POWER FACTOR IMPROVEMENT

K.R. Govindan
Kavoori consultants

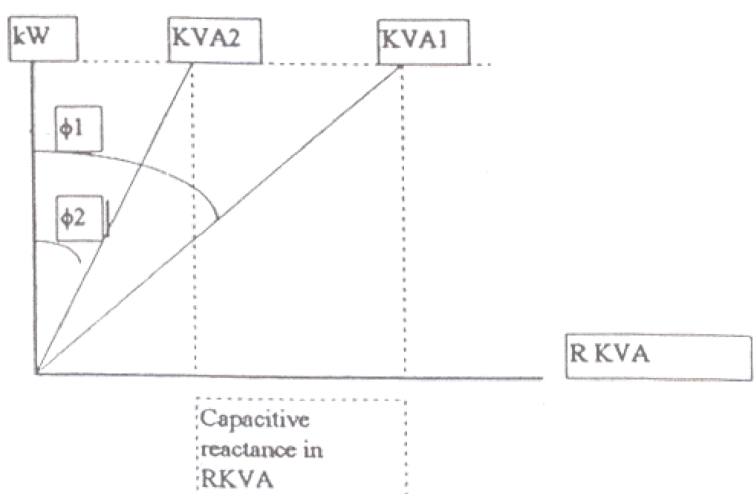
Alternating current circuits

Unlike Director Current Circuits, where only resistance restricts the current flow, in Alternating Current Circuits, there are other circuits aspects which determines the current flow; though these are akin to resistance, they do not consume power, but loads the system with reactive currents; like D.C. circuits where the current multiplied by voltage gives watts, here the same gives only VA.

Like resistance, these are called “Reactance”. Reactance is caused by either inductance or by capacitance. The current drawn by inductance lags the voltage while the one by capacitance leads the voltage. Almost all industrial loads are inductive in nature and hence draw a lagging wattles current, which unnecessarily load the system, performing no work. Since the capacitive currents is leading in nature, loading the system with capacitors wipes out them.

Capacitors for power-factor improvement

Whatever the power factor is, however, the generating authority must install machines capable of delivering a particular voltage and current even though, in a particular case, not all the voltage and current products is being put to good use. The generators must be able to withstand the rated voltage and current regardless of the power delivered. For example, if an alternator is rated to deliver 1000A at 11000 volts, the machine coils must be capable of carrying rated current. The apparent power of such a machine is 11 M V A and if the load power factor is unit this 11 MVA will be delivered and used as 11 MW of active power i.e. the alternator is being used to the best of its ability. If, however, the load power factor is say, 0.8 lagging, then only 8.8 MW are taken and provide revenue, even though the generator still has to be rated at 1000A at 11 kV. The lower the power factor, the worse the situation becomes from the supply authorities’ viewpoint. Accordingly, consumers are encouraged to improve their load power factor and in many cases are penalized if they do not. Improving the power factor means reducing the angle of lag between supply voltage and supply current.



It can be seen from the diagram that, voltage being constant, reduction in supply current means reduction in kVA load, that is the demand; the kVA approaches the kW as the angle between them is progressively reduced, which is ideal. This can be achieved by supplying the required leading RKVA, to wipe out the inductive KVA, by connecting capacitor banks. Hence all industries employ capacitor banks.

To calculate the capacitance required in RKVA, a simple numerical multiplier can be derived, as shown below:

To calculated the capacitance required in RKVA, a simple numerical multiplier can be derived, as shown below:

From the sketch the following formula can be derived:

Capacitance required in kVAr = Average Max. demand * Average P.F.*(tanΦ1 – TanΦ2)

Or,

Cap. Reqd. kVAr = M.D. * P.F. * (Tan (Cos^{-1} Present P.F.) – Tan (Cos^{-1} Preferred P.F.)

A simple multiplier chart is given in annexure 1, for determining the value of reactive kVAr required for improving the power factor from the present value to a preferred value.

