Power Quality Improvement Technique
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Lecture - 08
Improvement of Power Factor by Capacitor

Welcome to our NPTEL lectures on Power Quality Improvement Technique. Today we are going to discuss about Improvement of the Power Factor rather by Improvement of the Power Factor by Capacitor or the capacitor bank. But what is implication of the capacitor also in the other entities, that also we required to discuss. When discussing the standard we have discussed that, switching on and the switching off the capacitor bank has its implications on the power, other part of the power quality apart from correcting the power factor.

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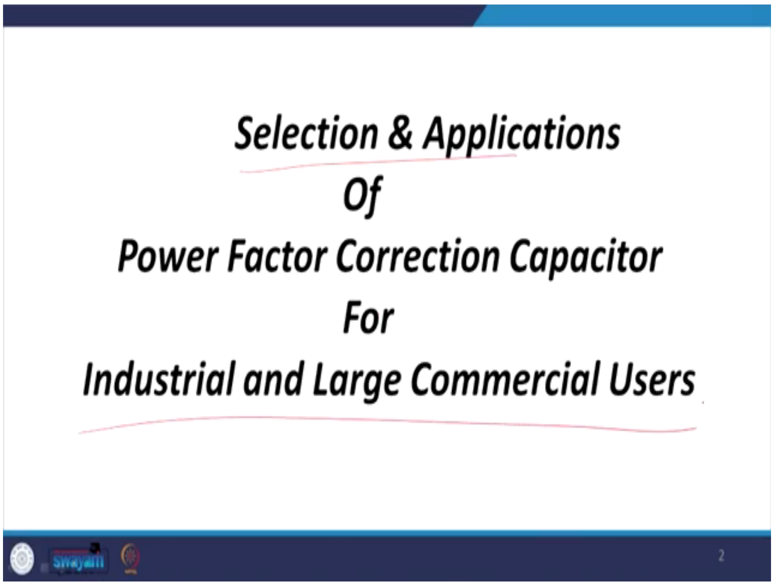

So, we shall discuss in detail, that is selections of the power factor correction capacitor for the industrial and the large commercial users.

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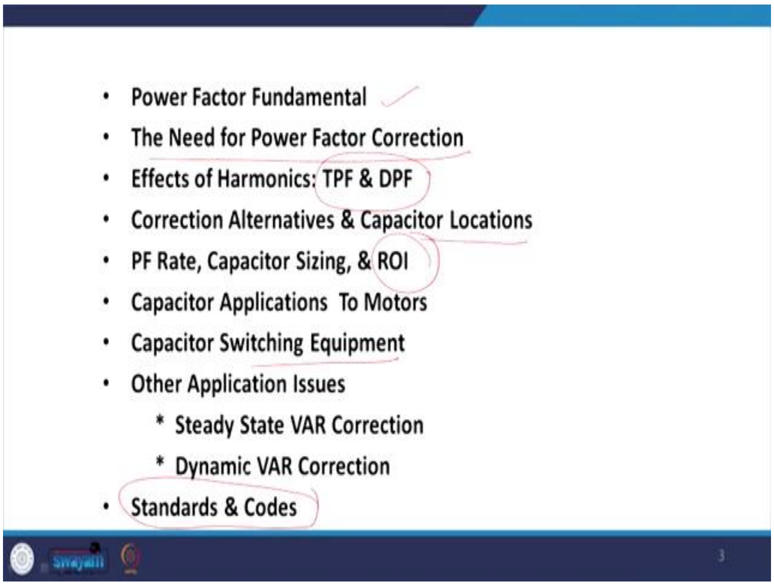

Now, we shall discuss about the power factor fundamental that we are all us aware of it. But we have to start with that. The need for the power factor corrections, we know that. Why we require the power factor correction, otherwise we required to take more current. Effect of the harmonics and the total power factor and the displacement power factor. Corrections of the correction alternatives and the capacitor locations. Thereafter, we shall see that capacitor sizing and the return to the investment, return on the investment, capacitor application to the motor. Capacitor switching equipment and we shall see thereafter steady state VAR and the dynamic corrections and the standard and the code.

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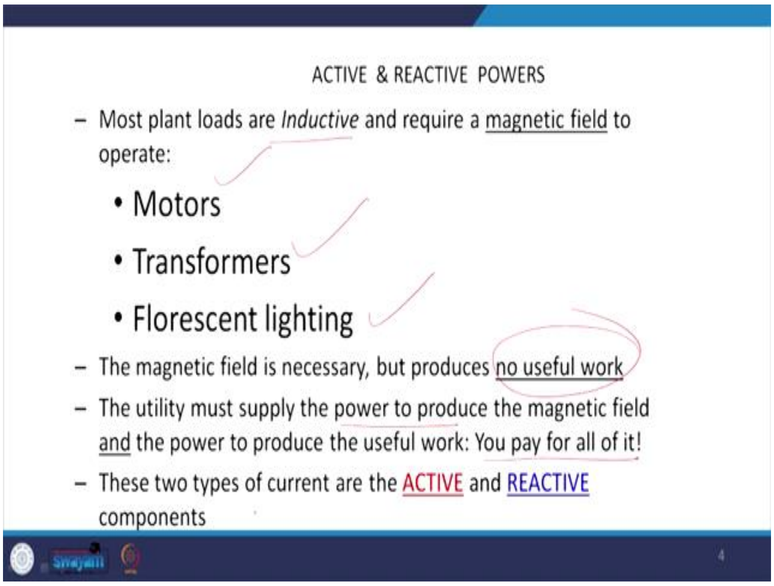

So, most of the plant loads are inductive. So, you have a predominantly induction machines and require a magnetic field to operate, these are motors, transformer, and the florescent lighting. The magnetic field is necessary, but produce no useful work, so that is the magnetic part of the current. The utility must supply the power to produce the magnetic field and the power to produce the useful work. Pay for it all so, you required to pay for the both. This type of the current are the active and the sub-active and the reactive components of the current.

