INCREASING EFFICIENCY OF A POWER DISTRIBUTION SYSTEM

The Electrical Power is generated at a Power station and is distributed to the consumer through a maze of HV/LV distribution lines and step down transformers. A large HT consumer receives the power at its incoming transformer, converts into LT voltage and further distributes to various departments. A major consumption of electrical energy is in form of inductive loads of electrical motors. The inductive load requires both Active as well as Reactive power.

ACTIVE POWER

Active power is converted into productive work, hence it is the useful power. The utility company normally bills the active power, measured in kilowatts (KW). This is also known as the real power.

REACTIVE POWER

In order to generate a magnetizing field for performing useful work, the induction machine also needs power. This is called the Reactive Power. The reactive power does not do any useful work, but is shuttled between the generation point and the inductive machine. The reactive Power is Measured in Kilo Vars (KVAr).

DISADVANTAGE OF REACTIVE POWER

Reactive power is essential for an inductive machine to work, but as it only shuttles between the generation point and the induction machine, it simply loads the distribution network. The distribution network has to carry the additional current required by the reactive load.

I^2R loss:

When the current passes through any conductor, it generates heat equivalent to the resistance of the conductor. This heat is a clear loss and is known as the heat loss which add to the transmission losses. The loss is proportional to the square of the current passing through the conductor multiplied by the resistance of the conductor (Current ^{2} X Resistance). It is also called the I^2R loss.

Capacity Constrain:

As we have seen earlier the distribution network comprises of a maze of Ht/LT cables and distribution transformers. Every cable and transformer has a limited capacity to deliver the power. This capacity is measured in KiloVolt Ampere (KVA). Both active and reactive power are derived from this and they have the following relationship:

$$KVA^2 = KW^2 + KVAR^2$$

$$KW/KVA = \text{Power factor}$$

An example:

Let us that we have 80 KW inductive load at 0.8 lag powerfactor. To run this load we will require

80 Kw / 0.8 = 100 KVA distribution transformer

The reactive load of the system will be

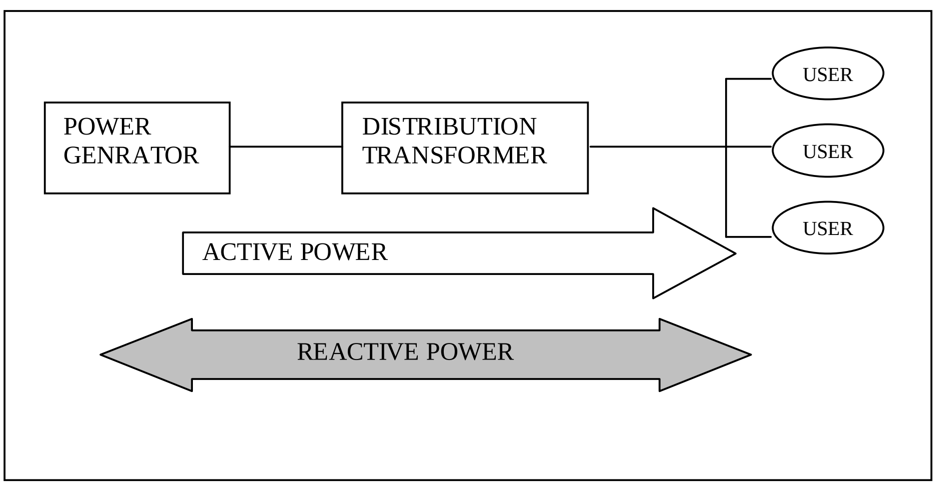
SQRT(100^2 – 80^2) = 60 KVRr

Assuming the system voltage of 415 volts. It will need nearly 28 amperes of additional current from the distribution system only for compensation of the reactive load.

To summarize, the reactive component has the following disadvantages in the power distribution network.

- It Increase in transmission losses (I^2R) in long transmission line.
- It constrains the distribution capacity.

The following diagram shows how active and reactive powers flow in the distribution system:



CONTROLLING REACTIVE POWER

Fortunately there is a simple solution to take care of the reactive power required by the induction machines by connecting capacitors in parallel. In Inductive loads the current lags volts by 90 degrees, while in the capacitive loads, the current leads volts by 90 degrees. So, if a capacitor is connected parallel to inductive load, the reactive power will be supplied by the capacitor. The capacitor acts as a Reactive Generator, and it releases the distribution system of supplying reactive power prior to its connecting point.

CONNECTING FIXED CAPACITORS

The easiest solution is to connect fixed value of capacitors of suitable value across the motor which will release the distribution system of the reactive power, but in real life there are other issues which makes this solution not so attractive.

- It can be good mainly for a fixed load.
- The capacitors must be switched on/off along with the inductive load. Also connecting the capacitor across motor terminal directly may damage the motor windings while switching off due to resonance effect.

