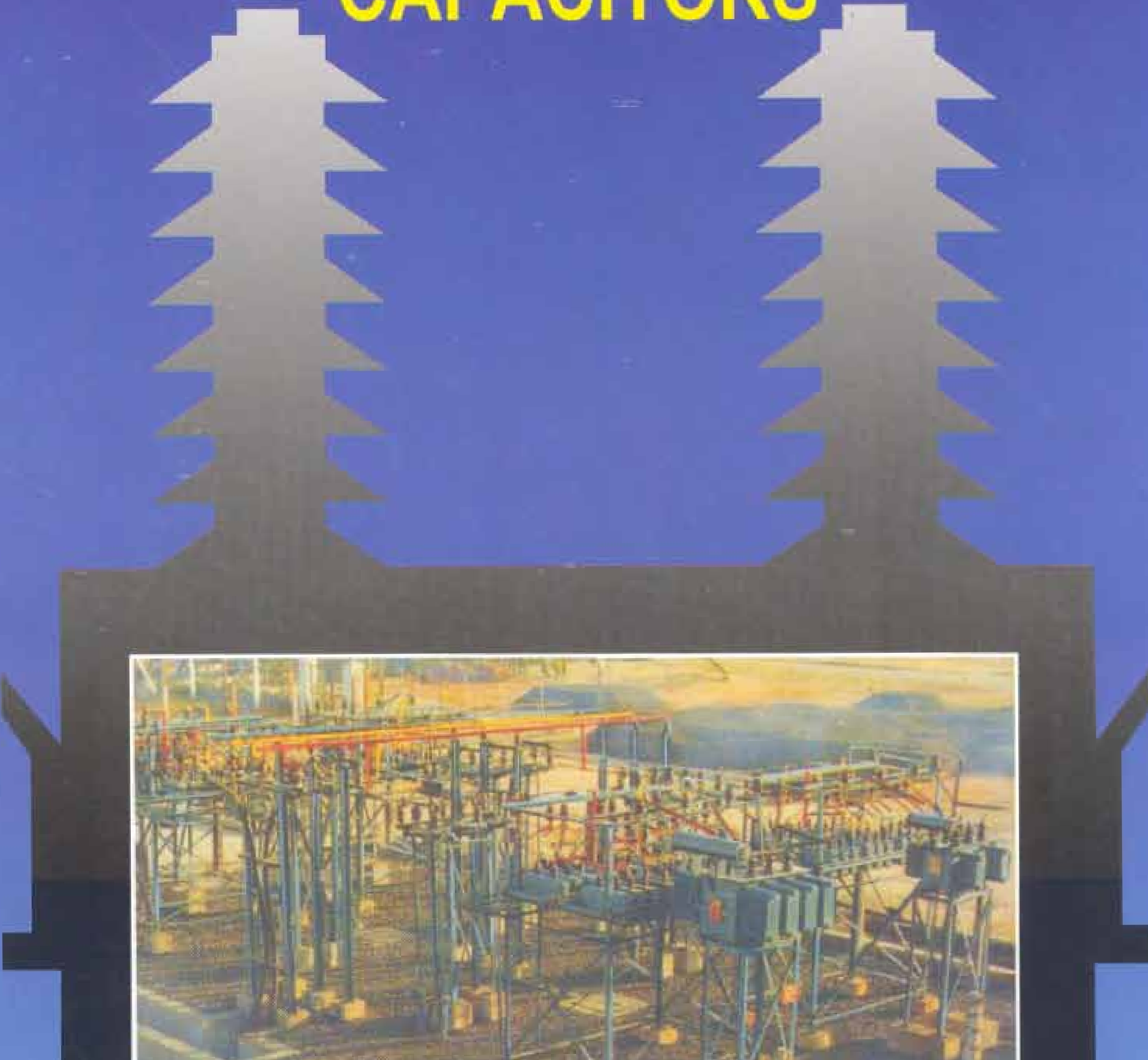
UNISTAR®

CAPACITORS



APPLICATION TO HIGH VOLTAGE POWER SYSTEM

A. APPLICATION OF CAPACITORS TO POWER SYSTEMS

1. LOCATION OF HT CAPACITORS

Typical locations of HT capacitors in Power System are depicted in Figure-1. These locations can be grouped as follows- -

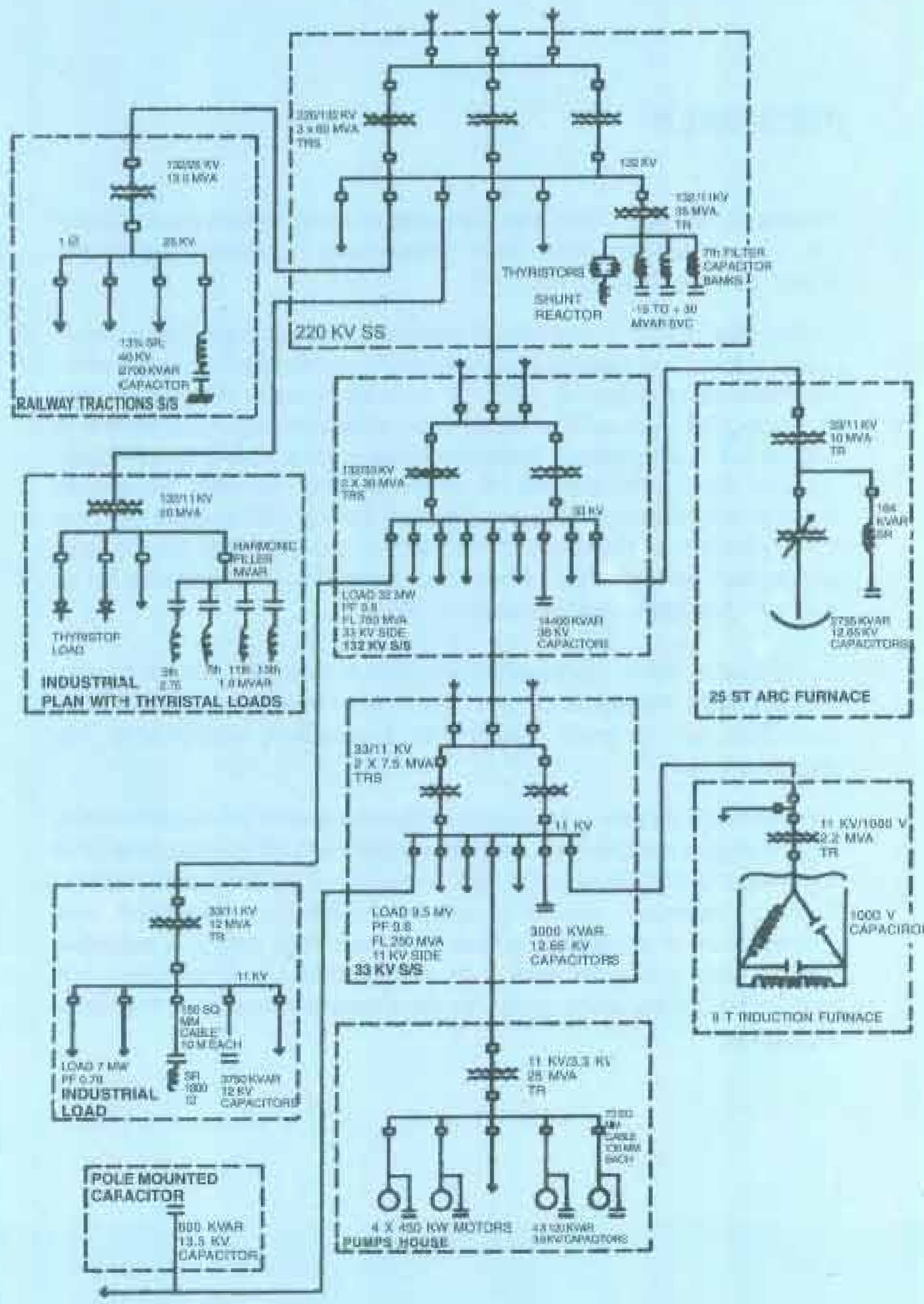


FIGURE-1
TYPICAL LOCATION OF HT POWER CAPACITRORS IN POWER SYSTEMS

1.1 SWITCHED CAPACITOR BANK IN DISTRIBUTION STATIONS AND INDUSTRIES FOR GROUP COMPENSATION

In distribution stations capacitor banks are installed to provide reactive KVA to the load and thus relieving the source from supplying unproductive KVAr.

