Abstract—Various inductive loads used in all industries deals with the problem of power factor improvement. Capacitor bank connected in shunt helps in maintaining the power factor closer to unity. They improve the electrical supply quality and increase the efficiency of the system. Also the line losses are also reduced. Shunt capacitor banks are less costly and can be installed anywhere. This paper deals with shunt capacitor bank designing for power factor improvement considering overvoltages for substation installation.

Keywords— Capacitor Bank, Overvoltage Consideration, Power Factor, Reactive Power

I. INTRODUCTION

Most ac electric machines draw apparent power in terms of kilovoltamperes (KVA) which is in excess of the useful power, measured in kilowatts (KW), required by the machine. The ratio of these quantities (KW/KVA) is called the power factor \( \cos \Phi \) and is dependent on the type of machine in use.

\[
\text{Power Factor (cos } \Phi \text{)} = \frac{\text{Useful Power (kW)}}{\text{Apparent Power (kVA)}}
\]

A large proportion of the electric machinery used in industry has an inherently low pf, which means that the supply authorities have to generate much more current than is theoretically required. In addition, the transformers and cables have to carry this high current. When the overall pf of a generating station’s load is low, the system is inefficient and the cost of electricity corresponding high[2]. To overcome this, and at the same time ensure that the generators and cables are not loaded with the wattless current, the supply authorities often impulse penalties for low pf [3][4].

Some of the machinery or equipment with low pf are listed below:
1. Induction motors of all types
2. Power thyristor installations
3. Welding machines
4. Electric arc and induction furnaces
5. Choke coils and induction furnaces
6. Neon signs and fluorescent lighting

The method employed to improve the pf involves introducing reactive (kVAR) into the system in phase opposition to the wattless or reactive current.

Standard practice is to connect power capacitors in the power system at appropriate places to compensate the inductive nature of the load.

II. POWER FACTOR IMPROVEMENT

The apparent power (KVA) in a.c. circuit can be resolved into two components, the in-phase component which supplies the useful power (KW), and the wattless component (kVAr) which does no useful work. The phasor sum of the two is the KVA drawn from the supply.

The cosine of the phase angle between the KVA and the KW represents the power factor. This is shown by the phasor diagram in Fig. 1(a).

To improve the power factor, equipment drawing kVAR of approximately the same magnitude as the load kVAR, but in phase opposition (leading), is connected in parallel with the load. The resultant KVA is now smaller and the new power factor (cos \( \Phi_2 \)) is increased (Figs. 1(a) and (b)). Cos \( \Phi_2 \) is controlled by the magnitude of the kVAR added. Thus any desired power factor can be obtained by varying the leading kVAR. A typical arrangement of shunt capacitor connected in parallel with a load is shown in Fig. 2.
Advantages of Power Factor Improvement

The benefits that can be achieved by applying the correct power factor correction are:

a) Reduction of power consumption due to improved energy efficiency. Reduced power consumption means less greenhouse gas emissions and fossil fuel depletion by power stations.

b) Reduction of electricity bills

c) Extra kVA available from the existing supply

d) Reduction of I^2R losses in transformers and distribution equipment

e) Reduction of voltage drops in long cables.

f) Reduced electrical burden on cables and electrical components.

III. CAPACITOR BANK

Capacitor bank is an assembly of number of capacitors which are used to contribute kVAR in the electrical system and finally improve the power factor. Shunt capacitors bank are arrangements of series/parallel connected units.

a) Grounded Wye - Connected Banks

Grounded wye capacitor banks are composed series and parallel-connected capacitor units per phase and provide a low impedance path to ground. Fig. 3 shows typical bank arrangements.

Advantages of the grounded capacitor banks include:

- Its low-impedance path to ground provides inherent self-protection for lightning surge currents and give some protection from surge voltages. Banks can be operated without surge arresters taking advantage of the capability of the capacitors to absorb the surge.
- Offer a low impedance path for high frequency currents and so they can be used as filters in systems with high harmonic content. However, caution shall be taken to avoid resonance between the SCB and the system.

Some drawbacks for grounded wye SCB are:

- Phase series reactors are required to reduce voltage appearing on the CT secondary due to the effect of high frequency, high amplitude currents.