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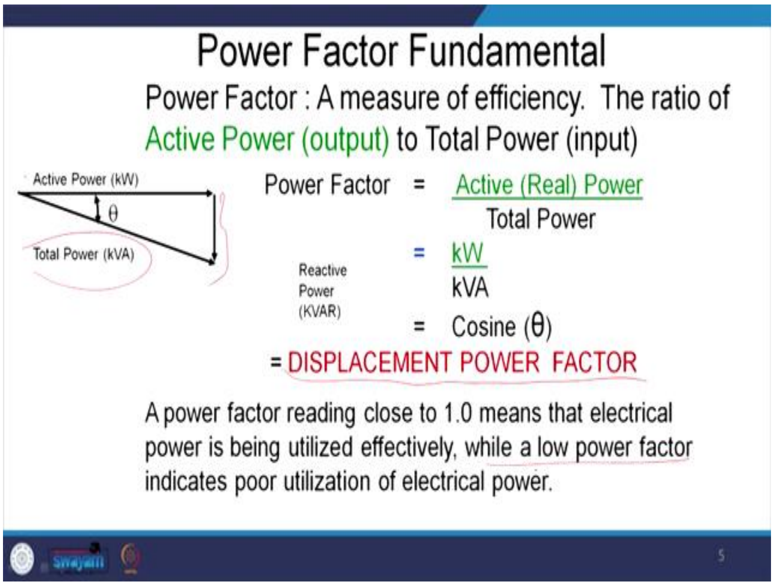

So, you know all that is the active power that is in the kilowatt and this is the reactive power and ultimately you will be charged so based on the kVA not the active power. Thus, if you reduce this hypotenuse, this perpendicular ultimately, then you will be paid only for active power. So, it make sense to reduce this part of the component. So, power factor, a measurement of efficiency. The ratio of active power to the total power that is you all know, ultimately it is a cosine. And sometime in the case of the power electronics we will see that there is another term, there is a displacement power factor.

The power factor reading close to 1 means the electrical power is being utilized effectively. While low power factor indicates that poor utilizations of the electrical power. Most of the power is wasted in the magnetics.

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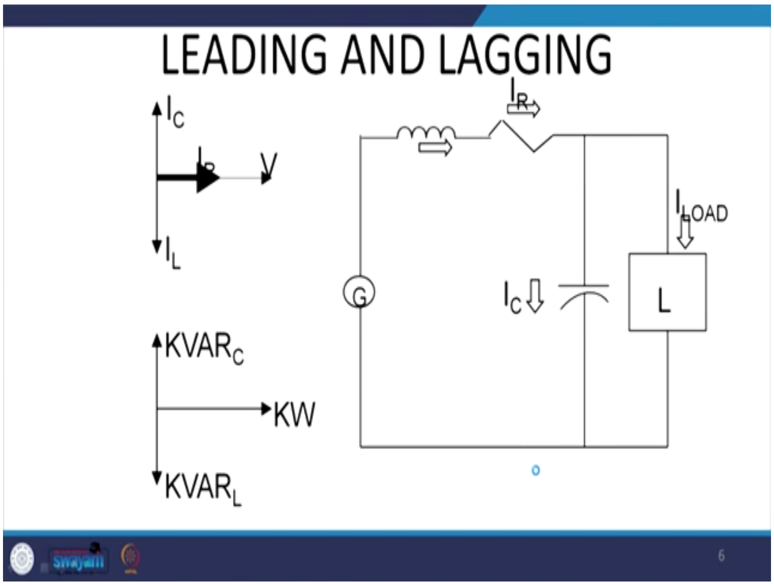

So, for this reason this is we can have a leading and lagging power factor, this is inductor and for this is in you have a capacitor, we can have a load. So, for this reason we require to correct the load and we can have a resonance condition when capacitive VAR and the inductive VAR are matches each other and thus system behaves as a resistive circuit.

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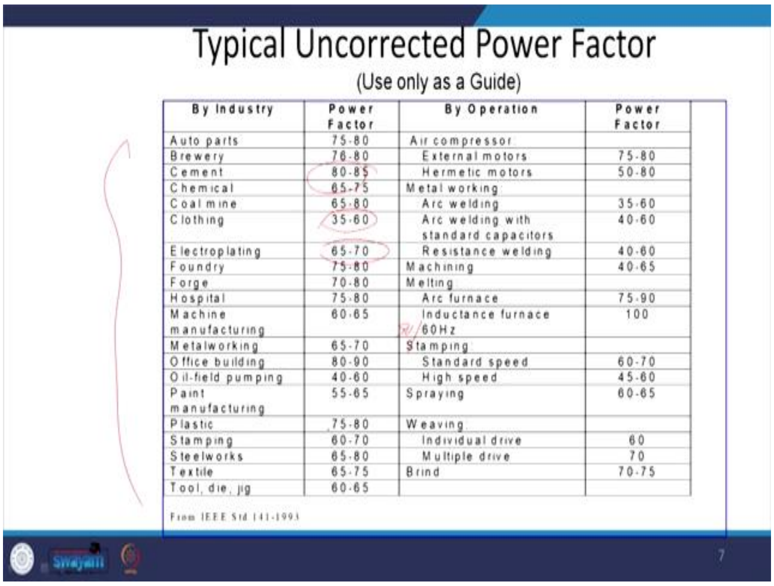

By Industry	Power Factor	By Operation	Power Factor
Auto parts	75-80	Air compressor	
Brewery	76-80	External motors	75-80
Cement	80-85	Hermetic motors	50-80
Chemical	65-75	Metal working	
Coal mine	65-80	Arc welding	35-60
Clothing	35-60	Arc welding with standard capacitors	40-60
Electroplating	65-70	Resistance welding	40-60
Foundry	75-80	Machining	40-65
Forge	70-80	Melting	
Hospital	75-80	Arc furnace	75-90
Machine manufacturing	60-65	Inductance furnace 60Hz	100
Metalworking	65-70	Stamping	
Office building	80-90	Standard speed	60-70
Oil-field pumping	40-60	High speed	45-60
Paint manufacturing	55-65	Spraying	60-65
Plastic	75-80	Weaving	
Stamping	60-70	Individual drive	60
Steelworks	65-80	Multiple drive	70
Textile	65-75	Brind	70-75
Tool, die, jig	60-65		

From IEEE Std 141-1993

Now, you see that, industry uses different components. Industry as well as we ourselves. And what is the power factor of it? Auto parts, that is power factor of 0.7 of 7 to 80 and there is air compressor. So, thereafter cement 80 to 85 percent hermetic motor and that clothing it may be very low it is 35 to 60, thereafter electroplating it is 60 to 70 and so on. And we have different kind of weaving, individual drive, standard speed, high speed for the stamping, for melting arc furnace, inductance furnace 50 or 60 hertz both. So, we will have this overall power factor problem. And these are all industrial users you can see that, average power factor is in between of 0.75-0.65, even arc welding is 0.35.