Capacitors are operated through suitable breakers with necessary protections and are hence called switched capacitor banks. Normally a standardised capacitor bank rating is installed to give voltage support to the sub-station. In 132 KV, 14400 KVAr and in 33 KV sub-station, 3000 KVAr capacitor banks are connected. These standard ratings used by Electricity Boards are also discussed in 1.7 below.

In industries group compensation is used to reduce the maximum demand and thereby effecting savings in electricity bills. Due to the reduction in maximum demand, load can be increased, which facilitates expansion of the Plant without going in for application for increase in maximum demand from Electricity Company.

The table shows in Figure-1 a total of 4000 KVAr is required to reduce the maximum demand of 8970 KVA to 7180 KVA at .975 power factor thus effecting a demand reduction of 1790 KVA. This requirement has been split into 2 banks to take care of variation of loads. 2 banks of 3.75 & 1.8 MVAr at 12 KV have been provided to give 2.5 & 1.5 MVAr at 11 KV. Why higher KVAr banks are used is discussed in 2 below.

1.2 CAPACITORS IN RAILWAY TRACTION SUB-STATION

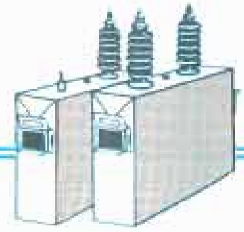
Railway traction load is very different from normal industrial load. The load in sections vary vastly from almost no load condition when there are no trains to sudden surge of load when electric trains (some time more than one) passes through the section. Electric engines produces high harmonic currents specially 3rd, 5th & 7th order which distorts the wave form. Railway traction being single phase system capacitors have to be protected from harmful effect of third harmonic. That is why 13% reactor is used in series with capacitors to avoid resonance and to reduce overloading from 3rd and higher harmonic components of current.

Capacitor voltage is selected taking into consideration the poor regulation due to the typical loading pattern, over voltage due to series reactor and harmonics.

Figure-1 shows a typical railway traction S/S using 40 KV 2700 KVAr single phase capacitor bank with 13% reactor in series. The bank gives an output of 1.2 MVAr at 25 KV. The bank may consist of ten units forming two strings, each string having 5 units in series. A protection CT is connected between the two strings at mid or near mid point forming an arrangement of "H".

1.3 POLE MOUNTED CAPACITORS ON DISTRIBUTION OVERHEAD LINES

On long distribution overhead lines, specially on rural feeder, considerable voltage drops are noticed due to line losses. To improve the voltage, pole mounted capacitors are used, which are directly connected to the transmission lines without any switching device. These capacitors are normally 3 phase type in standard KVAr rating of 100/150. Three single phase capacitor units of rating 100/200 KVAr can also be connected in external star formation making a bank rating of 300/600 KVAr. Normally one capacitor per phase is used to avoid over voltage due to the failure



of parallel connected capacitors. On the incoming side, off-load isolators or disconnecting links and drop out fuses are used so that capacitor can be disconnected after de-energising the line. On-load isolators or capacitor switches (Vacuum or SF6 type) which can break small capacitor currents of 600 KVAr are also available indigenously, which, if used, can disconnect the capacitors without de-energising the transmission line. Since these capacitors are connected permanently on the bus, they have to face high over voltages during light load perioc. It is therefore recommended to use 13.5 KV capacitors for 11 KV system.

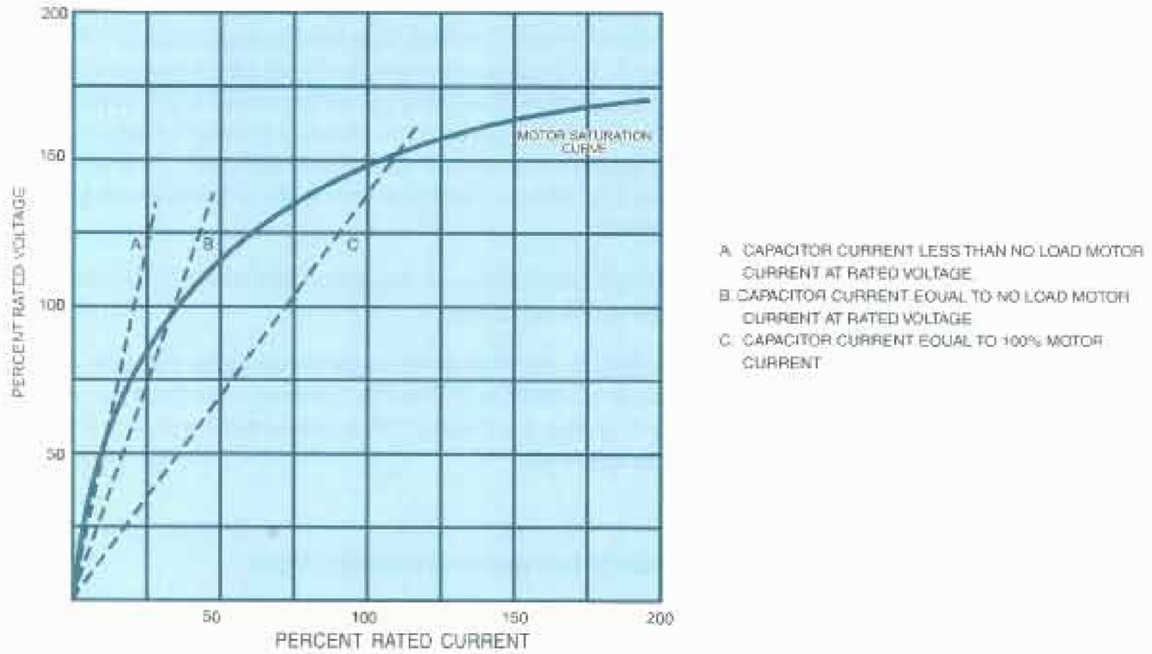
1.4 CAPACITORS FOR INDIVIDUAL COMPENSATION OF MOTORS

Capacitors are used for individual compensation of motors, transformers, etc., the compensation of motors being the most common one.

When the main load consist of a few big size motors individual compensation of motors ensure that the overall power factor is good, and since capacitors are switched On and Off along with the motor, over compensation is avoided. KVAr required for a motor can be arrived at by calculating KVAr required to improve the power factor to the desired level. In Figure-1 there are 4 motors, each of 450 KW at 0.88 power factor. 100 KVAr capacitor at 3.3 KV can improve the power factor to little more than 0.95.

Actual rating of capacitor works out to 120 KVAr at 3.6 KV. Reason for higher voltage is explained in 2 below.

FIGURE-2



Over voltage may result when the motor & capacitor combination is disconnected from the line. The inertia of the motor and its mechanical load will keep the motor rotating and the motor will operate as induction generator. The voltage of self excitation for a given motor and capacitor combination will depend on the inter-section of the capacitor volt-ampere line and the motor magnetization curve shown in Figure-2. If capacitor current is less than the motor current at no-load as shown by line A, then the over voltage due to self excitation will not occur. As a general rule capacitor KVAr is limited to 90% of no-load KVA of motor to avoid over voltages. 450 KW motors in Figure-2 have a no-load current of 23 Amps, i. e. no-load KVAr is 131.5 KVAr. Capacitor unit giving 100 KVAr at 3.3 KV is less than 90% of no-load KVA of the motor.

