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Concepts of Reactive power, Low Power Factor and methods of power factor improvement are briefly explained before answering the specific questions.

What is reactive power:

Power factor is defined as the ratio of real power to apparent power. This definition is often mathematically represented as kW/kVA, where the numerator is the active (real) power and the denominator is the (active+ reactive) or apparent power. Though the definition is very simple, the concept of reactive power is vague or confusing even to many of those who are technically knowledgeable.

Explanation for reactive power says that in an alternating current system, when the voltage and current go up and down at the same time, only real power is transmitted and when there is a time shift between voltage and current both active and reactive power are transmitted. But, when the average in time is calculated, the average active power exists causing a net flow of energy from one point to another, whereas average reactive power is zero, irrespective of the network or state of the system. In the case of reactive power, the amount of energy flowing in one direction is equal to the amount of energy flowing in the opposite direction (or different parts -capacitors, inductors, etc- of a network, exchange the reactive power). That means reactive power is neither produced nor consumed.

But, in reality we measure reactive power losses, introduce so many equipments for reactive power compensation to reduce electricity consumption and cost.

Confusions:

The undisputable law of conservation of energy states, “energy can neither be created nor be destroyed”; yet we talk about Conservation of Energy!! The confusions erupt when we yells out the theory of conservation ignoring other theories of thermodynamics - like one, which states that entropy (low quality energy) is ever increasing. Mathematical sum of total energy has no meaning to an energy user, and hence he must be concerned about the efficiency of conversion and conservation of energy. Similarly, though we can mathematically prove that loss in reactive power is no real loss and no reactive energy is lost, we have several other reasons to be concerned about reactive power improvement. This can be better explained by physical analogies.

Physical Analogies:

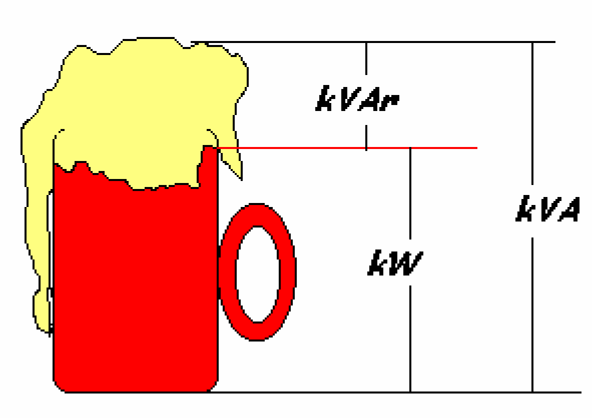
Suppose I want to fill a water tank with water, one bucket at a time. Only way is to climb a ladder, carrying a bucket of water and pouring the water into the tank. Once I fill up the tank, then I have to go down the ladder to get more water. In this one cycle of going up the ladder and coming down I have done some work or the energy required to go up is more than the energy required for coming down.

If I had climbed the ladder with an empty bucket, and I had come down with the same bucket I am not doing any work. The energy for upward and downward motion is the same. Though I have not done any work – worth paying for- I require some energy.

That is, the energy that it takes to go up and down a ladder carrying nothing either way requires reactive power, but no real power. The energy that it takes to go up a ladder carrying something and come down without carrying anything requires both real power and reactive power.

The analogy can be extended for explaining 3 phase system if If we put 3 ladders going up to the tank and 3 people climb up in sequence such that there is always a steady flow.

Another analogy, a bit simplistic, is the "Beer Mug analogy".



Power Factor = Active power/Apparent power = kW/kVA
= Active power/ (Active Power +Reactive Power)
= kW/(kW+kVAr)
= Beer/(Beer +Foam)

The more foam (higher kVAr) indicates low power factor and vice versa.

(In Electrical terms kW, kVA, and kVAr are vectors and we have to take the vector sum).

What causes low power factor in Electrical System:

Various causes, which can be attributed for low PF, may be listed as follows.

