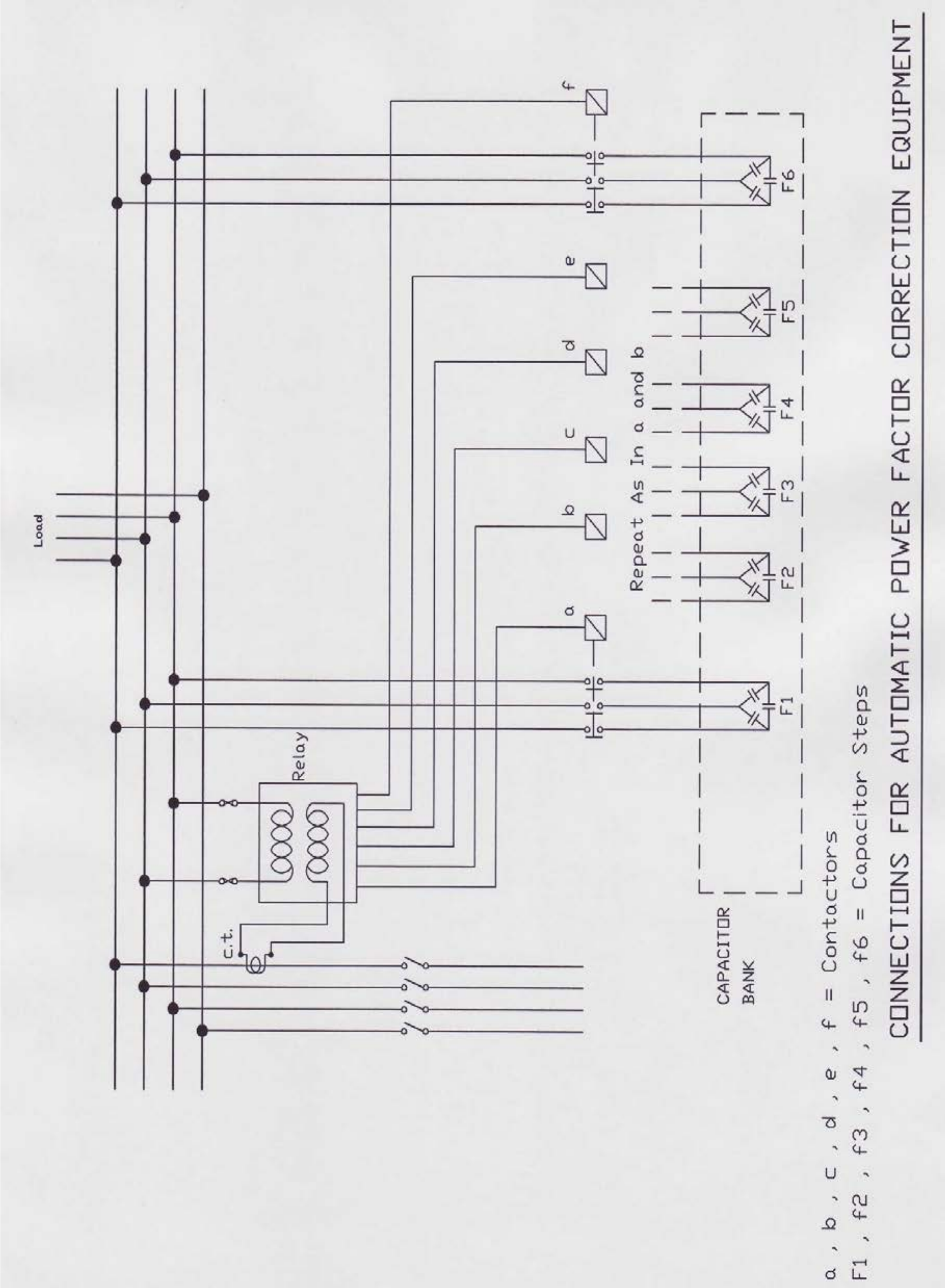


Diagram 3: Typical connection of an automatic relay

4.0 General

i) Selection of Current Transformers for power factor relays.

a) The primary rating of the CT is based on the line current of the system at its original power factor.

b) The secondary rating depends on the current rating of the power factor relay used and is usually 5 amps.

c) The burden of the CT depends on the Volt-Ampere consumption of the relay and is usually less than 5 VA. If the CT is far from the battery, a 10 VA CT may have to be used to take into account of the I^2R losses in the cables.

d) In some cases, it may be necessary to summate the currents in more than one circuit. A suitable auxiliary summation CT can be used.

ii) **Rating of Switchgear**

The duty imposed on switchgear and fusegear used with capacitors is heavier than that in normal circumstances due to:-

a) At the instant of switching, a large transient current will flow.

b) High overvoltage transients can occur when capacitors are disconnected by switching devices which allow restricting of the arc.

c) The switchgear has to carry continuously the full rated current of the capacitor at all times the capacitor is in circuit.

d) At light loads when the voltage may be higher than normal, the capacitor currents will be increased accordingly.

e) If harmonics are present in the supply voltage, the capacitor current will be increased.