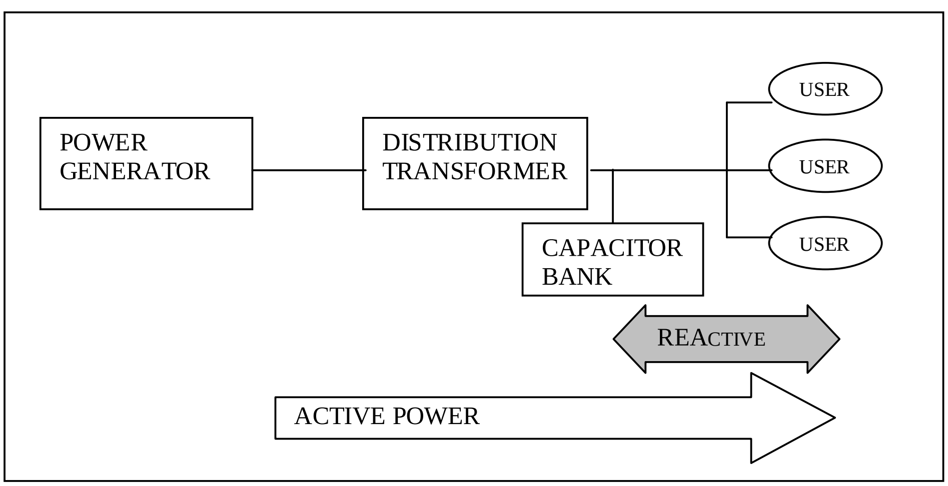
- As a leading powerfactor can be damaging, the capacitors are selected such that the powerfactor remains between 0.9 and 0.95, so the advantage of optimum (near unity) powerfactor can not be achieved. And one has to live with the losses.

- A variety of capacitors are required to be fitted on loads located all over the plant alongwith suitable switchgears. Maintenance of these capacitors is difficult and lots of manual operations required to ensure their switching on and off with the load. The derated capacitors are not easily detected and replaced, and overall powerfactor is affected adversely.

BULK CORRECTION

Instead of connecting individual capacitors, it is better to connect a switched capacitor bank with a controller that can monitor the power factor continuously and switch on or off required steps of capacitors. Such banks can be connected at the distribution point. Since they function automatically, they can take care of the variable reactive demand from that point onward.

The following diagram shows the flow of active and reactive power after the bulk correcting capacitors are installed at the outgoing of the distribution transformer.



Such system will release the distribution transformer, HT distribution line and the generator of supplying the reactive power, and works out to be a cost effective solution both the user company and the utility company.

ADVANTAGES OF BULK CORRECTION CAPACITOR BANKS

The bulk correction capacitor bank at the distribution transformer outgoing point offers the following advantages.

- Maintains powerfactor near unity (0.995 and better) using automatic control.
- Reduces line (I^2R) losses substantially in the HT power line.
- Releases the transformer and distribution capacity to connect more active load.
- Improves voltages in the line.
- Reduces transformer losses.
- Reduces the KVA demand if the power was imported from outside.
- Avoids powerfactor penalty levied by the utility company and eligible for the rebate

The following calculations shows how much can be saved by connecting such bulk capacitor bank at a typical substation without any upgradation in existing installed capacity.

FIXED V/S AUTOMATIC CAPACITOR SWITCHING

Traditionally, to compensate for the low power factor, fixed capacitors of appropriate values were installed as near as the inductive load as possible. Because of the variability of the load, the value of capacitors were chosen such that it does not overcompensate and reach a leading powerfactor. Because of this the preferred range of power factor remained within a range of 0.9 lag to 0.95 lag. Trying to improve power to near unity with fixed capacitor requires very close manual monitoring as leading power factor is detrimental to both, the utility company and the inductive machines. With Fixed bank , the following problems were found.

- Power factor could not be achieved to its optimum point (0.99 and better) and losses could be compensated only upto a certain limit (not beyond 0.95)
- Most capacitors had their own switches, and the operators had to make sure to switch off (or switch on) the capacitor when the inductive load was switched off (or on).
- Since capacitors have no moving parts, they had to be periodically checked for their healthiness. It was very time consuming to test and replace a faulty capacitor as they were scattered all over the plant.

- A variety of capacitors had to be kept in inventory for proper replacement as the loads would comprise of a variety of sizes of inductive motors.

Now, with advent of latest microprocessors, reliable controllers are developed which can switch in/out the capacitor bank as per the need and maintain a power factor to near unity. Using such automatic bank has many advantages vis-a-vis fixed type capacitors.

- All capacitors are grouped together at one point and are easy to monitor and maintain

- The power factor can be maintained to near unity, and that too automatically.