Two typical applications of capacitors for furnace have been shown in Figure-1.

Capacitors for Arc Furnaces:
A typical 25 tonne furnace needs 2200 KVAr capacitors to improve the power factor from .85 to .90. The following are recommended while designing capacitor schemes for Arc Furnaces:

a) Capacitors to be in ungrounded star formation.

b) Capacitors to be used with detuned reactors.

c) Preferably capacitor bank to be provided with separate switchgear. If common breaker is used to effect economy, then off-load isolator to be provided for disconnecting the bank whenever required. Isolators should be operated only when furnace is off.

d) PT/RVT to be used for quick discharge of capacitor bank.

e) Capacitor bank voltage to be chosen higher than the system voltage thus providing an added margin of safety to withstand over voltages due to harmonics.

In Figure-1, a bank of 2735 KVAr at 12.65 KV with 164 KVAr series reactor is provided which gives 2200 KVAr at 11 KV.

Capacitors for Induction Furnace:
Capacitors are also used in induction furnace for power factor improvement as well as for phase balancing.

A general arrangement has been shown in Figure-1.In this, some capacitor banks are fixed type and some are switchable type for balancing the load. Normally capacitor requirement and ratings are worked out by furnace suppliers.

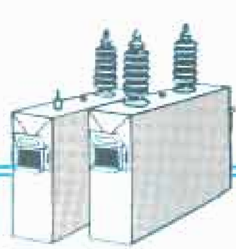
The following should be carefully considered while working out capacitor specifications:

a) Rated voltage of the capacitor should be equal to the furnace voltage rating. 10% over voltage margin available in the capacitor should not be used for continuous operation.

b) Wherever separate discharge coils are used in conjunction with the switching contactors, it should be ensured that discharge coil rating is sufficient for quick discharge of capacitors and the contactor should not be re-switched before the capacitors are discharged to safe values.

c) Good ventilation should be provided to see that the ambient temperature is within the limit of IS 13985 and proper cooling is effected.

Capacitors for Medium and High frequency furnace:
Water cooled capacitors are generally used for medium and high frequency induction furnaces. Copper tubing for circulation of water and other features for dissipation of losses are built into the assembly of each individual capacitor. Special care is required to see that water used for cooling



contains no contaminant that will react with or build up deposit in copper tubing. If water is contaminated some method of purification must be employed as capacitor life will depend on the efficiency of the cooling coils.

1.5 CAPACITORS FOR STATIC VAR CONTROL OF EHV STATIONS OR LARGE FURNACES

Static var control is used in EHV system for voltage support, more effective reactive compensation and improving stability under dynamic conditions, etc. and in arc furnaces to smoothen out the voltage fluctuations.

Static var system most commonly consist of thyristor controlled reactors with thyristor switched capacitors.

In Figure-1, SVC is shown with thyristor controlled reactor and fixed capacitors. Capacitors are connected with series reactors tuned to various harmonics like 3rd, 5th, 7th, 11th & 13th, etc. to filter out the harmonics generated by thyristors as well as present in the system, at the same time they give reactive output at power frequency. The capacitor requirements and specifications are worked out by SVC suppliers.

While selecting capacitor voltage, the following should be kept in mind:

i) Voltage rise due to tuned reactors.

ii) Voltage rise due to harmonic current flowing in the tuned filter.

iii) Voltage rise due to unfiltered harmonic current flowing in the filter.

iv) Abnormal system fluctuations.

1.6 FILTER BANKS

Many industries have fairly stable load but high content of harmonics due to the use of thyristors. High harmonics over-load incoming transformer effecting its load capacity. It also adversely effects other loads connected in system. Filter banks offer one of the most economical solution to purge the system from unwanted predominant harmonics, reduce distortion and simultaneously improve the power factor. For this, first total capacitor requirement is worked out which is required at 50 Hz to improve the P. F. to desired level. This total requirement is then broken up into number of filter banks like 5th, 7th, 11th etc. depending on the requirement for filters for particular harmonics. Complete details and extent of harmonics must be known to design proper filter bank. Capacitors and series reactors are suitably rated and designed to withstand harmonic voltages and currents.

Figure-1 shows typical industrial load having filter bank of 5th, 7th, 11 th & 13th harmonics. Tuned reactors are provided on neutral side to reduce the cost of the system. Capacitor voltages are rated higher to take care of over voltages due to harmonics, series reactors and system voltage variations. Complete system at 11 KV gives 5 MVAr to improve the P. F. to desired level.

1.7 STANDARDISATION OF CAPACITOR RATINGS FOR ELECTRICITY BOARDS

Electricity Boards are using power factor correction capacitors in their sub-stations to boost the voltages and to relieve transmission system and generating machines of supplying reactive loads. To maintain rated voltages at the consumer end, normally higher voltage levels are maintained at sub-stations and due to the regulation these voltages further go up during the no-load period.

Central Electricity Authority has therefore considered all these factors and has standardised certain rating of capacitor bank for use of Electricity Boards in their sub-stations.

These standard ratings are given below:

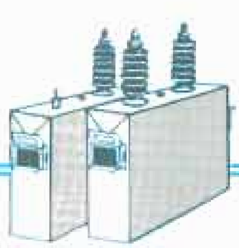
Std. Ratings of Capacitors

		For Bank		For Unit			
System voltage KV	Type of capacitor External/Internal	Rated voltage KV	Rated output MVAr	Rated voltage KV	Rated output KVAr	Type of connection	Output available at system voltage KVAr
11	External	12.65	1.8	7.3	150	Y	1361
		12.65	3.0	7.3	200	Y	2268
	Internal	12.65	1.8	7.3	150	Y Y	1361
		12.65	3.0	7.3	200	Y Y	2268
33	External	38	7.2	11	150	Y	5430
		38	14;4	11	150	Y V	10860
	Internal	38	7.2	7.3	200	Y Y	5430
		38	14.4	7.3	200	Y Y	10860
66	External	76	14,04	11	65	V Y	10616
		76	21.6	11	100	Y Y	16290
		76	28.6	11	100	Y Y	21770
	Internal	76	14.4	7.3	200	Y Y	10862
		76	21.6	7.3	200	Y Y	16290
		76	28.8	7.3	200	Y Y	21720

Many Electricity Boards have already adopted these standard ratings. Normally system conditions remain same in many of the industries. The above standard rating can also be used by them. The advantages of using standard ratings are quicker deliveries and easy availability of spares.

2. SELECTION OF RATED VOLTAGE OF CAPACITOR BANK

Capacitors are very sensitive to over voltages and may get damaged under excessive voltage conditions. Thus the question of fixing rated voltage of capacitor needs careful consideration. Capacitors are designed to withstand 10% over voltage for prolonged operation (IS 13925 Part (1):1998 fixes limit of this prolonged operation as 12 hours a day). In practice the voltages in distribution stations are higher during light load periods. To take care of poor voltage regulation and to minimise the switching operations, higher voltage ratings are selected for distribution stations as detailed in 1.7 above.



It should be noted that the capacitor output reduces in square proportion with the reduction in voltage. In Figure-1, the effective ratings of the banks on 33 KV & 11 KV bus are as given below:

$$\text{On 33 KV bus - } \left(\frac{33\ \text{KV}}{38\ \text{KV}}\right)^2 \times 14400\ \text{KVAr} = 10860\ \text{KVAr.}$$

$$\text{On 11 KV bus - } \left(\frac{11\ \text{KV}}{12.65\ \text{KV}}\right)^2 \times 3000\ \text{KVAr} = 2268\ \text{KVAr.}$$

It has been observed that voltage in rural feeders go as high as 12 KV during light loads, or at nights due to the voltage regulation. Therefore the recommended rating of pole mounted capacitors as given by REC is 13.5 KV, which takes care of these excessive over voltages. Use of series reactor with capacitor causes voltage rise on capacitor terminal. Therefore, while selecting capacitors with series reactors, the voltage rating needs to be increased.