Location of power-factor improvement capacitor banks:

Any installation including the following types of machinery or equipment, is likely to have low power factor which can be corrected, with a consequent saving in charges, by way of reduced demand charges, lesser low power factor penalties:

1. Induction motors of all types (which from by far the greatest industrial load on a. c. mains).
2. Power thyristor installation (for d.c. motor control and electro-chemical processes).
3. Power transformers and voltage regulators.
4. Welding machines
5. Electric-arc and induction furnaces.
6. Choke coils and magnetic system.
7. neon sins and fluorescent lighting.

Typical power factors encountered in various industries are given in Table 1, (See Annexure 2) but it must be emphasized that these power factor values are for guidance only. The actual power factor can vary from installation to installation.

Apart from penalties like maximum demand charges, penalty for low power factor, the factory cabling and supply equipment can be relieved of a considerable wattles or reactive load, which will enable additional machinery to be connected to the supply without enlarging these services. Additionally, the voltage drop in the system is reduced.

The method employed to achieve the improvements outlined involves introducing reactive kVA (kvar) into the system in phase opposition to the wattles or reactive current mentioned above the effectively cancels its effect in the system. This is achieved either with rotary machines (synchronous condensers) or static capacitors.

It is usually found that the expense of correcting a low per factor by means of static capacitors is less than the saving effected in the first 18 months; subsequent annual savings are there after clear profit.

The points to be considered in any installation are:

1. Reliability of the equipment to be installed.
2. Probable life.
3. Capital cost.

4. Maintenance cost.
5. Running Costs.
6. Space required and ease of installation.

Individual correction:

Where loads consist of reasonably-sized motors, say 7.5 kW and above, operating with a low-diversity factor, or where there are special drives running continuously, then individual correction of each motor can be considered. The main advantage of individual correction is that both motor and capacitor are switched as one unit and no additional control gear is required for control of the capacitor.

Apart from reducing the demand, which is separately charged by the power utilities, it can be seen that the current drawn is reduced by applying capacitors and improving power factor; and consequently, the I^2 R losses in the distribution elements, i.e., cables, transformers, busses etc.,
Hence, the most appropriate location at which the capacitor bank to be installed is as near as possible to the inductive loads, mainly the motors, Fig. 1. If not possible due to environment or areas classifications, they have to be installed at the nearest distribution board. A case study is enclosed in annexure 3, for highlighting the reduction in losses.

Individual power factor correction of motors:

As seen, the best location of connecting the capacitor bank is across the terminal of an induction motor, but care should be taken in deciding the kVAr rating of the capacitor in relation to the magnetizing kVA of the machine. If the rating is too high, damage may result to both motor and capacitor, as the motor, while still revolving after disconnection from the supply, may act as a generator by self excitation and produce a voltage higher than the supply voltage. If the motor is switched on again before the speed has fallen to about 80% of the normal running speed, the high voltage will be superimposed on the supply circuits and there may be a risk of damaging other types of equipment. As a general rule the correct size of capacitor for individual correction of a motor should have a kvar rating not exceeding 85% of the normal no load magnetizing k VA of the machine. However, 85% does not constitute an invariable rule, and for slip-ring motors and direct-on-line started squirrel cage motors on drives which never entail running over synchronous speed, the figure may be exceeded, although never beyond 90%.

Power losses in capacitors – The dielectric loss:

In practice, every dielectric excepting vacuum, has some resistance, which allows a small current in phase with the supply voltage pass through, an consume power, this is known as dielectric loss

When the dielectric of a capacitor is a vacuum, no losses take place in it, and the current taken by a capacitor leads the applied voltage by exactly 90^o, the power being zero. With any other dielectric, however, there is a loss, known as the dielectric loss, which has the result that the current does not lead the voltage by the full 90^o. The phase angle by which the lead falls short 90^o is called the loss angle. If this angle is represented by the sign δ, then the phase angle is (90^o – δ) and the power factor of the capacitor is cot. (90- δ), which equals tan g. Because of the small value of the angle g, the loss factor is normally referred to as 'tan δ'. The current taken by a capacitor is equal to I = s CV, and the power absorbed by a capacitor is equal to VI cos δ which is equal to VI tan δ (as shown in figure) for low values of δ, below 0.1.