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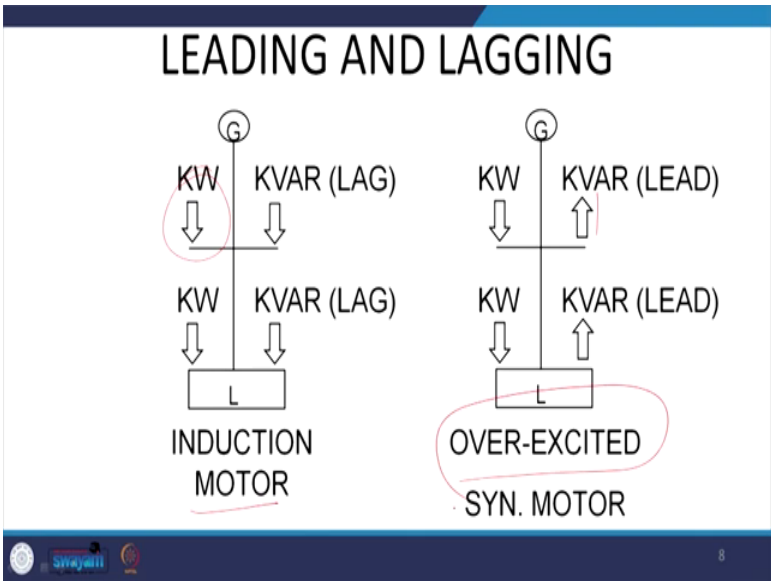

So, for this reason we required to do something to improve the power factor. That is also a issue of the power quality. So, this is the kilowatt and ultimately if you have to generate the lagging power factor that is a kilowatt and the kilowatt VAR you will feed. But instead of that, you can have a over excited synchronous generator, kilowatt and KVAR it is coming in this direction leading. And thus, this can be. But for problem is that to you operate by the mechanical power, real power is being wasted by this synchronous generator. So, that it generates the capacitive VAR. Instead of that, why cannot we have a static device to generate the capacitive VAR?

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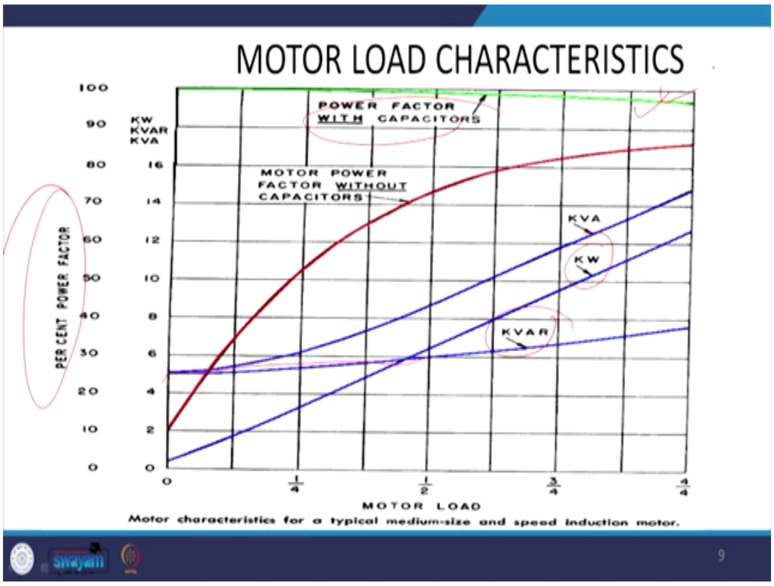

This is the motor load characteristics you know; this is the percentage of the power factor that is power factor 1 is marked as a 100 percent. And you can see that this is a motor load and this is the power factor with the capacitor and we can almost get point 100 percent or 1 power factor. And it is the motor power factor without capacitor. And so, this is a red one and blue one is a KVA and according to the loading it will improve. And of course, this straight line is the real power watt and you can see that this one is the KVAR.

KVAR is quite high in the lower rating, when it is not loaded, percentage of it. So, when it is not loaded, predominantly it will be generating the inductive VAR and one solution can be given by the capacitor power factor with the capacitors.

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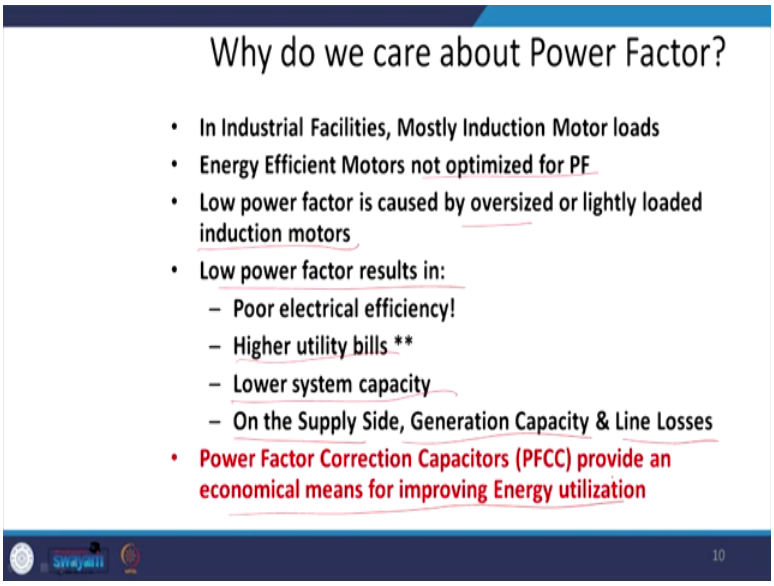

So, in industrial facilities, mostly we have a induction motors loads. Energy efficient motors, not optimized for the PF. So, we can that generate the low power factor. Low power factor caused by oversize or the light loaded induction motor. When you are loaded that machine properly, it will take good power factor but if you are not loading it, predominantly it will have a magnetizing component and thus it will degrade the power factor.

Power factor has so many problems. So, low power factor results in the poor electrical efficiency, higher utility bills, lower system capacity on the supply side, generation capacity and the line losses. Apart from that power factor corrections capacitors provide an economical means to provide the improving the energy efficiency. That is one of the greatest merit of this entity.

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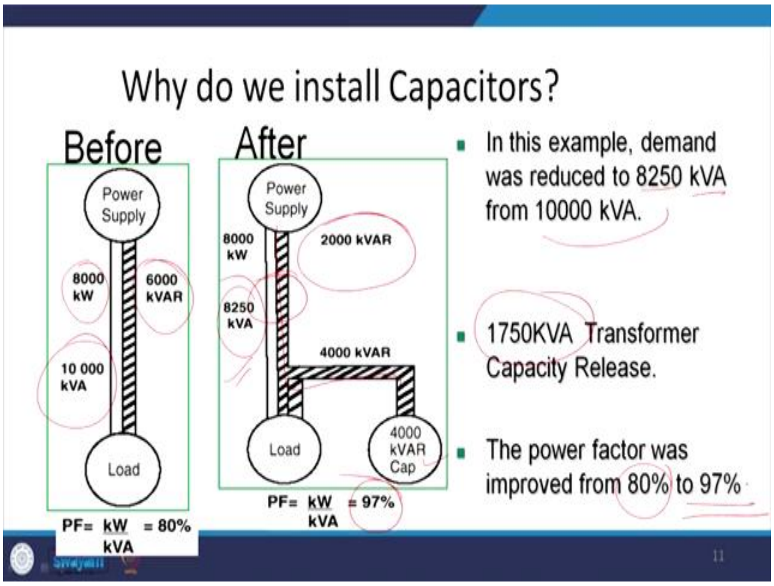

So, for example you take it, power supply you require you essentially required 8 kilowatt of power and ultimately you also send, your system is loaded because current has to flow through it. Voltage is constant, also 600 kVAR, our overall kVA is definitely 10000 and ultimately you get power factor of 0.8. On the other hand, if you have this capacitor bank of 4000 VAR. Then what will happen? This power will sink. This capacitor VAR will supply the power. Ultimately net kVAR coming from the line is 2 kilowatt.