Capacitor also causes voltage rise at the point of connection. Normally this rise of voltage is limited to 2% to 3% for most of the application. However, when a large capacitor bank is used, the voltage rise due to capacitor could be higher. This voltage rise should be calculated and capacitor voltage should be raised accordingly.

Capacitor can withstand only rated voltage continuously whereas system voltages normally vary by 10%. It is therefore recommended that capacitor rating should correspond to the highest system voltage. Wherever series reactors are used or in future if there is a possibility of providing a series reactor because of change of pattern of load, then capacitor voltage needs to be increased to take care of reactor over voltage.

We give below suggested ratings of capacitors for different system voltages.

			In KV		
System voltage	3.3	6.6	11	22	33
Capacitor rated Voltage	3.6	7.2	12	24	36
Capacitor rated voltage when used with 6% series reactor	3.8	7.6	12.65	25.3	38

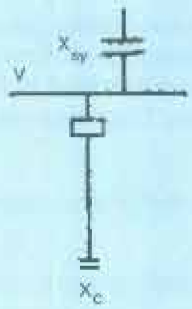
The above table is a good guide for selection of capacitor voltage for normal system. In case of abnormal voltage variations or excessive harmonics due to thyristor or non-linear loads, it is advisable to work out capacitor rated voltage on case to case basis.

3. PARALLEL SWITCHING

Capacitor at the time of switching-on momentarily offers very low impedance, resulting in a large flow of current at much higher frequencies to the capacitors. As the capacitor charge builds up the current comes to a steady state rated value. This initial current flowing during switching is called inrush current, which is commonly mentioned in multiples of rated current of the bank.

The inrush current and frequency of oscillation involved during isolated switching or parallel switching can be calculated as per the formula given below.

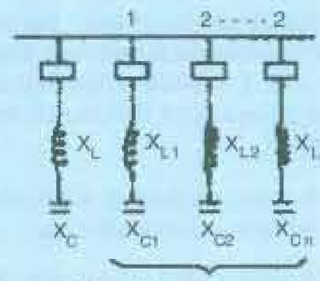
ISOLATED SWITCHING



Inrush current = $\dfrac{\sqrt{2}\,V}{\sqrt{3}\,\sqrt{X_C \cdot X_{sy}}}$ Amps.

$$f = 50\sqrt{\frac{X_C}{X_{sy}}}\ \text{Hz}$$

PARALLEL SWITCHING



$$X_{Ceq} = X_{C1} + X_{C2} + \cdots X_{Cn}$$

$$X_{Leq} = X_{L1} + X_{L2} + \cdots X_{Ln}$$

Inrush current = $\dfrac{\sqrt{2}\,V}{\sqrt{3}\,\sqrt{(X_C+X_{Ceq})\,(X_L+X_{Leq})}}$ Amps.

$$f = 50\sqrt{\frac{(X_C+X_{Ceq})}{(X_L+X_{Leq})}}\ \text{Hz}$$

Where:

- Xc - Impedence of capacitor being switched.
- X_{sy} - Impedance of system in ohms.
- V - Line voltage.
- f - Natural frequency.
- XL - Inductive impedance of the capacitor feeder being switched.
- Xceq - Equivalent capacitive impedance of capacitor banks already in service.
- XLeq - Equivalent inductive impedance of capacitor bank feeder already in service.

For isolated capacitor bank (single bank switching) the inrush current at the time of switching-on is quite manageable by the capacitors as well as most of the breakers. In Figure-1, peak inrush current for 38 KV, 14400 KVAr bank as well as 12.65 KV, 3000 KVAr bank are about 10.17 and 12.87 times the rated capacitor current respectively. Their natural frequency of oscillations are 415 & 525 Hz respectively.

When one or more capacitor banks are in service and the next bank is switched on, then all the operating banks discharge into the switched bank and this current is very large, and basically depends upon the impedance available between the energised and the switched bank. The impedance is normally very low as it consists of the impedance provided by the connecting cables, overhead jumpers and switchgear busbars etc. Normally the impedances of overhead jumpers and busbars are very small as compared to cable impedance. In Figure-1, there are two cases of parallel

switching. In industrial load, the inrush current when 1800 KVAr bank is switched last, is 211 times the rated current at 12 K. Hz. In pump house, when three motors are already running and the fourth motor is switched on, the capacitor connected to this motor will draw an inrush of 96 times the rated current at 5 K. Hz. In the first case, where the inrush current is 211 times, a small series reactor of 0.2% of capacitor rating is connected to one bank and after connecting this, the inrush value reduces to 24 times the rated current. In the second example, the inrush current values are lower because the cables are longer. Capacitors can be designed to take care of this inrush current and hence no series reactors are required.

4. HARMONICS

Capacitors do not generate harmonics, but are affected most when harmonics are present in the system. Capacitor impedance is inversely proportional to frequency. So it offers low impedance to harmonic current with the result all harmonics present in the system tend to flow in capacitors. Capacitors have large margin of 30% built in for harmonic currents. This margin is sufficient for most of the applications.

Wherever harmonics are excessive, it can damage capacitors due to over load or possible resonance. Following remedies are suggested:

i) Relocate the capacitor to the other parts of circuit to reduce over current due to parallel resonance.

ii) Increase or decrease the capacitor to reduce over current due to resonance.

iii) Capacitor can be switched off durin.g periods in which over currents are likely to occur.

iv) Design capacitors to take care of excessive harmonics.

v) When all the above remedies are inadequate, it may be necessary to install a reactor in series with capacitors. Normally capacitor bank is tuned between 200 to 225 Hz. In Figure-1, under arc furnace, series reactor is rated as 6% of capacitor impedance which works out to tuning at 204 Hz.

5. CAPACITOR UNIT PROTECTION

Individual capacitor units are provided with fuses for protection. There are two most common types of fuse protections used:

a) Internal element fuse.

b) External fuse.

The fuse is required to operate, once the element or the unit to which it is connected fails. Therefore, the purpose of the fuse is not to protect that element or the unit but to isolate it and thereby protect other elements or the units which are connected in parallel to the failed one. Internal fuse is connected with each and every element in a capacitor unit. There are many elements in parallel. In the event of a dielectric failure of one element, all the parallel connected elements discharge into the failed element and this operates the fuse of the faulty element. The isolation of this element causes small over voltage on the other parallel connected elements which they can sustain. Hence, the unit continues to be in service with a loss of fraction of its output. Internal fuse capacitors have simple and compact banking arrangement. Fuses get tested along with the capacitor unit. The disadvantages of internal fuse capacitor is that no external indication is available when the whole unit ultimately fails. Every unit in a bank is to be tested for finding out the faulty unit. It also does not protect the unit on insulation failure although such occurences are rare if the banks are maintained properly. But if leakage goes undetected, insulation failure can result, causing unit to burst. Internal fuses cannot prevent that whereas external fuse can.

In capacitors with external fuse, the primary fault in the element of the capacitor unit causes secondary faults. This increases the current flowing through the fuse which blows and thereby isolates the complete unit from the bank. External fuse rating is so selected that it carries normal current along with allowable harmonics continuously and does not malfunction due to inrush currents associated with capacitor .switching.

For small banks selecting a fuse double the current rating of capacitor units works reasonably well but large banks require careful selection of fuse rating, taking into consideration large discharge currents.