The dielectric absorption may be considered to be equivalent to a low resistor in series with the capacitor (see figure 1.7 (a)) or a high resistance parallel shunt in the capacitor; these are related by the equation.

rCw = 1/RCw

Where r is the low series resistance and R the high parallel resistance. Losses in power capacitors are expressed in terms of watts per Kvar, e.g. tan g = 0.0006, loss = 0.6 watts/kvar. Since our aim is to reduce the losses or increase the utilization of the available power to the maximum, we have to select capacitors with lowest power loss. While ordering the capacitors, we have to insist on test certificate from the vendors specifying this loss.

Composite Dielectric Capacitors

Stresses in the composite dielectrics:

The effect of using a composite dielectric of material having different permittivities is to increase the stress in the material with the lower permittivity. This effect is very important in present-day capacitor technology as most h.v. capacitors now have a composite dielectric. For instance, polypropylene film, with a permittivity of 2.2 but of high dielectric strength, is wound with paper of a relatively high density of 1.1 and permittivity 6.0 but of lower dielectric strength and impregnated with oil of high permittivity. (6).

The end of the nineteen-sixties, saw the advent of the mixed dielectric capacitor with ratings up to 225 kvar. The mixed dielectric consists of oriented polypropylene (OPP) film interleaved with paper. The paper acts as a wick, permitting the impregnating fluid to penetrate between the layers of film. As a result the loss factor was drastically reduced from 2.5W/kvar (tan 8 = 0.0025) to 0.6 W/kvar (tan 8 = 0.0006).

Except in special cases, it is of course essential to provide suitable discharge devices for all low-voltage capacitors and these may be mounted internally or externally at the capacitor terminals. The discharge devices must be capable of discharging the capacitor down to 50 V within 60 seconds of disconnection from the supply.

General characteristics of polypropylene film

Film can be obtained in a number of thicknesses which is Europe typically includes 4,5,6 and normally used 8,10,15 and 18 micrometers, and in the USA in 44,50,55 and 60 gauge corresponding to 11.2, 11.7, 13.8 and 15.2 micrometers respectively. The film is used in 'mixed' dielectric constructions in the ratio 2:1 polypropylene: paper, i.e. in the inverse ration of their permittivities.

After much research work, orientated polypropylene film (OPP) was found to be suitable dielectric. It was compatible with the then acceptable PCB impregnant and was subsequently proved to be compatible with recent substitutes now in use. It was capable of accepting a stress of approximately 50 MV/m, 2 ½ times that of Kraft tissue paper, and possessed very low losses. These advantages offset the comparatively low permittiveity of 2.2 compared with the much higher value for kraft paper (5.5/5.9). Other thermoplastics such as polycarbonate and polyethylene terephthalate were used in combination with kraft paper, but did not possess the low loss of polypropylene.

Because plastics film does not readily absorb fluids it is necessary to employ kraft paper as a wick to ensure full impregnation of the element. In a mixed dielectric, the voltage stress appearing across the components in inversely proportional to the permittivity of each component. The fact that plastic film will accept a voltage stress 2 ½ times that of kraft paper, and that kraft paper has permittivity approximately 2 ½ times that of polypropylene film, means that each part of the composite dielectric is being utilized to the best advantage and the low permittivity of the film is turned to advantage. In a mixed dielectric high-voltage capacitor, two layers of film and one of paper are normally used between electrodes, the paper being the middle layer.

Capacitors employing meltallized polyproplene (mPP) technology.

With the advantage in technology in the manufacture of dielectrics for capacitors, tissue paper which was commonly used for manufacture of capacitors, both for LT and HT applications, was gradually substituted by polypropylene film, as the these films have the advantage of high dielectric strength, low dielectric losses and high resistance to failures.