So, overall if you square it up, that kVA rating will be 8250 and you got a 97 percent of the power factor. Thus, this power handling capability of this line has been comprehensibly increased. So, you can overload it further for the real power.

So, that is an example. So, demand reduces to 8250 from 10 kVA from 10000 kVA and thus what happen. So, this much 1750 kVA transformer capacity has been released due to that and power factor was improved to 80 percent to 97 percent.

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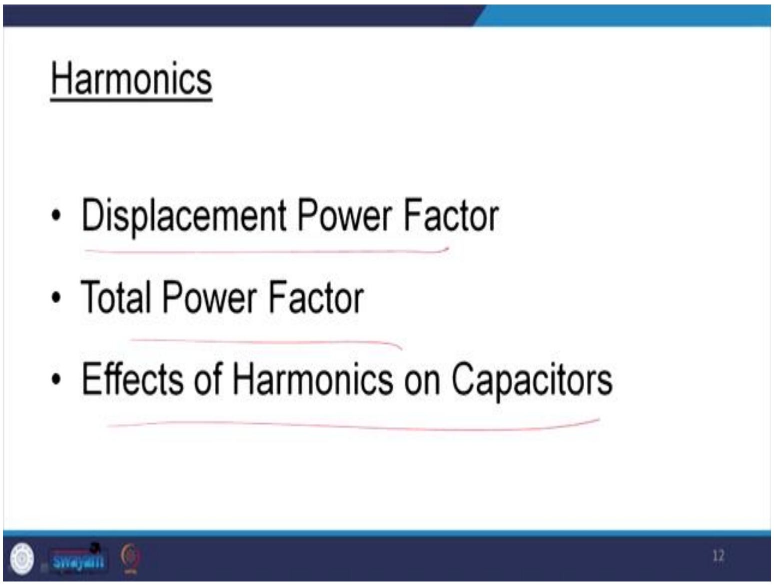

So, there is another few issues and that is with the harmonics mainly in power electronics. That is displacement power factor, total power factor, the effect of the harmonics on the capacitor. These are the few entities we required to be discuss now.

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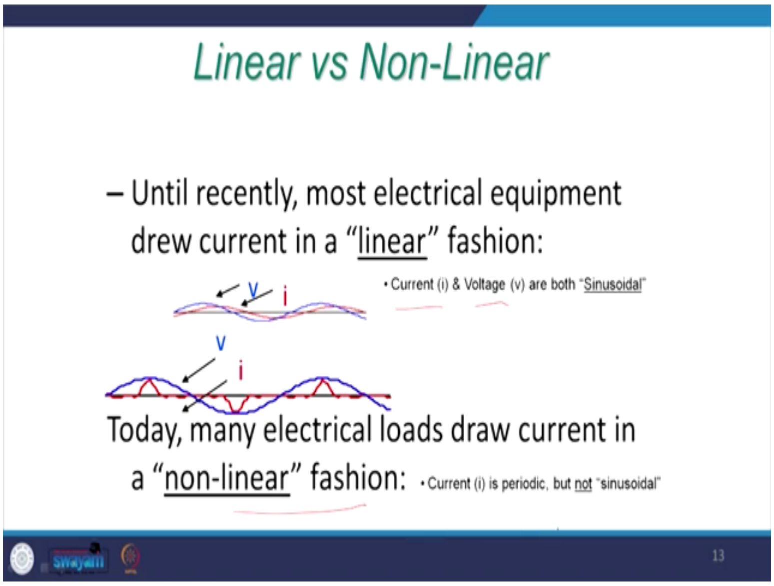

So, till now we have talking about the linear load. Until recently most electrical equipment draw the linear, draw the current in linear fashion from the linear voltage. This is a voltage and current, it may have a phase lag or phase lead depending on the current is inductive or capacitive, but current and voltage are both the sinusoidal. But you can see nowadays because of the non-linear load adjustable speed drive, voltage and current are far from the sinusoidal and they are non-linear and current is not sinusoidal.

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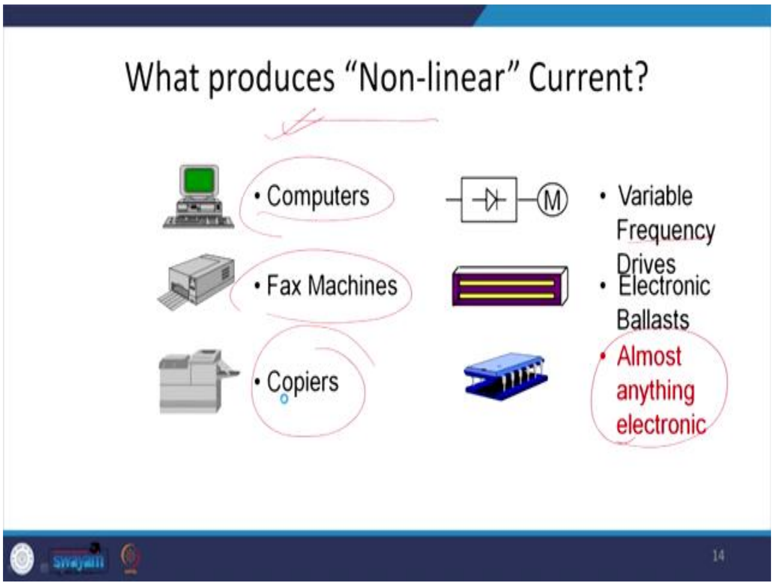

So, it is because of the non-linear current. For example, computers. Computer comes with the SMPS. SMPS is essentially a AC to DC conversion, thereafter DC to DC conversion. And its DC to DC conversion definitely has a rectifications. This rectification is a non-linear conversion and thus it causes the injection of the harmonics. Same way for the fax machine, same way for the photo copy machines, copiers or the variable frequency drive, V/f control drive or you may have a electronic ballast that is for the chokes. And almost any electronic component generally require a DC supply, regulated DC supply and thus you require to convert AC to DC and you cause, you put or inject the harmonics.