In a capacitor bank failure of one unit causes overvoltage on parallel connected healthy units. To keep this over voltage within safe limits of 10% certain minimum no. of units in parallel in each series groups are required depending upon the type of connection (single star & double star). The table gives the minimum number of capacitor units required in parallel in a bank.

No. of series group in a Bank	Minimum no. of units to be connected in parallel per series group/phase/star to limit overvoltage on healthy units to less than 10%	
	Single Star Bank	Double Star Bank
1	4	2
2	8	7
3	9	8
4	10	9

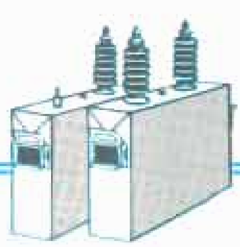
Two types of external fuses can be used:

a) Expulsion fuse

b) HRC fuse

Expulsion fuses are used for unit protection which works satisfactorily for normal sizes of banks. While deciding fuse arrangement the energy stored in parallel connected capacitors should be taken into account. Normally the total energy should not increase 10000 watts sec; This corresponds to about 2500 KVAr. Hence, when parallel connected KVAr is more, then either bank configuration should be changed or the other type of fuse, i.e. HRC fuses should be used.

Both internal as well as external fuses have their own advantages and limitations. For a particular application whether external fuse is better suited or internal, can be decided by an application engineer. Hence, his advice should be sought for deciding the type of fuse protection for the required application. In general it is advisable to go in for capacitors with internal element fuses for smaller banks as the choice of higher economical unit sizes are available. In case of large bank, capacitors with external fuses are preferred so as to have easy identification of failed units.



6. BANK PROTECTION

Apart from unit fuses, the following protections are recommended for a capacitor bank a whole. a typical capacitor bank protection scheme is shown in Figure-3.

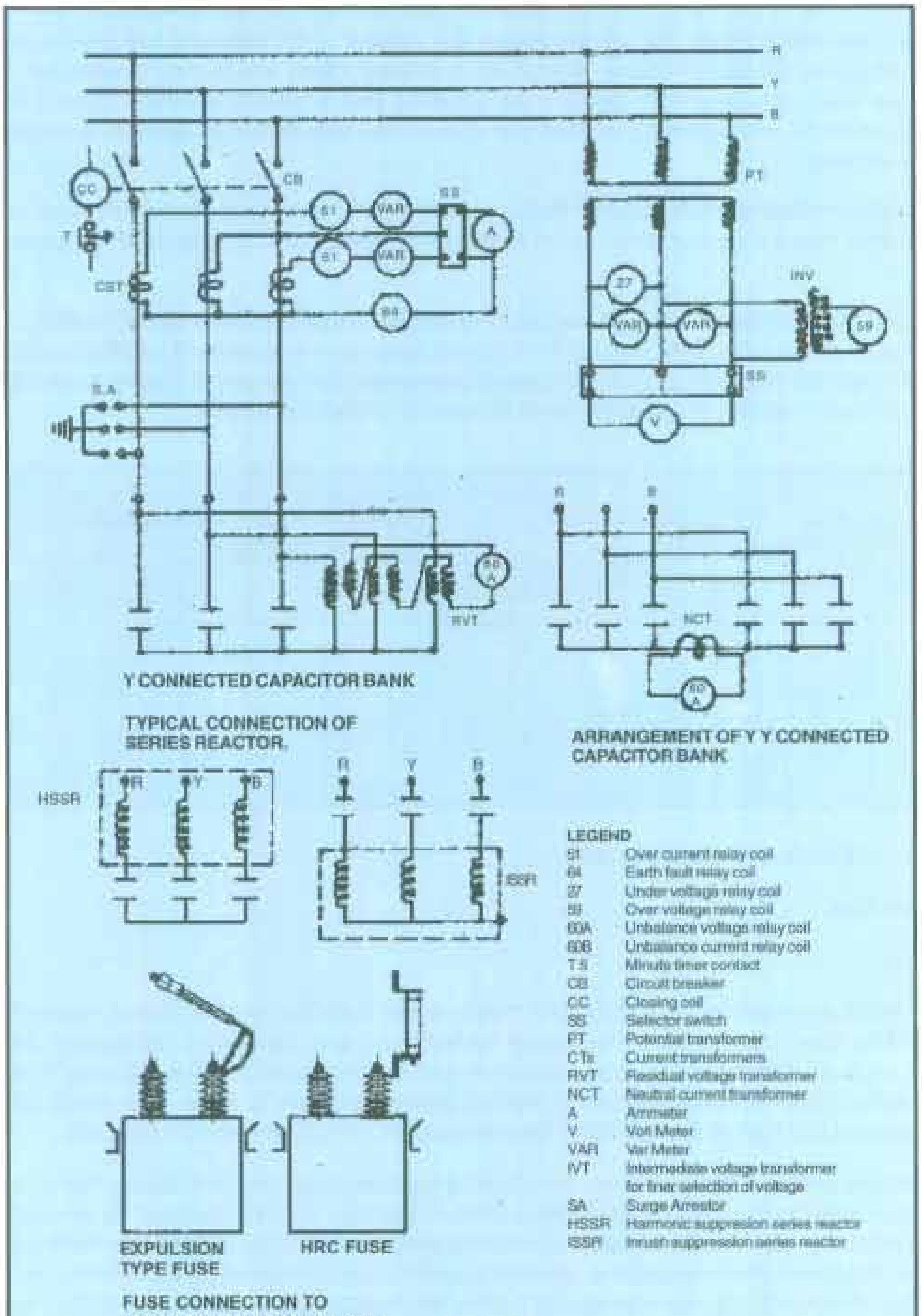


FIGURE-3

TYPICAL CONNECTION OF AUXILIARY, EQUIPMENT PROTECTION AND METERING.

6.1 OVER CURRENT AND EARTH FAULT PROTECTION

Over current protection is provided to disconnect the bank in case of overloading caused due to over voltage or excessive harmonic currents. It also protects the bank from any short circuit taking place between breaker and capacitor bank. Normally IDMTL type over current relay is used to trip the bank before current exceeds 1.3 times its rated value. Static relays are used with timer; to give fixed time lag to avoid tripping of capacitor bank on inrush during switching, or during transients. Normally relays are provided on two phases. When separate relay for short circuit protection is provided its setting is decided on the basis of inrush currents. Earth fault protection is provided with a minimum setting of 10%.

6.2 OVER VOLTAGE PROTECTION

Capacitors are very much susceptible to over voltages. Hence a relay is provided to ensure that whenever system voltage exceeds 110% of capacitor rated voltage or permissible maximum capacitor voltage, the bank is tripped. Normally IDMTL type over voltage relay having settings in seven equal steps of 10% each is provided. Sometimes when finer settings in between 10% settings are required, a small intermediate voltage transformer as shown in Figure-3 is provided.

6.3 NO VOLTAGE PROTECTION

Once supply fails capacitor bank should trip and should not be recharged till it discharges to a safe value of 50 volts or less. To ensure this, under voltage relay of instantaneous type with low voltage setting is used to trip the bank. A timer is provided to block the reswitching of capacitor breaker for five minutes, which is the time required by capacitors to discharge to safe value.

6.4 UNBALANCE PROTECTION

High voltage capacitor banks are normally connected in ungrounded star formation connecting units in series and parallel combination. In the event of failure of one unit, parallel connected units are subjected to over voltages. This over voltage could be of small consequence if great number of units are connected in parallel, but could be very dangerous if only a few units are connected in parallel. Therefore unbalance protection is used to trip the bank. Two types of unbalance protection are most common which are explained below:

Voltage Unbalance Protection:

Capacitors are connected in ungrounded star and three single phase PTs or a five limb RVT is connected in parallel having neutral interconnected with capacitors as shown in Figure-3. Secondary of PT/RVT are connected in open delta formation. In balanced condition, the open delta voltage is almost zero, but in the event of failure of capacitor unit the neutral is shifted and this shift is reflected in open delta winding. Table-I below gives open delta voltage as well as percentage overvoltage on parallel connected units in case of the failure of one unit in a bank. Here the rated PT/RVT voltage is considered same as capacitor rated voltage and secondary line to line voltage as 110 volts.