In India also polypropylene film has been extensively used for the last fifteen years in the manufacture of capacitors both for HT and LT systems, initially along with condenser tissue as per in mixed dielectric design, and finally with total elimination of condenser tissue paper in “All film design”. While this construction has been highly successful in the case of HT capacitors and is still being used exclusively by all Indian manufacturers in the case of LT capacitors, unfortunately, All-film design did not prove its utility, firstly because of non availability of hazy PP in thinner gauges of 8-12 micron required for 440 volts, and defect in the single layer of PP film created dead short in the capacitor resulting in hazardous failures. Therefore in the case of using mixed dielectric i.e. PP film and condenser tissue paper continued till a substitute could be found.

MPP Film:

With the promotion of electronics in the country metalized film came to be used for manufacture of electronic capacitors. In this case, PP film was neutralized with a thin layer of aluminium deposited on one side under vacuum, so that the need for separate aluminum foil was totally eliminated.

Advantages

1. High dielectric strength of PP film:

The voltage stress that PP film can withstand is 45V to 60V per micron, a Pp film of 10 micron thickness will be adequate for low voltage applications up to 440V. If paper were to be used instead with dielectric strength of almost 50% a thickness of 20 micron paper will be required for the same purpose.

Because of reduction in thickness due to use of P film, the capacitor becomes much smaller in size for the same output.

2. High temperature with standability:

While paper can withstand temperature up to about 85 degree C. polypropylene can withstand temperature up to 115 degree C.

3. Low dielectric loss:

While mixed dielectric capacitors employing paper have dielectric losses ranging from 1.8 to 2.5 watts/ kVAr, polypropylene capacitors have losses ranging from 0.4 to 0.8 watts/ kVAr.

4. Low weight and compact size:

Polypropylene film due to its lower thickness being much lighter than paper, and aluminium foil of 6 micron thickness normally used being substituted by an aluminium deposit of 0.2 micron thickness, the total weight of each winding for the same number of turn is considerably reduced. As a result, the total size and weight of the capacitor with MPP technology as compared to mixed dielectric technology is hardly 30%.

5. Self-healing property:

Because of these advantage, capacitors of MPP technology have totally replaced capacitors of mixed dielectric design and are more readily accepted by customers due to their fail-safe operation and easy site repairs if at all any outage takes place.

Technical specifications of MPP L.T. capacitors

a) MPP capacitors are self healing type where in any internal fault will be removed by self-healing, thereby reducing the output to a very small extent, keeping the balance unit intact.

b) With use of CRCA metal container and oil impregnate, better cooling is achieved for 5KVAr units, since temperature rise is limited, use of oil is not considered necessary.

c) Power losses are much lower.

A table comparing the advantages and polypropylene over mixed dielectric capacitors is given below:

S. NO.	Parameters Capacitors	HT Mixed Dielectric Capacitors	HT 100% Polypropylene
1.	Losses	Up to 2.5 Watts/ kVAr	Less than 0.5 watts/ kVAr
2.	Running Costs	Due to Higher losses, running costs will be higher.	Due to lower losses, running costs will come down to 1/5 t of Mixed Dielectric Capacitors.
3.	Life	Will have life of 10 to 15 years depending on the site conditions.	Same life as Mixed Dielectric capacitors.
4.	Temperature rise	Due to higher losses, temperature rise is more.	Due to lower losses, temperature rise is less
5.	Reliability	Due to higher temperature rise, reliability is lower than 100% polypropylene capacitors.	More reliable in view of lower losses and lower temperature rise.
6.	Energy Cost	Due to higher losses, energy cost will be more.	Due to lower losses, energy cost will be lower than mixed dielectric capacitors.
7.	Size	Very large	Much smaller than mixed dielectric capacitors.

The major drawback of MPP capacitor in the Indian scene is that a large proportion of MPP capacitors produced in India is of very inferior quality. Such cells are unable to show consistent output beyond a few days or few weeks and suffer depletion of capacity.

Main advantages of MPP design are:

- Very low loss of the order of 8 watts per kVAr
- Reduced dimensions and weight
- Facility of quick simple repairs at site
- Freedom from oil leakage
- Property of self-healing by which incipient faults are cleared quickly without external protective aid.

Capacitors and Capacitor Banks

The basic construction of a capacitor.

Power capacitors consist of a number of basic elements which are constructed by winding two layers of aluminium foil interleaved by several layers of tissue, paper of mixed dielectric of paper and plastics film.