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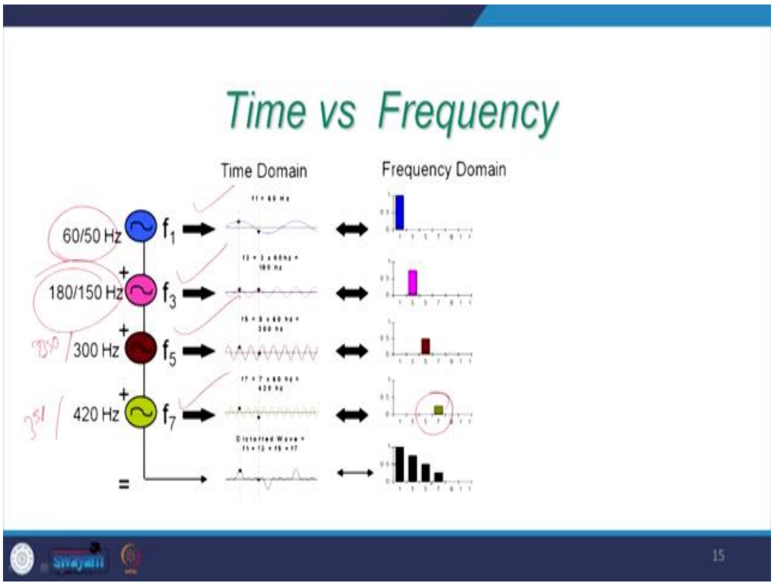

So, this is the way you know, actually you can see. So, you know in case of the 50 hertz or the 60 hertz supply, this is the fundamental and you will have a frequency like this. And if you have the (it is 360) if you have 50 hertz or the 3rd harmonic that will be you know, of though it will be a co phaser for the 60 hertz or 50 hertz, so it will be shifted here. Similarly, you will have a 5th harmonic that will be either 250 or the 300 hertz, so that will be something like this. Similarly, 350 or 420 hertz that will be something like this.

And ultimately whatever the waveform you have shown here, this it can be think of you can see that, you just add up this waveform and ultimately you constitute this waveform. So, you have some portion of the fundamental, some portion of 3rd, some portion of 5th, and some portion of the 7th harmonic. So, that you get this kind of the picky current. So, this is called, so we required to define another term that is the distortion factor.

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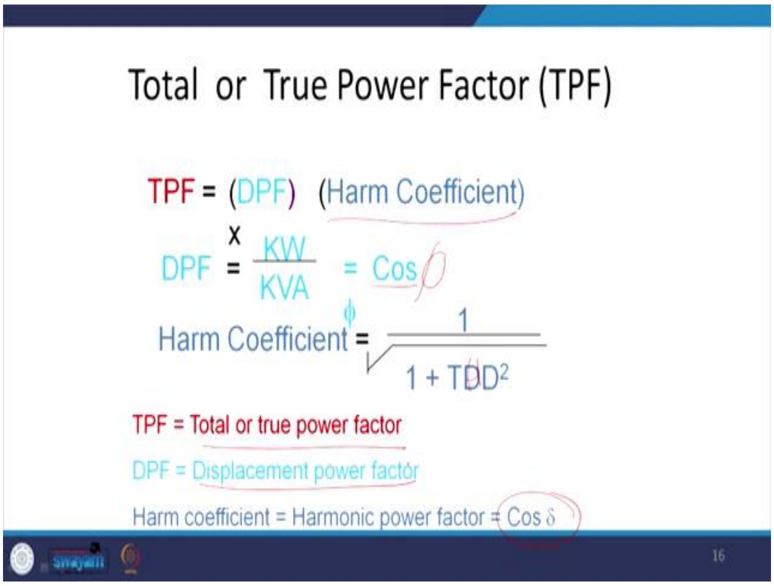

So, total power factor or TPF that is a harm coefficient sometime we say. That is DPF equal to KW by K it is cos phi. And thus, the harmonic coefficient will be 1 by 1 plus THD square where TPF is a total or the true power factor, DPF is a displacement power factor. The harm coefficient or the harmonic factors is given by the cos delta.

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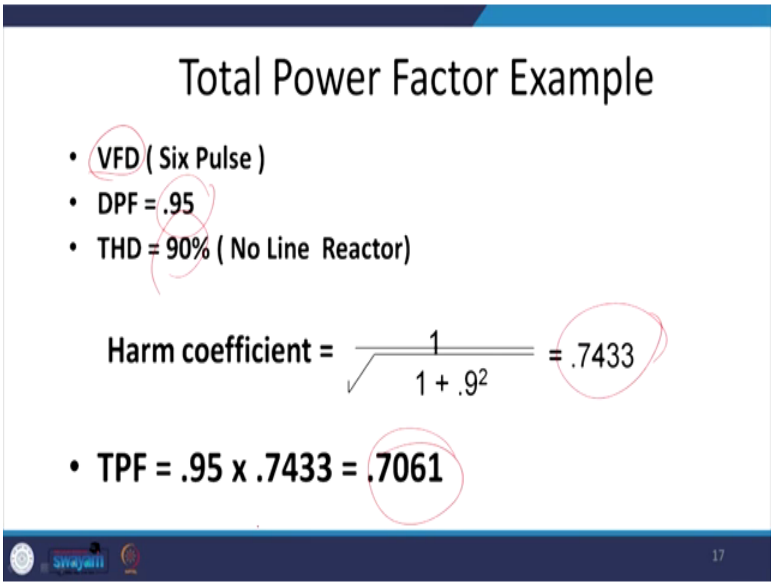

Now, for the variable frequency drive, this is abbreviation of the FFD and displacement power factor is 0.9 and for the THD may be 90 percent, the harmonic coefficient you can calculate. You will be 0.743. Thus, you multiply effective power factor or the total power factor will be 0.7061.

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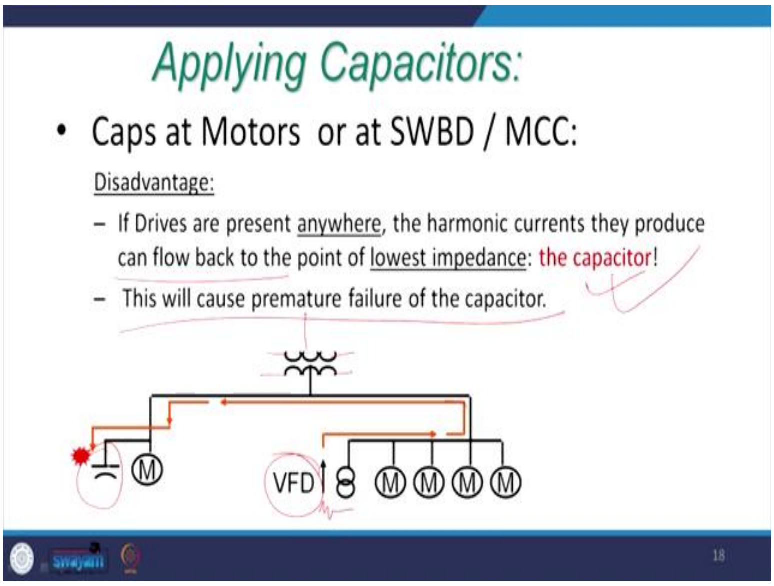

So, we require to put the capacitor. I have told you to mitigate the reactive power problem. But if it is there the adjustable speed drive, then there will be a lot of disadvantages. So, placing of this capacitor when you have this adjustable speed drive, then there is a problem. For example, you see that this is the transformer, from their power is coming and there is a one entity, that is a variable frequency drive and ultimately it is a harmonic source. And there is a another machines.