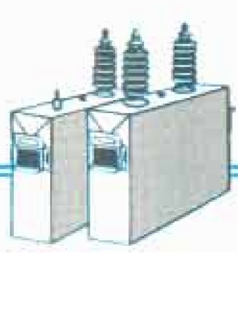


TABLE - I

No. of units in parallel per series group per phase	% Overvoltage and corresponding open delta voltage on failure of one unit in a bank					
	with one series group		with two series groups		with three series groups	
	% O/V	Open delta voltage in volts	% O/V	Open delta voltage in volts	% O/V	Open delta voltage in volts
2	20.00	38.1	50.00	23.81	63.63	17.31
3	12.05	23.8	28.57	13.61	35.00	9.53
4	9.09	17.31	20.00	9.53	24.13	6.57
5	7.14	13.60	15.38	7.33	18.42	5.01
6	5.88	11.21	12.50	5.95	14.90	4.05
7	5.00	9.53	10.52	5.01	12.50	3.40
8	4.35	8.28	9.09	4.33	10.77	2.93
9	3.85	7.33	8.00	3.81	9.46	2.57
10	3.45	6.57	7.14	3.40	8.43	2.30

Unbalance voltage relay is connected across the open delta winding which trips the bank when the voltage exceeds the set value. Normally IDMTL type relay is used to avoid unnecessary tripping on transients.

Current Unbalance Protection:
In this scheme capacitors are connected in double star formation with neutrals interconnected through a neutral CT. as shown in Figure-3. In balance condition there is no current flowing through the CT, but in the event of failure of a capacitor unit the neutral of one star shifts. This causes flow of current in the neutral.

Table-II below gives percentage overvoltage on parallel connected healthy units and corresponding neutral current in % of rated capacitor unit current in the event of unit failure in a double star bank having one to four series groups.

TABLE - II

No. of units per series group per phase per star	% Overvoltage and corresponding open delta voltage on failure of one unit in a bank.							
	with one series group		with two series groups		with three series groups		with four series groups	
	% O/V	Natural current in %	% O/V	Natural current in %	% O/V	Natural current in %	% O/V	Natural current in %
1	20.0	60.0	140.0	60.0	260.0	6.0	380.0	60.0
2	9.1	54.5	41.2	35.3	56.5	26.1	65.5	20.7
3	5.9	52.9	24.1	31.0	31.7	22.0	35.9	17.0
4	4.4	52.2	17.1	29.3	22.0	20.3	24.7	15.6
5	3.5	51.7	13.2	28.3	16.9	19.5	18.8	14.9
6	2.9	51.4	10.8	27.7	13.7	19.0	15.2	14.4
7	2.4	51.2	9.1	27.3	11.5	18.6	12.8	14.1
8	2.1	51.1	7.9	27.0	9.9	18.3	11.0	13.9
9	1.9	50.9	6.9	26.7	8.7	18.1	9.6	13.7
10	1.7	50.9	6.2	26.6	7.8	18.0	8.6	13.6

Suitable ratio can be selected for neutral CT and a relay can be connected across it's secondary winding as shown in Figure-3 to trip the bank. Normally instantaneous type relay is connected with fixed time delay relay to avoid tripping of bank on transient condition.

7. AUXILIARY EQUIPMENT

Major auxiliary equipments like switching equipment, series reactors, discharge device and lightning arrestors, which require special consideration for capacitor duty are discussed below. Other equipments like cables, isolator -', etc. are the standard type except that their current ratings should be minimum 1.4 to 1.5 times the capacitor ratings.

7.1 SWITCHING EQUIPMENT

Circuit breakers which are used for switching on and off capacitor banks must be restrike free. This normally means that the breakers must have a high breaking speed or be designed in such a way that the insulation between the contacts is increased very rapidly. Breaking actually takes place when the current passes through the zero point i.e. when the amplitude of the voltage across the capacitor is at its peak. After half a cycle the system voltage reaches maximum again but with opposite polarity, so that the voltage across the contacts of the breaker must therefore ensure that the insulation between the contacts is sufficiently high to prevent restriking. Each restrike raises the voltage on the capacitor, and the voltage across the contacts of the breaker increases in steps and the insulation of the system may be damaged.

Most of the breaker manufacturers have got their breaker tested for certain capacitor loads or the arc chamber design they are using, are tested by their foreign collaborators. Various types of breakers in use on 11 KV are vacuum, minimum oil and bulk oil. On higher voltage of 33 KV and above vacuum (upto 33 KV) and SF-6 breakers are most common in use. It should be ensured that breaker can take minimum 130% of capacitor current continuously.

7.2 SERIES REACTOR

The following reactors may be required for different purposes:

Inrush Suppression Reactor:

These reactors are used to suppress the inrush current during switching a parallel connected bank. A small reactor ranging from 0.2 to 1 % of capacitor impedance is used. Reactor can be connected on line side or neutral side of capacitor. If connected on line side the reactor has to be rated to full short circuit rating which increases the cost of reactor considerably. Better option is to connect on neutral side when SR does not have to clear fault current therefore the cost of such reactor is less. However when double star bank is used.SR has to be provided on the neutral of each star bank. Reactors should preferably be air cored and suitable to take 130% of capacitor rated current continuously.

Harmonic Suppression Reactor:

This type of reactor is used to keep harmonics away from the capacitors. For this, the circuit consisting of reactor and capacitor must be tuned to frequency below that of the lowest harmonic one wants to eliminate. 6% series reactors are commonly used to eliminate resonance at 5th harmonic and reduce inflow of higher harmonics.

Filter Circuit Reactor:

This is essentially similar to harmonic suppression reactor except that reactance is so dimensioned that the combination of reactor and capacitor gives very low reactance at particular harmonic which is to be filtered. For example, a fifth harmonic filter reactor shall have about 4% of capacitor reactance.

Conservator, explosion vent, breather, dial type thermometer valves for filteration are recommended fittings for inrush and harmonic suppression as well as filter circuit reactors. For bigger reactors (750 KVAr & above) 'Buchholz' relay is advisable. Normally, radiators are directly welded to the tank. However, for 750 KVAr or bigger reactors detachable type radiators can be provided on request.

Dry type reactors are also available for indoor as well as outdoor application. These reactors are single phase and are in coil formation. It is mounted on an insulated base. Proper magnetic clear-ances between the reaCtors and between reactors & other objects should be maintained as per manufacturers' recommendation. These reactors are costly as compared to oil cooled reactors.

7.3 DISCHARGE DEVICE

All power capacitor units must be directly connected to a discharge device unless they are con-nected to other electrical equipment that provides a discharge path. If the latter form of discharging is used then there must be no disconnecting switch, fuse cutout, etc. between the equipment used for discharging the bank and capacitor units. In HT capacitor units discharge resistors are provided inside the unit. These are designed to reduce the voltage across its terminal to 50 Volts or less within 5 minutes after disconnection from supply.

For quick discharge PTs or RVTs are used, which are connected to three phases of high voltage capacitor bank. Discharge takes place in couple of seconds. LT side of PT/RVT can be used to monitor discharge. Capacitors also get discharged very quickly when they are directly connected to transformers, motors, etc.