- No human monitoring of capacitor switching is required when switching any inductive load.

- The inventory need of capacitors will be uniform and minimum.

- Modern controllers provide facility of finding faulty stages much quicker and quicker replacement means direct saving by improved power factor.

- Since the fixed type capacitors also required switch and/or contactor there is only a marginal cost increase of putting an automatic controller and its associated equipment compared with fixed type of installations, but the benefits are much higher.

ADVANTAGES OF AN APFC PANEL AT DISTRIBUTION SUB-STATION.

For a utility company a distribution sub-station can be one of the ideal location to install an automatic power factor correction capacitor panel.

- By compensating the reactive demand at sub station level on LT side, the transmission losses (I^2R) in long HT lines are directly saved as it doesn’t have to carry the additional current for the reactive demand.

- The transformer losses (%) are saved in proportion of the improvement of the power factor as seen in the following formula

  % Distribution losses reduced = 1-(old P.F./new P.F.)^2

- Payback of the panel is less than 1-1/2 years in most cases.

- At the substation, the imbalance of unequal load is minimum hence standard delta connected capacitors can be installed effectively and also the panel consists of sizable KVAr, the cost per KVAr will be minimum.

- Easy to monitor and maintain.

TRANSMISSION LOSS SAVINGS USING 200 KVAr CAPACITOR BANK

Transformer Rating	11kv / 440 Volts 750 KVA
Typical Load	360 KW at PF = 0.8 lag
HT Cable Resistance	0.150 ohms/km *
Typical length	10 kilometers
Achievable PF	0.98 lag
Capacitor Bank Size	200 KVAr

* data taken from an available source.

1. Initial loading on transformer KVA1 = 360 / 0.8 = 450 KVA

2. Initial Primary current I1 = 450 X 1000 / 1.7320 X 11000 = 23.62 Amps

When 200 KVAr Capacitor Banks are connected to this load, the power factor will improve to 0.98 lag. The new loads are as follows:

3. New KVA Loading on Transformer KVA2 = 360 / 0.98 = 367.34 KVA

4. Final Primary Current I2 = 367.34 X 1000 / 1.7320 X 11000 =19.28 amps

REDUCTION IN CABLE RESISTANCE (I^2R) LOSSES

The reduction in KVA demand will reduce the current flow in the transmission line of the primary side of the transformer. Assuming a cable length of 10 Kilometers and the wire resistance of 0.150 ohms per kilometer, the following calculation shows the reduction in energy loss in the cable.

Resistance of the cable R = 3 X 0.150 X 10 = 4.50 ohms

Watt Loss = W = $(I1^2 - I2^2) \times R$

= ((23.62 X 23.62) – (19.28 X 19.28)) X 4.50

= (557.90 – 371.72) X 4.50 = 837.81 watts = **<u>0.838 KW</u>**

Reduction in energy loss during one year:

E = 365 X 24 X 0.838 = **<u>7341 KWH</u>**

RELEASING DISTRIBUTION CAPACITY

When the Reactive Energy is compensated by the capacitor bank, there will be an amount of capacity of the transformer and generating system released to deliver that much more Active Energy. This additional active energy is available without addition or upgradation of the installed capacity. The following calculation shows the effect of a 200 KVAr capacitor bank on a 11kv/440 V 750 KVA transformer distribution.

Transformer Rating	11kv / 440 Volts 750 KVA
Transformer Loading @ 60%	450 KVA
Initial Power Factor	0.80 lag
Achievable PF	0.98 lag
Capacitor Bank Size	200 KVAr

1. Kilowatt Delivered at 0.80 lag PF

   KW1 = 450 X 0.80 = 360 KW

When a 200 KVAr Capacitor bank is connected to this distribution transformer, the power factor will improve to 0.98 lag. This will release the active load capacity of the transformer and distribution system.

2. Kilowatt Deliverable at 0.98 lag PF

   KW2 = 450 X 0.98 = 441 KW

Total release of capacity KW = KW2 – KW1
= 441 – 360 = 81 KW

Computing the year around effect, the system will be able to deliver additional

365 X 24 X 81 = **709560 KWH (Units)**

CONTROLLER TECHNOLOGY

In bulk correction capacitor banks, the capacitors will be subjected to frequent switching. Since the capacitors are frequently switched, they must be of robust type. Currently, capacitors made from All PP film and foil has a proven track record of good performance in adverse fluctuations, harmonic contents in the power line and frequent switching.

However, the heart of such switching action is the controller which performs the monitoring and switching function. There are two types of controllers available. 1) PF sensing type and 2) VAR sensing type.

PF Sensing Controllers

These controllers normally monitors the angle between current and voltage and switch a capacitor bank on or off depending on the comparison between set PF and actual PF. Normally only one phase is sensed for taking a corrective decision.