1. Inductive loads. Especially lightly loaded induction motors, and transformers.
2. Induction Furnaces
3. Arc Lamps and arc furnaces with reactors.
4. Fault limiting reactors
5. High Voltage.

The reactive power required by these loads increase the amount of apparent power in the distribution system and this increase in reactive power and apparent power results in a lower power factor.

How to improve Power Factor

Power factor can be improved by adding consumers of reactive power in the system like Capacitors or Synchronous Motors.
It can also be improved by fully loading induction motors and transformers and also by using higher rpm machines. Usage of automatic tap changing system in transformers can also help to maintain better power factor.

Question:Under which circumstances may power factor corrections

A) reduce electricity consumption in a plant

Ans: Power factor improvement in plant, by adopting any one of the aforementioned options, will generally compensate for the losses and reduce current loadings on supply equipment, i.e.; cables, switchgear, transformers, generating plant, etc. That means, power factor corrections – whenever there is scope for correction- will reduce electricity consumption in the plant and in turn the electricity cost. Many of these losses are not properly monitored in many industries and hence the savings are not quantified. This may be one of the reasons for the **argument that PF improvement reduces only electricity costs in case the power utility is offering a tariff where a reactive power demand charge are part of the monthly electricity bill.**

Power factor improvement will lead to reduction in electricity consumption, when it is done at the equipment level or at the Control Center level. (A case study is given to demonstrate the savings in both these cases) But it will not lead to reduction in electricity consumption if the plant, receiving power from a common grid, carries out the correction at the supply voltage/incoming voltage level, just to compensate for the reactive power drawn from the grid. If the plant does the above correction in their own self-generating grid supply, there will be a saving in cost (either in terms of electricity cost or in fuel cost) due to reduction in generator losses.

B)reduce electricity costs only

Ans: Power factor correction will reduce electricity cost only, when the plant receiving power from a common grid carries out the correction at the supply voltage/incoming voltage level, just to compensate for the reactive power drawn from the grid. But, even this improvement in PF may not always reduce the electricity cost as the contract demand in a plant is very often fixed on a fictitious consumption in the plant. On many occasions contract demand is fixed based on the future expansion plans, and based on the high diversity factor taken during design stages. In most of the cases the Utilities charge for a minimum contract demand irrespective of the consumption and a reduction in kVA may not produce any benefit as long as the contract demand is re-fixed to actual value.

Generally PF is improved to 0.95-0.98, as improving PF further to unity may lead to higher payback periods.

c) reduce both electricity costs and electricity consumption

Ans: In all other cases, other than the above mentioned exception, whenever **improvement of power factor** is carried out, it will eventually lead to reduction in electricity consumption and hence electricity cost.

However, payback on investment due to power factor correction depends on the type of installation and various other factors like power tariff, loading pattern of equipment, method of power generation/utilization, operating philosophy of the plant etc.

Generally power factor correction is done in two ways.

1. Individual correction
2. Group correction.

Advantages and disadvantages of both these methods are tabulated below.

Individual Correction

Advantages	**Disadvantages**
Increased load capabilities of distribution system	Small capacitors cost more per kVAr than larger units.
Can be switched off with equipment thus no additional switching is required	Economic breakpoint is generally 10HP
Better voltage regulation	Difficult to install in special application areas like flame proof/increased safety
Capacitor sizing is simple	Add more equipment for maintenance
Capacitors coupled with equipment can be relocated during rearrangements	When the capacitor rating is too high- more than magnetizing kVA of the machine- it may damage the motor and other connected equipment

Group correction

Advantages	**Disadvantages**
Increased load capabilities of the service	Switching means be required to control amount of capacitance
Reduced material costs relative to individual correction	Individual switches are required
Reduced number of equipment for maintenance /Easy access for checking	Does not reduce cable losses, below the point of correction
Self Excitation of induction motors due to high capacitors avoided	Higher pay back
Cost per kVAr is less as larger units can be installed	Does not contribute to down line equipment life/efficiency improvement
Demand management is easy, and PF can be corrected near to unity	Leading power factor on Self Generating plants if not switched properly
Can be installed in substations and hence suitable for hazardous areas	Chances of switching directly the capacitor loads on power outages

Individual correction

For example, when an induction motor, which is the most widely spread contributor to the reactive power in a plant, needs reactive power it is not necessary to draw it from the generators in the transmission grid, but a capacitor near the motor terminals can supply it. This relieves the generator and all the transmission lines between generator and motor of having to transmit those VARs and hence the current in the lines will be smaller than when the capacitor is installed. This will reduce the heat loss (I^2 R) losses and reduce voltage drop in the system.