7.4 SURGE ARRESTOR

Surge arrestors are used to protect ungrounded capacitor banks connected on a circuit exposed to lightning surges. For switched capacitor bank, lightning arrestor should be placed close to capaci-tors. The arrestor protective ratio (i.e. impulse withstand level of capacitor to impulse protective level of surge arrestors) should preferably be higher than 1.5. Surge arrestors also give protection against switching surges. Surges originating due to restrike of breakers should be avoided as this may damage the arrestors. To take care of heavy discharge of capacitors use of station class arrestors is advisable.

B. ADVANTAGES OF CAPACITORS

The use of capacitors offer several advantages like savings in electricity bills, improvement in system voltage and release of capaci-y, etc. Some of these advantages have been illustrated below:

1. SAVINGS IN ELECTRICITY BILLS

High voltage consumers normally pay their electricity charges in 2 part tariff, i.e. maximum demand charges and charges for the units consumed. Considerable amount of money can be saved by reducing the maximum demand. Refer to Figure-1, wherein an industrial consumer has a 12 MVA transformer and has a maximum contracted demand of 9.5 MVA and the minimum demand charges payable is 75% of contracted demand i.e 6.75 MVA.

Maximum demand for a load of 7 MW at .78 power factor	$= \frac{7}{.78}$ MW = 8.97 MVA

After installing 5550 KVAr capacitor which gives 4000 KVAr at 11 KV, power factor improves from 0.78 to 0.975

Hence the maximum demand after installation of capacitors	= 7.18 MVA
Therefore reduction in maximum demand	= 8.97 MVA - 7.18 MVA
	= 1.79 MVA.
Taking maximum demand rate as Rs. 60,000/- per MVA,	
monthly reduction in electricity bills	= Rs. 60,000/- x 1.79
	= Rs. 1,07,400/

If we consider the cost of capacitors, associated equipments and installation as Rs. 275/- per KV Ar the total cost comes to Rs. 15.26 lacs, which can be recovered within 15 months.

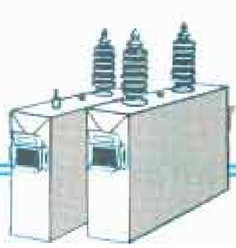
2. REDUCTION IN TRANSMISSION LOSSES

Electricity Boards, who have to transmit power from long distance can substantially reduce their transmission losses by installing capacitors. Let us consider a 33 KV transmission line and 33 KV receiving station as shown in Figure-1.

The average load of sub-station for 9.5 MW at .8 power factor	= 11.875 MVA
Hence, the load current	$= \frac{11.875 \times 10^3}{1.732 \times 33}$ Amps.
	= 208 Amps.

Installation of 3000 KVAr 12.65 KV capacitors (which give 2268 KVAr output at 11 KV) improves the power factor of the sub-station from 0.8 to 0.89

Hence, the load of the sub-station after installation of capacitors	$= \frac{9.5}{0.89}$ MW = 10.67 MVA
Therefore, the current flowing in the transmission line	= 187 Amps.



Considering the transmission line to be 40 km long and having its impedance as (0.5 + j1 0 4) Ohms per Km.

The total loss before installation of capacitors $= 3 \times I^2 R$

$$= \frac{3 \times 2082 \times 0.5 \times 40}{1000} \text{ KW}$$

$= 2596$ KW

The total loss after installation of capacitors

$$= \frac{3 \times 187^2 \times 0.5 \times 40}{1000} \text{ KW}$$

$= 2098$ KW

Hence savings $= (2596 - 2098)$ KW

$= 498$ KW

Net savings considering the load factor of 0.5 and electricity charges as 75 paise per unit. = Rs. 498 x 24 x 365 x 0.5 x 0.75

= Rs. 16,35,930

3. RELEASE OFTRANSFORMER & TRANSMISSION CAPACITY

Use of capacitor improves the power factor thereby reducing maximum demand. Thus, sub-station can take some more load. In Figure-1, if we consider a 33 KV sub-station, it has two transformers of 7.5 MVA each to cater to a load of 9.5 MW at .8 power factor. After installation of capacitors power factor improves to .89 and therefore the load in MVA reduces to 10.67 MVA. This relieves 1.2 MVA capacity to feed additional load, which works out to more 10% of the load.

Similarly we have seen in 2 above that the use of capacitor reduces the transmission line current from 208 Amps to 187 Amps. Here again the reduction works out to 10%, which means that transmission line can be further loaded by that much percentage of additional load.

4. IMPROVEMENT IN BUS VOLTAGE

Installation of capacitors improves the voltage at the point where they are connected. Rise in voltage is given as per the following formula:

$$\text{Percentage voltage rise} = \frac{\text{Capacitor MVAr} \times \text{\% of transformer impedance}}{\text{Transformer rating in MVA}}$$

In case of the industrial consumer where 12 MVA transformer having a percentage impedance of 10 has 4000 KVAr capacitors, the voltage rise works out as follows:

$$\text{Percentage voltage rise} = \frac{4 \times 10}{12} = 3.3$$

This is an added advantage of installation of capacitors where voltages are depressed.

C. HIGHLIGHTS OF UNISTAR HIGH VOLTAGE CAPACITORS

1. TECHNOLOGY

Universal Cables Limited is one of the oldest manufactures of power factor correction capacitors. Initially Universal Cables collaborated with M/sToshiba of Japan who apart from giving technical know-how had also provided Plant and Machinery. Later on in 1977, when General Electric of USA came out with the revclutionary technology of mixed dielectric capacitors, Universal Cables entered into a technical collaboration with them and started making capacitors with this new technology using biaxially oriented polypropylene film and capacitor tissue paper impregnated with PCB oil. Performance-wise ttiese capacitors were very good, but it contained poly chlorinated diphenyl. Studies show that this liquid is an environmental contaminant and totally injurious to certain aquatic, birds and animal life. There were problems of disposal of failed capacitors, which contained this liquid. Government of India directed capacitor manufacturers to switchover to non-PCB and non-toxic oils. Pursuant to this, Universal Cables went in for another collaboration in the year 1983 with the same General Electric Co. of USA for mixed dielectric as well as 100% polypropylene capacitors impregnated with non-PCB oils. Universal Cables now make non-PCB capacitors in all polypropylene design, which have been supplied to various Electricity Boards, Utilities and Industries. These capacitors are giving very good service. Manufacturing of mixed dielectric capacitors has been phased out as it offers no advantage over All PP capacitors and are costly. At the same time they are fire hazards.

2. RAW MATERIALS OF CAPACITOR

The following are main raw materials for high voltage capacitors:

1. Capacitor grade po ypropylene film.
2. Electrical grade aluminium foil.
3. Impregnating oil.
4. Discharge resistors.
5. Bushings.

The film used for capacitors is biaxially oriented polypropylene which has rough (hazy) surface. The haziness is achieved by itching the film on both the sides to make its surface rough. This is to help penetrate oil through its layers during impregnation. Polypropylene film and Aluminium foil is imported.

There are many types of non-PCB oils used all over the world. In Universal Cables, we use JARYlec/ Nisseki Condensor oil, which has excellent properties when used for 100% polypropylene design. This oil is imported from Japan/France and like other non-PCB oils, is termed flammable, but it has a high fire point of 160°C.

Discharge resistors is an integral part of HT capacitors, which is connected across the capacitor terminal inside the capacitor can. These resistors can withstand high voltage surges very well, are compatible with oil and are very reliable. The bushings used for capacitors are made of porcelain having a metal band to facilitate solder sealing/welding with the capacitor container. Special compounds are used to strengthen the solder point. Bushings and resistors are available indigenously.

3. MANUFACTURING PROCESS

A. CAPACITOR UNIT

i) Winding :

Power Capacitors consist of a number of basic elements, which are constructed by winding 2 layers of aluminium foil inter-leaved by layers of polypropylene. In case of mixed dielectric capacitors, tissue paper is placed between the polypropylene films. These elements are wound on a machine. During winding process taps are inserted for making connections. In an alternative method aluminium foils are extended on either side by staggering them and these are called extended foil design. Our present day production utilizes this method.