And what happen? Since it is a high frequency, so high frequency will get the path through the capacitor. So, drives present anywhere, the harmonic current they produce can flow back to the point of the low impedance that mean through the capacitor. And thus, capacitor will be unnecessarily overloaded with the harmonics power and which may cause a premature failure of this capacitor. So, you have to keep in mind that once it is used with the frequency contaminated domain, then placing of the capacitor is very important to check the to increase the longevity of the capacitor life, so that de-rating can be prevented.

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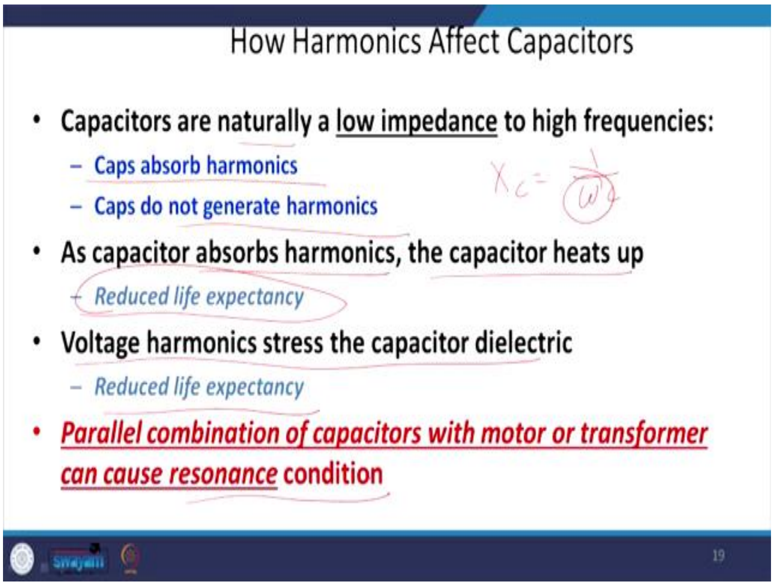

So, what generally we do? How the harmonics affects the capacitor? Capacitors are naturally because you know Xc equal to 1 by omega c. So, higher is the omega, lower is the impedance. The capacitors are naturally a low impedance to high frequencies and thus capacitor absorbs the high frequencies. Capacitor do not generate harmonics. So, there is an advantage of it.

As capacitor absorb harmonics, the capacitor heats up and reduces the life of the capacitor. So, ultimately its insulations, it is destroys and life get reduced. Voltage harmonic stress in the capacitor dielectric and thus what happen, they reduce the life expectancy of the capacitor. Parallel combinations of the capacitor with a motor or the transformer can cause resonance condition. That is also a challenging phenomena. We shall give some problem in your assignments, where there is a leakage reactance and may be you are turn on, because the capacitor.

Capacitor was not there, so you are switched it on lot of load, inductive load to mitigate that you turn on the capacitor. The leakage reactance and the capacitor can set a particular frequency oscillations and thus if this, that frequency is close to seven harmonic or something like that then there will be a seventh harmonic resonance and that may throw out the whole system out of gear. Let us see that.

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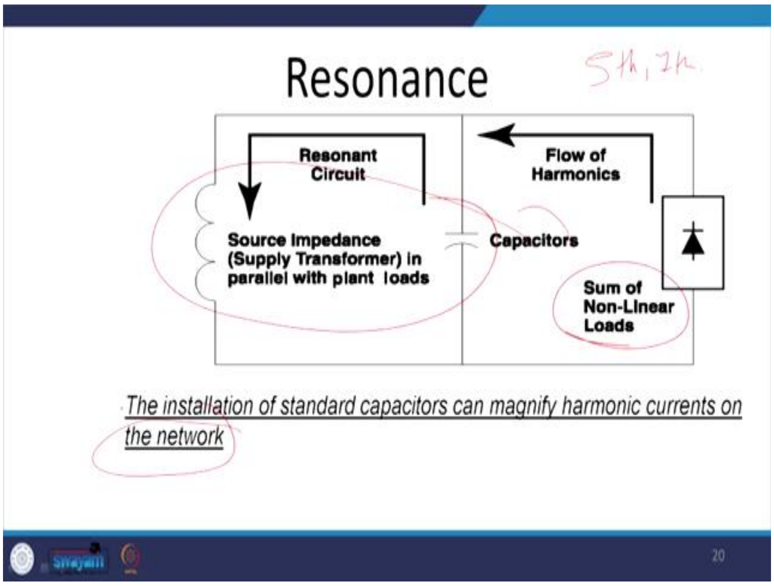

There is, a sum of the non-linear load that generate 5th harmonic, 7th harmonic and so on. So, you have a capacitors and you have a inductor, this may set to a particular frequency and this frequency may be close to the your particular harmonic it is been generating. And that harmonic will find the resonance into this tuned circuit and it will set the resonance for the harmonics. Thus, installation standard of the capacitor can magnify harmonic current in the network. That is a one of the biggest disadvantage nowadays, because there you have a harmonic generator and this oscillations will lead to the harmonic resonance.

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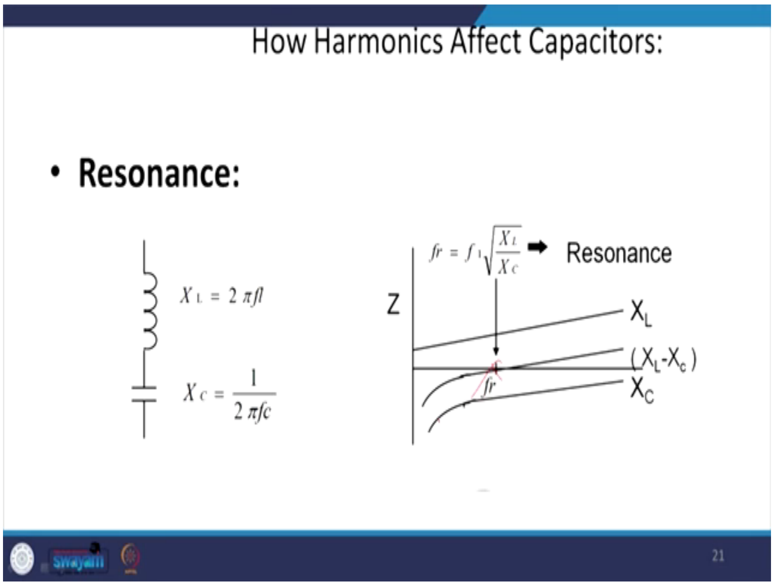

So, for this reason we have to, we know that what is harmonics ultimately for a series harmonics it is X_L and this is X_C. Ultimately this is an X_C and X_L. So, this will be the natural frequency of oscillations when X_L equal to X_C.