A 10% drop in terminal voltage from the rated, will reduce the Induction motor torque by approx 19%, increase full load current by approx 11%, reduce overload capacity and increase temperature rise by approx 6-7 degrees.

The power factor of an induction motor

- ✓ Increase with increase in horsepower rating of the motor.
- ✓ For a given rating the power factor increases with increase in speed.
- ✓ Decreases with reduction in load conditions.

Hence, the best and easiest method of power factor improvement starts from proper selection and utilization of motor.

The case study given below shows that the there is substantial reduction in losses, when the capacitor is installed at the motor end. The I^2Rlosses in motor feeders, transformer outgoing feeders, and that inside transformer windings are estimated. Subsequent loss reduction n generator windings and in the bus-bars are not quantified. The advantage of voltage and efficiency improvement due to reactive power compensation is also not quantified. It can be observed that even the easily quantifiable losses itself will be sufficient to justify the investment on power factor improvement through capacitor banks.

It may also be noted that reduction in kVA demand can also result in reduction of electricity cost, depending upon the tariff structure.

Another important point to be noted here is that, if the motor or transformer cables are of smaller size than what is shown in the case study or if the length are more the losses would be higher than projected.

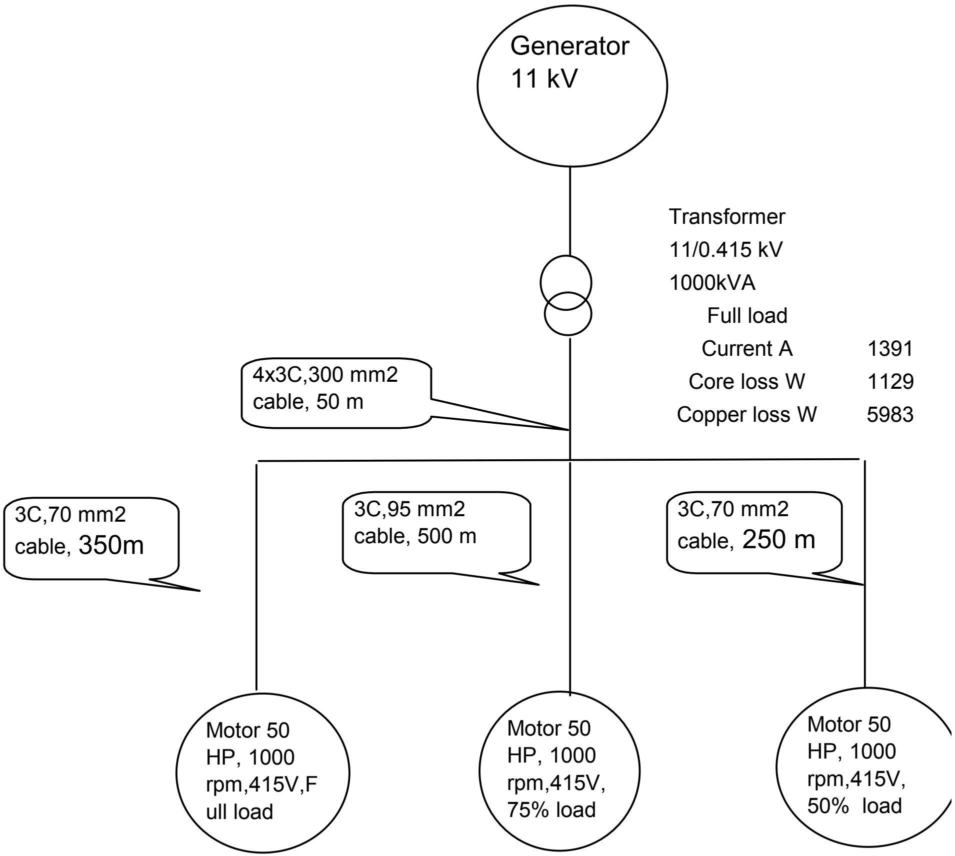
Group Correction

A case study of correcting power factor at the motor control center level is also given below. It can be seen that the savings due to reduction in motor cable losses, which is quite substantial, is not possible in this case. The pay back time will be higher as the scheme requires additional switchgears and controls.

This method can be adopted, if the disadvantages of individual correction as mentioned above are significant.

Case Study

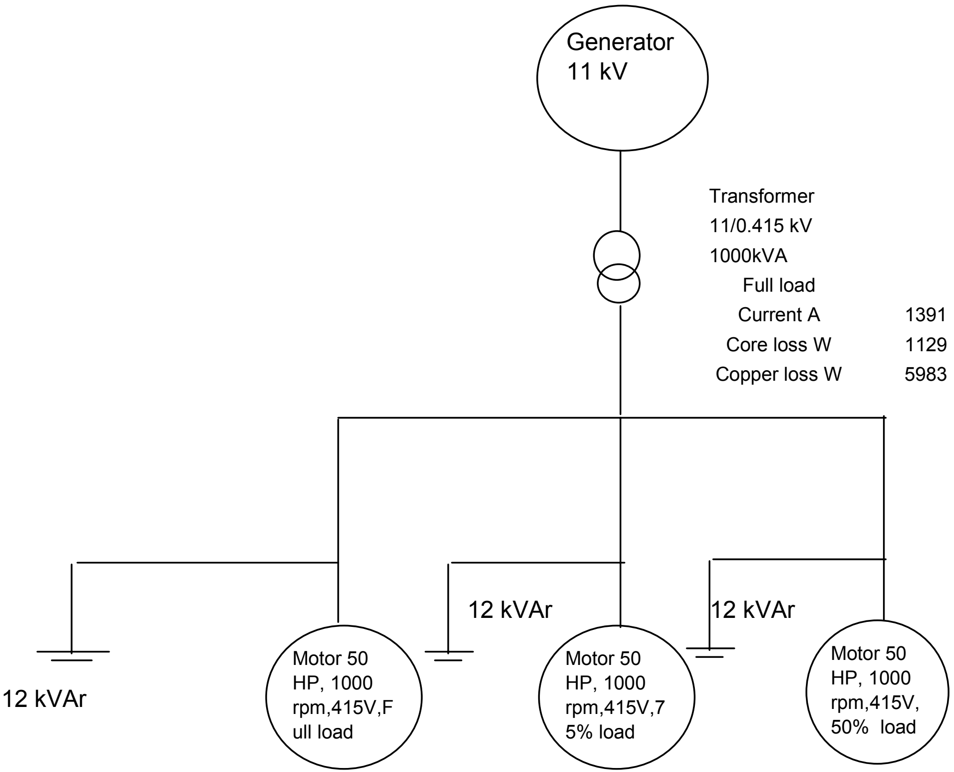
Single Line Diagram with load calculations



Load kW	37.3	28.0	18.65
Load efficiency %	94	93.5	92
Load PF	0.86	0.82	0.74
Load Current A	64	51	38
Correction factor for improving PF to 0.95	0.264	0.369	0.58
Total System kW	**89.9**		
Total System A	**153 pf 0.81**		
Total System PF	**0.81**		
Total system kVA	**111.0**		

Capacitor kVAr for improving pf to 0.95	10.5	11.0	11.8

Note: Load current is calculated for the specified output kW at the specified efficiency