The winding is carried out in an air-conditioned, humidity controlled and dust free room. Dust is enemy NO.1 for capacitors. The particles floating in the air are in general tiny objects such as waste threads, small particles of sand, metal fragments, dust, exfoliated human skin, fume, carbon black, cigarette smoke, oil mist and other particulate matters generated by living beings. These particles are very small and usually are not visible to the eye. Around industrial plants, in one cubic metre of air there are about 10 million particulate matters of size above 0.5 micro mm in diameter, which are dangerous to capacitors. To eliminate these, apart from air-conditioning and humidity control, Universal Cables have installed high efficiency particulate air filters to remove these micro contaminants and air borne particles. A clean room is created conforming to US Federal Standards in cleanliness levels. Winding machines are also fitted with special foil embossers to create a pattern on the foil, which helps in better impregnation *of* capacitor elements, which is of vital importance for all polypropylene capacitors.

On completion of winding process the elements are individually inspected and tested. Elements are then assembled in parallel and series groups to achieve desired output. A pack thus formed is provided with insulation all round and then put in a clean steel container.

ii) Impregnation:

Capacitor units are then sent for impregnation. For 100% polypropylene capacitors proper impregnation is very vital. Capacitors are first dried under fine vacuum and controlled temperature. Simultaneously, impregnating oil is separately processed to improve its electrical properties and filtered to remove any trace of impurity. This oil is then filled in capacitors under vacuum. Special care is taken to see that oil is free from gases, moisture, ionic impurities, fine dust particles, etc. After the impregnation, units are taken out from the tank and sealed. Special oil filling accessories are provided to ensure that oil is filled upto the top of the bushing and no air remain trapped inside the unit.

iii) Testing:

Each and every unit is tested for routine tests as per Indian Standard. At regular intervals units are taken out for conducting various type tests like impulse, lossangle at elevated temperature, stability and partial discharge. Whenever a new design is adopted or modifications done in the existing design, such units are first tested for design process and proof test involving long duration high voltage high temperature test to check the life of capacitors.

UCL has in-house facilities to carry out all type tests and endurance tests as per relevant Indian/ International Standards.

B. CAPACITOR BANK

Capacitor bank is assembled by connecting individual units in series and or parallel combination to achieve desired output. Units are arranged on a steel rack or assembled in sheet steel terminal cover and then interconnected with busbars. Therefore, capacitor banking materials consist of mounting racks, interconnecting busbars, fuses in case of external fuse capacitor units, cable termination arrangement etc. Banking materials are therefore an integral part of capacitor bank. The most common banking arrangement is the open rack assembly, in which racks are made from angles and channels. Racks could be in single tier, two tier or three tier arrangement which can be placed on the floor directly or can be provided on an elevating structure to raise the bank to say 2.5 M above ground level. This is done to make the live parts inaccessible during its operation. The banks, which are kept on the floor are sometimes covered with wire mesh from all sides. Small capacitor banks are also arranged in terminal cover enclosing live parts. If HRC fuses are required then they are also connected inside the terminal cover. Capacitor units can also be mounted inside the cubicle. An exhaust fan is provided on the top and louvres are provided all round at the bottom for ventilation. Unless specially asked for, aluminium busbars are provided for making inter-connections. Two earthing points are provided with each unit and for the bank. The earthing busbars are normally half the size of main busbars. Capacitor units are assembled at the works and busbars are fixed. For ease of despatch the bank is dismantled and packed. These banks can be reassembled at site with the help of drawings and Bill of Materials provided.

C. PAINTING

Complete facilities are available for pickling, cleaning and phosphating of all steel containers and structures. The exterior of capacitor containers are first given a coat of red oxide primer followed by 2 coats of Ployurethane base paint of light grey shade 631 of IS 5. For special environment condition epoxy paint is provided on request. Banking structures, terminal covers etc. are also painted in the painting shop.

4. QUALITY CONTROL

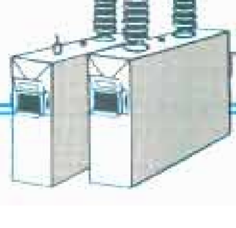
Universal Cables has unique facility of testing their raw materials before using in manufacturing. All the raw materials like polypropylene, paper, oil, etc. are checked for their various properties before the material is passed for manufacturing. Results are compared with the minimum acceptable limits. Any raw material failing to achieve the minimum acceptable level are rejected. Universal Cables also have complete facilities for type testing the capacitors at their works, which includes impulse, loss angle, stability and partial discharge and endurance test.

5. STANDARDS

Universal Cables makes power factor correction capacitors as per IS 13925 (Part 1):1998 (Superseding IS 2834-1986). Universal Cables can also manufacture capacitors conforming to other International Standards like IEC-60871 or BS-1650, etc.

6. RESEARCH & DEVELOPMENT

Universal Cables has a research and development department. Here trials are made with new raw materials and new designs and improvisations are made. It is the result of our R & D effort that we could successfully develop All polypropelene medium voltage capacitors varying in voltage level of 400 V to 1000 V. Dismal performance of MPP capacitors (metallized film capacitors) and exhorbitant cost of mixed dielectric capacitors encouraged us to bring down All PP capacitors technology to LT range by various modifications and improvisations in the HT technology. Universal Cables have successfully developed single layer All PP capacitor design for Lower Voltages and multilayer designs upto 1200 Volts. These capacitors are low on losses and can withstand high inrush currents, higher over voltages and large harmonic currents without loss of life. Today, Unistar All PP capacitors are considered the most sturdy capacitors.



7. SERVICES

Universal Cables have a team of well trained engineers to guide the customers on the application and selection of capacitors. The Company also undertakes turn-key projects for supply and erection of capacitors, if called for. UCL also has portable harmonic analyser to carry out harmonic analysis of the system.

D. INFORMATION TO BE GIVEN WITH ENQUIRY AND ORDER

Complete information given along with the enquiry helps to work out right type of capacitors and its associated equipments. Therefore while sending your enquiry please check on the following points.

1. When giving capacitor requirement, mention the required KVAr at the desired voltage. This is important because KVAr rating varies in square proportion with the change of voltage. Requirement of other equipment like series reactors, RVTs, protection equipments etc. may be clearly indicated. Use of reactor gives voltage rise on capacitor terminals and at the same time capacitor rating needs adjustment to compensate the loss of KVAr due to series reactor. It should therefore be stated whether such corrections have been made or not while arriving at the final rating.

2. In case you require us to work out the suitable capacitor rating for your system then the following should be furnished:

   a) The average load with existing power factor, desired power factor and the normal system voltage.

   b) Type of load should be mentioned. Whether induction motors, arc furnace, rectifiers or welding loads. In case of rectifier load, pulse number (six pulse or higher pulse) should be mentioned. Percentage harmonic content, if available, may be furnished.

3. System details like frequency, number of phases, fault level, incoming transformer rating with percentage impedance, voltage variation, maximum expected voltage with duration may also be furnished. If possible a single line diagram of the power system may be furnished.

4. If capacitor is to be connected directly to the terminals of the motor, then state motor rating, speed, existing and desired power factor and no-load current of the motor. It should be stated clearly whether motors are connected on different buses or on the same bus. If connected on the same bus, then parallel switching may be involved, for this individual cable length connected from switchgear to the motors should be furnished.

5. Details like ambient temperature, altitude above mean sea level, humidity, etc. may be mentioned.

6. Details of switchgear may be given, specially its suitability for capacitor switching should be confirmed.

7. Proposed location of capacitors, whether indoor or outdoor should be indicated. Any other special requirement, which may affect the design and operation of the capacitor should be indicated.