In the actual winding process two aluminium foils are would on the mandrel with one dielectric between the foils and one of the outside of one foil. This ensures that a foil will always be adjacent, in either direction, to a dielectric.

Two alternative methods of construction of the capacitor element are possible. (1) If the element is wound with aluminium foils, which protrude beyond the edge of the dielectric, it is referred to as an extended – foil element. (2) If the foils remain within the width of the dielectric it is called a buried – foil element. In the case of the extended foils the layer of foil are ‘staggered’ to permit connections to be made to the foil, after winding. In the case or the buried-foil winding, tinned copper tabs are inserted during the winding process to enable connections to be made. The alternative arrangements are shown in figure 3.

Maintenance and Tests

Visual Check

For damaged or dirty bushings, obvious leads, and finish damages needing touch-up.

Capacitance Check

The measured capacitance of a unit tests between 90% and 100% of nominal capacitance. If not, consult the manufacturer for comparison with original factory test value. Capaciance higher than 120% of nominal generally indicates one or more short circuited groups of internal windings, and the capacitor should be considered defective.

Capacitance readings should be made when the capacitor temperature is at 20 to 30 degrees Celsius.

Dielectric strength tests

Preferably made using a direct current voltage of 75 present of original factory test level equal to 3.2 times the nameplate voltage ratings. The test voltage should be held for ten seconds. On single phase units this voltage is applied bushing – to – bushing or bushing to ground stud for single bushing capacitors. On there phase RYB-connected units apply voltage phase to – neural at a direct-current voltage of 3.2 times the rated one line to neutral voltage between all pairs of bushings.

Avoid danger to personnel during this test from possible case repture by maintaining adequate shielding.

Discharge Resistance Check:

Discharge resistors are included in more high voltage capacitors to reduce the voltage from rated voltage to 50 units in five minutes or less. The actual value of resistance may vary with different designs but a maximum value can be determined from the following formula.

R = <u>300 Sec.* 1.1 * 1nV 81.414</u>
C nom 50

R - is in megohms.
Cnom - is in micro farads.
V - is the rated voltage in volts.

A resistance reading in the range of 70 to 100 percent of this value indicates the resistors are probably all right. If value lower that 70 percent are obtained, consult the manufacturer for precise limits.

For units rated 600 volts or less, replace 300 seconds in the above formula with a value of 60 seconds.

Capacitor Maintenance

Before re-fusing make a visual inspection and capacitance test. Also check for terminal-to-terminal shorts; can be performed using a medium voltage supply. A small 90 volt battery and an indicating light will detect more shorted capacitors than lower voltage.

Warning: Scrap capacitors only in strict conformance with EPA and other applicable regulations. Failure to heed this warning can cause sever personal injury or death, and damage to property.

Power factor improvement capacitors – location:

Assume a sectional load of 15 kW located at about 1000 from the main substation and connected by an aluminium cable of size D ½ x 240 Sq. mm cable.

D.C. resistance of the cable 0.125 / km load of the remove section 155 kW power factor of the load =8.

Consider the P.F. capacitor at the main substation bus.

Current drawn by the load at 0.8 P.F. = 240 A

Power loss in the cable = 2702 * 0.125 = 9.082kW.

If the P.F. correction capacitor is connected at the load section Distribution Board.

For a corrected power factor (of say) = 0.97

The current Drawn will be 222.3 a power loss in the cable for this current.
= 222.3 * .123

= 6.177 kW

Saving in power loss = 9.082 – 6.177
=2.905 kW

Saving in one year of operation, at 330 days, 24 hrs. a day = 23007.6 kWhr

Energy cost saved per year@ Rs. 4.25 / kWhr = 97782.3 of Say, Rs. 1.00 lakh.

To minimize the power loss and save energy and its cost, always locate capacitors at the section using maximum power, as close as possible to the respective substation panel.

Reference Book:
Energy & Fuel Users' Association Of India,(Jan.–March, 02),
4b – 1, Jp Tower,
7/2, Nungambakkam High Road,
Chennai – 600 034
Tel: 827 8604