Load kW	37.3	28.0	18.65
Load efficiency %	94	93.5	92
Load PF	0.95	0.95	0.95
Load Current A	58	44	30
Reduction in motor current A	6	7	8
Total System kW	**89.9**	considering efficiency factor also	
Total System A	**132 pf 0.95**		
Total System PF	**0.95**		
Total system kVA	**94.6**		
Ac resistance of cables in ohm/km	0.532	0.385	0.532
Reduction in motor cable losses W	20.11	28.30	25.54
Reduction in Transformer copper losses W	18.5		
Reduction in transformer cable losses W	31.75	cable resistance 0.12ohm/km	
Reduction Generator Losses	Not quantified		

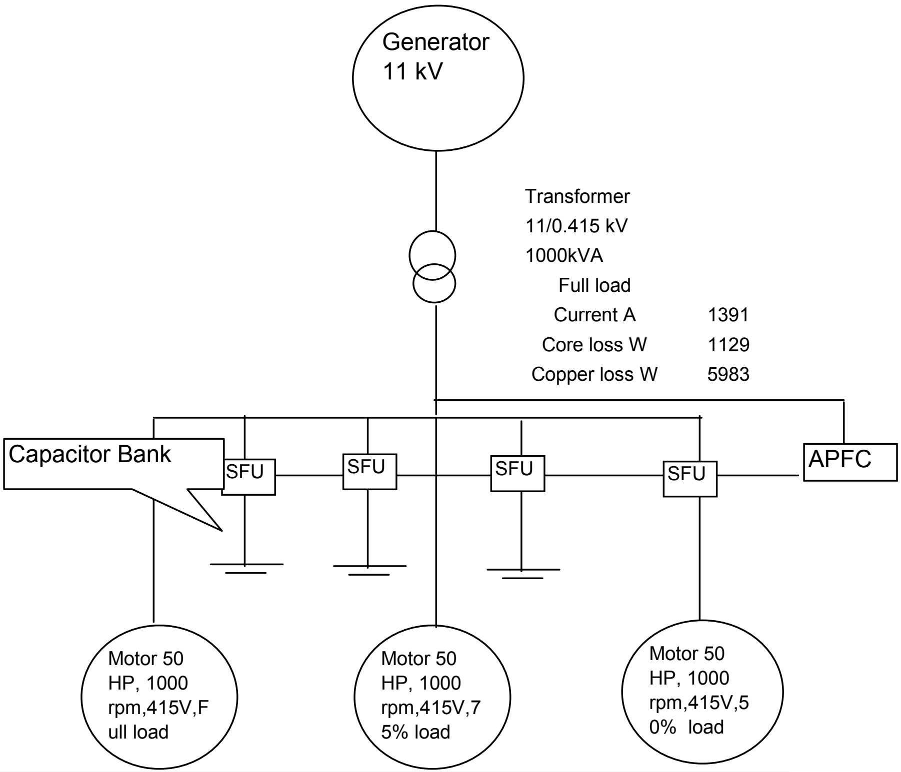
Total Losses W	124.20

Saving in Rs @Rs3.5/kWh for 8760 hrs	3808

Savings due to reduction in kVA demand @Rs 150/kVA for 12 months	29520

Investment	**7560**

Individual Correction



Load kW	37.3	28.0	18.65
Load efficiency %	94	93.5	92
Load PF	0.86	0.82	0.74
Load Current A	64	51	38

Total System kW	**89.9**
Total System A	**153 pf 0.81**
Total System PF	**0.81**
Total system kVA	**111.0**
Correction factor for improving PF to 0.95	**0.395**
Capacitor kVAr for improving pf to 0.95	**35**
System kVAafter improving pf to 0.95	94.60

Reduction intransformer current due to PF improvement A	21.00
Reduction in transformer cable losses W	31.75
Reduction in Transformer copper losses W	18.5
Total Losses W	50.25

Savings due to reduction in kVA demand @Rs 150/kVA for 12 months	29520

Investment for capacitor banks Rs	7000

Saving in Rs @Rs3.5/kWh for 8760 hrs	1541

Investment for additional switching devices	Rs 10000/-

Group Correction