When a capacitor bank becomes too large, making the parallel energy of a series group too great (above 4650 kVAR) for the capacitor units or fuses, the bank may be split into two wye sections.

b) Ungrounded Wye - Connected Banks

Typical bank arrangements of ungrounded Wye SCB are shown in Fig. 4. Ungrounded wye banks do not permit zero sequence currents, third harmonic currents, or large capacitor discharge currents during system ground faults to flow. (Phase-to-phase faults may still occur and will result in large discharge currents). Other advantage is that overvoltages appearing at the CT secondaries are not as high as in the case of grounded banks. However, the neutral should be insulated for full line voltage because it is momentarily at phase potential when the bank is switched or when one capacitor unit fails in a bank configured with a single group of units. For banks above 15 kV this may be expensive.

(i) Multiple Units in Series Phase to Neutral—Single Wye Capacitor units with external fuses, internal fuses, or no fuses (fuseless or unfused design) can be used to make up the bank. For unbalance protection schemes that are sensitive to system voltage unbalance, either the unbalance protection time delay shall be set long enough for the line protections to clear the system ground faults or the capacitor bank may be allowed to trip off for a system good fault.

(ii) Multiple Units in Series Phase to Neutral—Double Wye—When a capacitor bank becomes too large for the maximum 4650 kVAR per group the bank may be split into two wye sections. When the two neutrals are ungrounded, the bank has some of the characteristics of the ungrounded single-wye bank. These two neutrals may be tied together through a current transformer or a voltage transformer. As for any ungrounded wye bank, the neutral instrument transformers should be insulated from ground for full line-to-ground voltage, as should the phase terminals.
IV. DESIGNING OF CAPACITOR BANK

The meaning of designing of capacitor bank is to calculate the requirement of reactive power in the power system to maintain the unity power factor.

During the designing of capacitor bank the following points taken care for the better utilization of capacitor bank in the power system:

(i) Consideration of over-voltage as per IS 13925 (part I) 1998.
(ii) Overvoltage consideration due to series reactor
(iii) Consideration of fault level of the power system for which the capacitor banks are to be designed.

The schematic and general arrangement of capacitor bank is shown in Fig. 5 and 6 respectively.

This paper covers the designing of capacitor banks considering overvoltage as per IS and also due to series reactor. The discussion continues with the example of Process Industry.

DESIGNING OF 498 kVAR × 7.2 kV CAPACITOR BANK
(Consideration of over-voltage as per IS 13925 (part I) 1998)

Step 1: Calculation of Capacitor kVAR For PF Correction

The relation for calculating required kVAR for improving power factor from initial value to desired value is as:

Required kVAR = KW [(tan cos⁻¹(Initial power factor) – tan cos⁻¹(Final power factor)]

Where:

(a) Initial power factor is the existing power factor of the electrical system.
(b) Final power factor is the desired power factor of the electrical system.
(c) KW (kilo watt) is the total load on the electrical system for which power factor has to be improved.

Let us take an example of Process Industry. The data is given is:

Motor rating = 11 KW, Normal voltage = 6.6 KV
Over voltage = ± 10%, Initial Power factor of motor = 0.83
Desired power factor = 0.96

Now,
Required kVAR = 1100 [(tan cos⁻¹ 0.83 – tan cos⁻¹ 0.96)]
Required kVAR = 418 kVAR at 6.6 KV

Step 2: Over Voltage Consideration

As per IS 13925, HV capacitors can take only rated voltage continuously. Also, capacitor design shall accommodate 10% over voltage for a period of 12 hours in a day, For example, 11 KV system, if voltage variation is 10%, capacitors shall be rated (11X1.1 = 12.1 KV). This will ensure proper performance from capacitors.

When reactors are used in series with capacitors, it gives voltage rise at capacitor terminals. For example, a 6% reactor will increase capacitor voltage by approx 6%. Therefore, capacitor rated voltage be corrected by raising the rated voltage further to that extent.

Now, the required kVAR to improve power factor from 0.83 to 0.96 is 418 kVAR at 6.6 KV. Thus, considering 10% over voltage in the electrical system, the capacitor is rated (6.6 X 1.1 = 7.2 kV) for proper performance.