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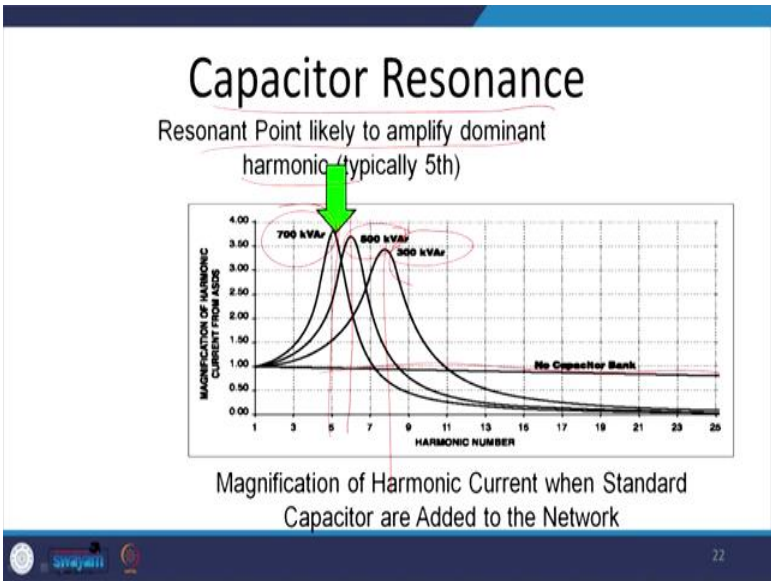

And so, that particular frequency should not be very close to the either 5th or 7th harmonic. So, for this reason capacitor resonance, this is a magnification of the harmonic current when standard capacitor added into the network.

You can see that resonant point likely to amplify the harmonic. That is what I saying, typically the 5th harmonic, so depending on the leakage reactance of the transformer and the values of the capacitor. So, what happened here? This is harmonic order. So, this is with the no capacitor bank. So, it is quite low, but what happen. So, you have introduced 700 kVAr of the capacitive power and you can find that it gives a resonance of 5th harmonic and that is quite detrimental. So, ultimately it will find low resistance for the 5th harmonic.

Similarly, this will, if you have 500 VAR then the frequency will be shifted to the higher side. So, you will have the resonance around the 6th harmonic. Generally, if it is a three phase three wire system 3rd harmonic is not present, you are and then also if you increase further, it can be the 8th harmonic. So, if you increase the kVAR compensation, there is a chance that it leads to the harmonic resonance and that will have a lot of detrimental effect into the power system.

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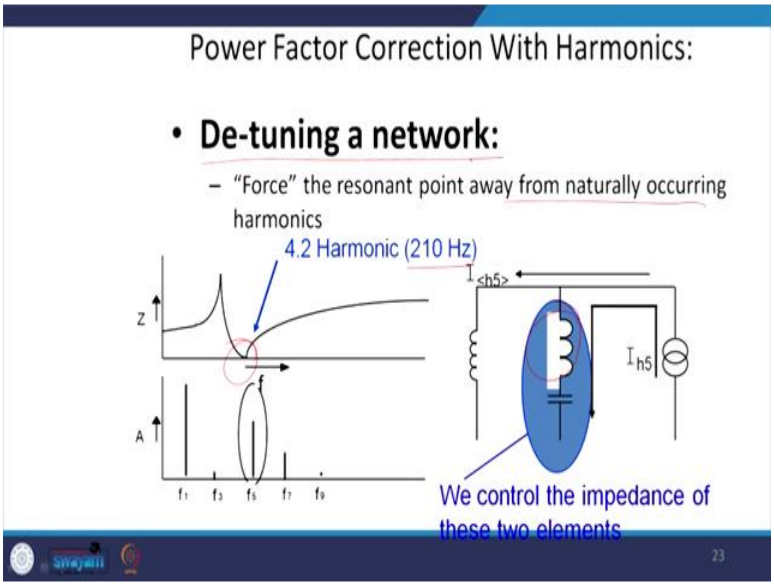

So, for this reason power factor corrections with the harmonic, we are now gradually avoiding and we go for the solutions with the active devices for the STATCOM and other devices. So, we required to de-tune this network. Force the resonance point away from the naturally occurring frequency and we will make it something like 4.2 harmonic for the 50 hertz or 60 hertz depends.

So, for the 50 hertz it will be 210 hertz, you have de-tune like this. So, we can a we control the impedance of the two elements. So that is basically the facts devices. And so, we can control the value of the inductor, so that effective inductance can be; effective impedance of this devices can be control and you will be de-tune it from the facts devices and thus it will not fall into the trap of the 5th harmonic or 7th harmonic.

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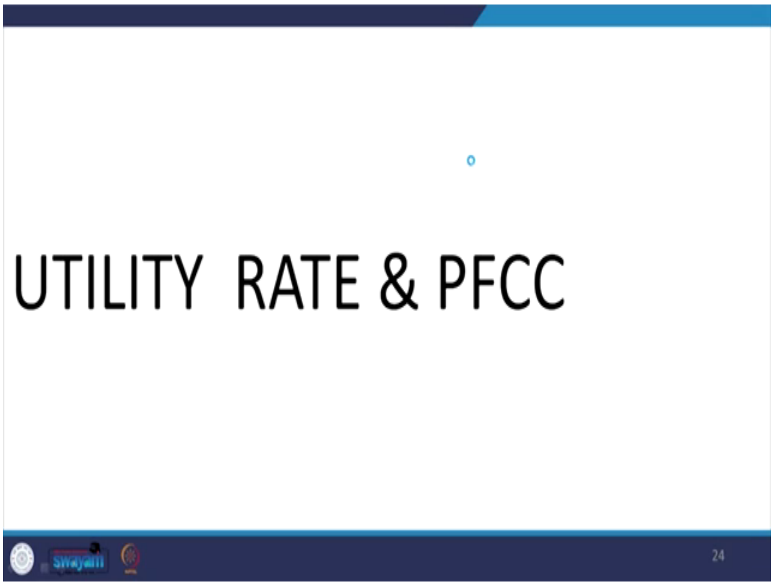

So, utility rate and the power factor correction. So, this is something is quite important.