In view of this, it is normal to have switchgear of ratings higher than the rated current of the capacitor. Often a factor of 1.5 times the rated current is used.

iii) **General Considerations in the Installation of Capacitors**

a) For capacitors directly connected to motor terminals, all capacitor banks should have a switching device equipped with an appropriate automatic trip.

b) A discharge device should be provided for every capacitor equipment unless it is connected directly to other electrical equipment providing a discharge path without a disconnecting switch, fuses cut-out, or series capacitor interposed.

c) Self healing dry type capacitors should normally be specified for all installation due to their superior qualities and ease of maintenance.

d) To reduce the current loading in the distribution system, the power factor correction should be done as close as possible to the load.

e) Apart from the individual and the bulk central corrections methods, other methods are possible. These are in effect variations and combinations of the above mentioned two methods. They are:-
- Group compensation e.g. One capacitor bank for a group of motors.
- Fixed central compensation.
- Combined compensation - a combination of fixed, automatic group and individual compensations.

f) Very often at the time of installing the power factor correction system, the load has not built up yet. The power factor correction system should thus either be designed to cater for future loads or provisions be made in switchgears, cables, accessories, space, etc. for easy extension of the system in the future.

iv) **Maintenance of power factor correction capacitors.**

a) Capacitors being static equipment, do not generally require the same degree of care as rotary machinery, but nevertheless, require regular maintenance.

b) Capacitors should normally be inspected every 12 months – preferably 6 months. Inspection time intervals are governed mainly by conditions on site. Humid atmospheres or those subjected to chemical fumes, dirt or dust requires more frequent attention.

c) Before examination the apparatus should be switched off and time allowed for complete discharge as stated on the rating plates. Current transformers must never operate with the secondary circuit open. If it is not being used, the secondary terminals must be short-circuited.

d) Conditions of exterior finish and protective paint should be in good condition. If necessary, it should be repainted.

e) The terminal box cover should be removed and inspected for abnormalities. Special care should be taken of

i) Condition of cable
ii) Condition of interior paint work (repainting if necessary)
iii) Tightness of nuts and bolts – especially of earth connections
iv) Removal of dust and other foreign matter
v) Cleanliness – particularly of insulators and terminals

5.0 Series Blocking Reactors

Where series blocking reactors (hereafter referred as 'reactors') are specified in the Drawings and/or Bill of Quantities, they shall be of dry type copper windings rated at 440 volts, 50 Hz and class H insulation connected in series with the capacitors suitable to operate in ambient temperature up to 40˚C. Unless otherwise specified in the Drawings and/or Bill of Quantities, the kVAr rating (reactance) of the reactor shall be 7% to the kVAr rating (reactance) of the capacitor to where the reactor will be connected.

The reactors shall be securely fastened and installed in a separate compartment of the power factor correction board. If necessary, rubber pad shall be used to reduce noise.

6.0 Switching Sequence

The regulator shall incorporate minimum following automatic switching sequence modes, viz. cyclic switching sequence and multi-step switching sequence allowing minimum following combinations of switching programme of capacitors stages:

a) 1:1:1:1:1:1:….
b) 1:1:2:2:2:2:….
c) 1:1:2:2:4:4:….
d) 1:2:2:2:2:2:….
e) 1:2:4:4:4:4.....
f) 1:2:4:8:8:8:….

The first three control output may be allowed to be set as fixed steps which are not included in the normal control cycle but are switched on immediately after the regulator is switched on and always remain switched on.

7.0 Comparison Method of Installation

Method	Advantages	Disadvantages
Individual Capacitors	Most technically efficient, most flexible	Higher installation and maintenance cost
Fixed Bank	Most economical, fewer installations	Less flexible, requires switches and/or circuit breakers
Automatic Bank	Best for variable loads, prevents over voltages, low installation cost	Higher equipment cost
Combination	Most practical for larger numbers of motors	Least flexible

Table 3: Different Method of Power Factor Correction

8.0 Practical Design Example

Given maximum demand (MD) = 685.60 kW
Assume Power Factor to be corrected is from 0.75 to 0.9. Calculate capacitor step for power factor correction and MCCB size at MSB where the power factor correction board will be locate.

a. Make assumption:

Power Factor Correction	= 0.75 to 0.9
b. Refer table 1, k value	= 0.398
Q (kVAr) pf correction at 3Φ $_{415}$	= MD × k = 685.6 × 0.398 = 272.87 kVAr $_{415}$
Q (kVAr) pf correction at 3Φ $_{525}$	= Q (kVAr) $_{415}$ × $(525/415)^2$ = 272.87 × 1.6 = 436.59 kVAr
Q (kVAr) $_{525}$ with 7% reactance (Industry practice)	= Q (kVAr) $_{525}$ × 0.93 = 436.59 × 0.93 = 406.03 kVAr ≈ 400 kVAr

c. Capacitor step:

Step 1	= 10% of Q (kVAr) $_{525}$ with 7% reactance = 40 kVAr ≈ 50 kVAr
If use step 1:1:1:1:1:1…..	= 50+50+50+50+50+50+50+50 = 400 = 8 step
If use step 1:1:2:2:2:2….	= 50+50+100+100+100 = 400 = 5 step

d. MCCB size at MSB

$$I_{415} = \frac{Q\ (\text{kVAr})_{525} \text{ with reactance} / (525/415)^2}{\sqrt{3} \times 415}$$

$$= \frac{400 / 1.6}{\sqrt{3} \times 415}$$

$$= 347.80\ \text{A}$$

I_{415} (50% higher) = 347.8 + 50%
= 521.7 A

MCCB size = 600 A

Therefore main incomer is 600A.

e. However we need to ensure that the capacitor in the first step must not be more than 5% of the incomer size, otherwise the system may not be initiated.

To verify, 5% of 600A = 30A equivalent to 21kVAr.

Therefore in this case the first step should be 20kVAr instead of 50kVAr.

f. Therefore the possible options for the steps may be as follow:

1) 1:1:1:1:1:1:…. (not possible, to many step to reach 400kVAr)
2) 1:1:2:2:2:2:…. (not possible, to many step to reach 400kVAr)

Possible step to use:

1:1:2:2:2:4:4:4 = 20:20:40:40:40:80:80:80
= 400
= 8 step

g. According to the market, maximum step = 14