Step 3: Sizing Calculations

In sizing calculations, we calculate the required kVAR at the 10% over voltage.
We have calculated that 418 kVAR is required at 6.6 KV now we will calculate that how much kVAR is required at 7.2 KV to improve power factor from 0.83 to 0.96. As we know that,

\[
\text{Reactive Power (kVAR)} = \frac{V^2}{X_C}
\]

Or

\[
X_C = \frac{V^2}{\text{Reactive Power (kVAR)}} = \frac{(6.6\times1000)^2}{418\times1000} = 104.21 \text{ ohm}
\]

Once we get the value of \(X_C\), we can calculate required reactive power (kVAR) at 7.2 KV.

\[
\text{Reactive Power (kVAR)} = \frac{(7.2\times1000)^2}{104.21} = 498 \text{ kVAR}
\]

Now it is clear that 498 kVAR at 7.2 KV (418 kVAR at 6.6 KV) is required to improve power factor from 0.83 to 0.96.

**DESIGNING OF 1326kVAR × 38kV CAPACITOR BANK**

(Consideration of over-voltage as per IS 13925 (part I) 1998 and due to series reactor)

Given load data: 3.6 MVA, normal voltage 33 kV, Over voltage +/- 10%, initial pf of Plant at full load 0.91, desired pf 0.99.

Load kW = kVA × PF = 3600 × 0.91 = 3394

Capacitive requirement is given by,

\[
\text{Required kVAR} = KW \left[ (\tan^{-1}\text{Initial power factor} - \tan^{-1}\text{Final power factor})\right]
\]

= 3394 (\(\tan^{-1}(0.91) - \tan^{-1}(0.99)\))

= 1062.73 kVAR or 1063 kVAR at 33 kV

Calculations for sizing of 1026 kVAR, 33 kV Capacitor Bank, when derated at 38 kV (considering 10% over voltage and 6% over voltage due to series reactor i.e. total 16% over voltage) and Series Reactor are as follows:

- Capacitor impedance \(X_C\) in ohms at 33 kV = 33 × \(1000/1.063\) = 1024.45 ohms
- Including 6% SR impedance in Ohms = 1024.45/0.94 = 1089.85
- Output of capacitor at 38 kV in MVAR = 33 × 1089.85 = 1.326 MVar or 1326 kVAR

**Capacitor Sizing for 1326 kVAR, 38 kV Bank**

Reactance of 1326 kVAR, 738 kV Bank \(X_C = (38)^2/1.326\) MVar = 1088.98 Ohms

Since it is to be provided with 6% overvoltage due to series reactor on the line side, hence

\[X_C = 1088.98 \times 0.94 = 1023.65 \text{ Ohms}\]

kVAR at 33 kV = \(\left(\frac{33}{1000}\right)\times1089 = 1063\) kVAR

Hence 1326 kVAR, 38 kV bank shall give the output of 1063 kVAR at 33 kV.

Reactance of 1326 kVAR, 38 kV Bank \(X_C = (38)^2/1.326\) MVar = 1088.98 Ohms

Reactor Impedance \(X_L = 0.06 \times X_C = 0.06 \times 1088.98 = 65.33\) Ohms

Reactor Rating = \(3 \times (20.146)^2 \times 65.33/1000 = 79.54 \text{ kVAR}\)

**Inrush Current Calculation**

For worst switching condition for Capacitor Bank rating of 1326 kVAR, 38 kV,

\[
I_{\text{inrush}} = \frac{\text{Peak L - L System Voltage}}{\sqrt{3} \times X_C} = \frac{\sqrt{3} \times 38000}{\sqrt{3} \times 1088.98 \times 65.33} = 116.32 \text{ amp. peak}
\]

Therefore,

\[
\text{Resonant Frequency} = \frac{50 \times X_C}{X_L} = 204.13 \text{ Hz}
\]

**V. RESULTS AND CONCLUSIONS**

Improvement of power factor makes the utility companies get rid from the power losses while the consumers are free from low power factor penalty charges.

By installing suitably sized power capacitors into the circuit the Power Factor is improved and the value becomes nearer to 0.9 to 0.95, thus, capacitor banks used for power factor correction reduce losses and increases the efficiency of the power system and also increases stability[6]. By using this APFC system the efficiency of the system is highly increased.

**REFERENCES**

[1] en.wikipedia.org/wiki/Power_factor_correction