VAR Sensing Controllers

VAR sensing controllers will monitor all 3 phases on continuous basis and integrate actual Kvars (Kilo Vars) needed by the system at any point of time. The decision of switching on or off of a cpacitor bank is made on the actual

KVAr demand and setting can be made as small as the stepsize of the smallest capacitor. This allows us to maintain the powerfactor near unity (0.999)

Comparison Between PF Sensing and VAR Sensing Controllers

Sr.No.	PF Sensing	VAR Sensing
1.	Can maintain PF upto 0.99 lag	Can maintain the PF near unity (0.999)
2.	As it senses only one phase, it assumes a balanced load and will not produce an optimum result. In case of unbalanced load the PF will have to be set lower in order that it does not go on the lead side.	As it senses all 3 phase and integrate KVAr, the optimum result will be achieved and no need to set the power factor away from the unity.
3.	As it senses only the power factor, it disregards the actual voltage and current and the load, hence it may switch an inadequate bank resulting into frequent switching and/or sometimes the hunting.	As the actual KVAR (lead or lag) is measured, it can switch on or off only the necessary banks and operates in a very stable manner without hunting.
4.	Since it only monitors the PF, other electrical parameters are disregarded	In order to computer the required KVAr, all basic electrical parameters are sensed, and such unit can store those in its internal memory, hence it can also provide information regarding Voltage, currents KVA, KW frequency etc, if necessary. It can work as an electrical data monitoring system.

The Capacitor Banks Switching Methods:

There are 3 popular methods of switching in / out a capacitor bank by the APFC controllers.

- First In First Out (FIFO)
- Geometric (1:2:4:8)
- Intelligent

FIFO
In this method, the capacitors are switched in or out sequentially. When there is a reactive demand the first capacitor is switched on, if there is still more need, the next one switches on and then the next, when the reactive demand reduces and if the capacitor needs to be switched off, then the 1st one will be switched off and then the next one.

This method ensure the equal usage of capacitors over a period of time. It is suitable when all the capacitor steps are of equal values.

Geometric (1:2:4:8:..)

This too is a sequential method, but the step sizes are unequal as the sequence suggest, 1:2:4:8:…. The second step must be double the size of the first, and the third 4 times the size of 1st, 4th is 8 times the size of 1st step. With this method, we are able to regulate required demand with less no. of stages and control it with the smallest size capacitor. eg.

With one bank of 10, 20, 40, 80 KVAR each, we can control 10+20+40+80 = 150 KVAR in step size of 10 KVAR using only a 4 stage relay.

Such controllers can be programmed as 1:2:2:2:2 or 1:2:4:4:4 or 1:2:4:8:8 depending on the availability of the bank sizes.

Intelligent :

In this method, the controller stores the value of each bank connected in its memory. When a demand arises, it will select the banks which needs to be switched on or off with the optimum combination to satisfy the demand, and switch on or off the selected bank at a time. This is a direct method of switching and reduces the wait period between switching in the above mentioned methods.

Compared with a 16 step FIFO method, assuming a 2 mins delay between switching, the FIFO controller can take 32 mins to switch on all the stages, while the intelligent controller can do that within 60 seconds.

Capacitor Switching Devices:

There are two popular devices for switching the capacitors
- Contactors
- Solid State Thyristors

Contactor Switching:
The most common practice of capacitor switching is using contactors. Since capacitor switching generates a very heavy inrush current, The contactor rating should be adequate.

Advantages:

- Simple design
- Lower cost esp. in smaller KVAr ratings

Disadvantages:

- Requires frequent maintenance and cleaning
- Generates spikes and ringing at time of switching due to high inrush current. This deteriorates the power quality and hampers the operation of sensitive electronic equipments.
- Takes much longer time to compensate the reactive power as we have to provide longer switching delays, for allowing the capacitor to discharge completely before it is switched in again.

Thyristor Switching:

This is a relatively new switching technology where the capacitor is switched using Solid State Thyristor instead of mechanical switch. The control circuit switches the capacitor at Zero current cross point to ensure smooth switching.

Advantages:

- Very fast switching. Compensates the reactive power in seconds.
- Minimum delay required to re-switch the capacitor. As the switching is made at a zero current crossing point, it does not require capacitor to discharge fully before switching on again.
- The Switching does not produce any spikes or harmonics hence much superior power quality. The transients affecting sensitive electronic equipment will not be generated a switching time.
- Since there is no mechanical switching involved, very little maintenance required.
- Switching of parallel multiple banks will generate very high inrush current when contactors are used. This damages the contactors. Thyristor Switching will not produce the inrush current hence any number of parallal switchings can be made safely.
- Capacitor life is much extended as they are always switched without any stress.

Disadvantages:

- Being a solid state device, there is a minor heat generation and wattloss.
- Little higher cost.

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