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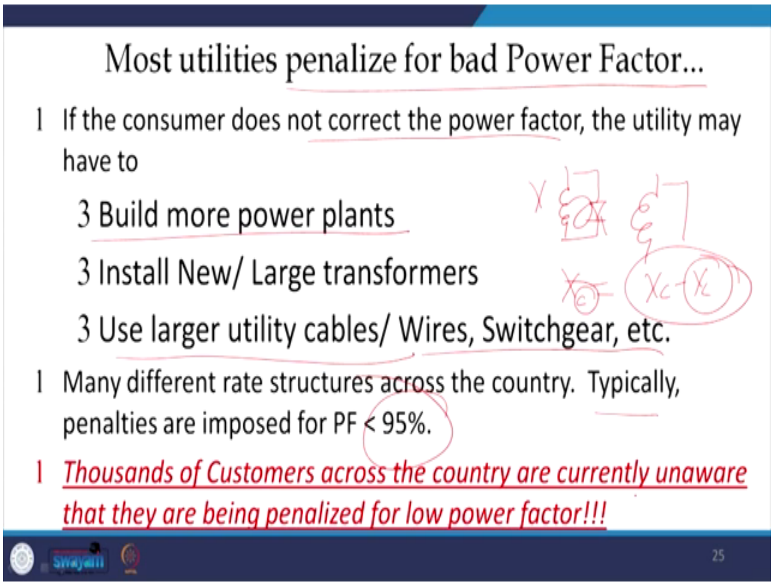

So, we know that most utilities penalize for the bad power factor; but there is a detrimental effect to it and solution has to be provided by the STC. So, you generally have a inductor and with the thyristors in parallel or you can generally have generally you can bypass this inductor or you can allow this inductor to flow. There after you can have a capacitor. And thus, what happen? A value of the inductor you can control the triggering of this thyristors. And thus, value of the X_C, what you get essentially X_C minus

X_L and where X_L will be the function of the, X_L will be the function of this triggering angle. And thus, you can change the effective value of capacitive inductor. So, that it does not tune to the particular harmonic.

If the consumer does not correct the power factor, the utility have to build more power plant, install new or the large transformer, use large utility cables, wires, switchgear, etcetera to handle the more kVAR rating. Many different rates structures across the country and typically in India we are being penalize in a industrial houses for having power factor less than 0.95. So, thousands of the customer across the country are unaware of this, that they are being penalized because of the low power factor. And ultimately, they we are coming to the commercialization of it and nowadays prepaid meters to reduce the theft and other issues. So, you may not aware of that, your current bill is eat out because of the low power factor.

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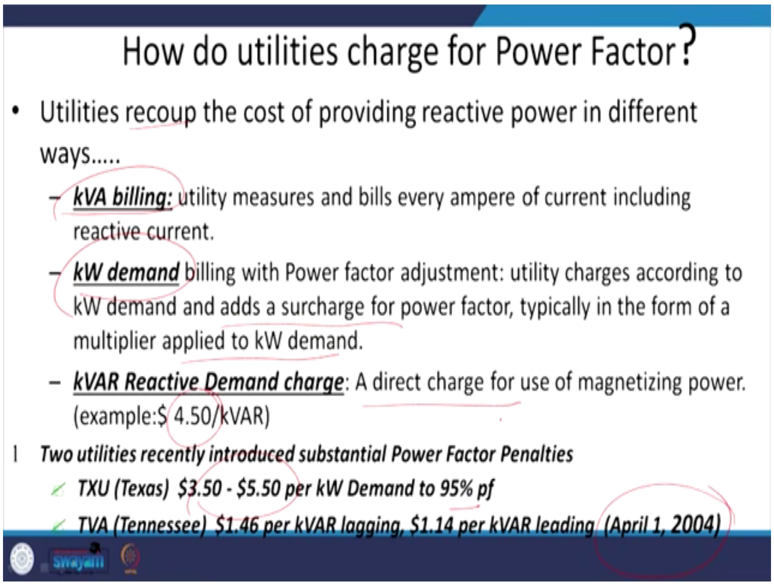

Now, this is for the industrial billing only, but it may be extended to the domestic billing up to a some level. So, if you are staying in a one society but you are having a so many air conditioning and all those issues, then of course, you may be charged for it. Utilities recap the cost of providing reactive power in different way. One is kVA billing: utility measures the bills every ampere of the current including the reactive current. And there after real power demand billing with the power factor adjustment: utility charges according to the kilowatt demand and adds surcharge of power factor typically in the form of the multiplier of the applied kilowatt demand.

Generally, this is the data I have taken from the USA. The kVAR reactive demand charge a directive charge use of the magnetizing power. For example, that is almost 4.5 dollar per kVAR. And two utility recently introduces this status from a Texas, are substantial power factor penalties for this much for power demand 0.95 and for in Tennessee 1.46 per kilowatt lagging and in this data is in 2004.

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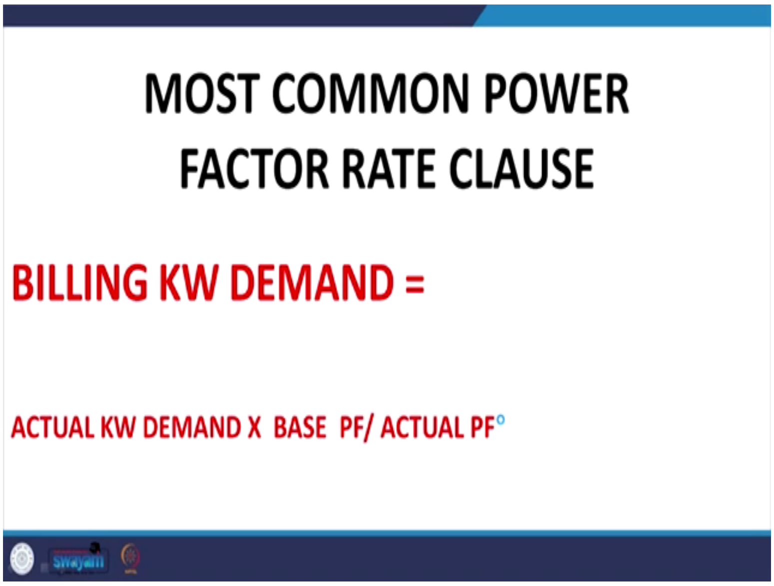

So, most of the common power factors and the rate cut clause that is very important for the power quality improvement for the consumer point of view, because he was working in an industry, they want to cut your electricity bills. And for this reason, we require to place the capacitor rightly but there is a hazards of placing capacitor that you may have some frequency generated, harmonic generated sources and that may cause the resonance.

So, we required to design properly the value of the capacitor.

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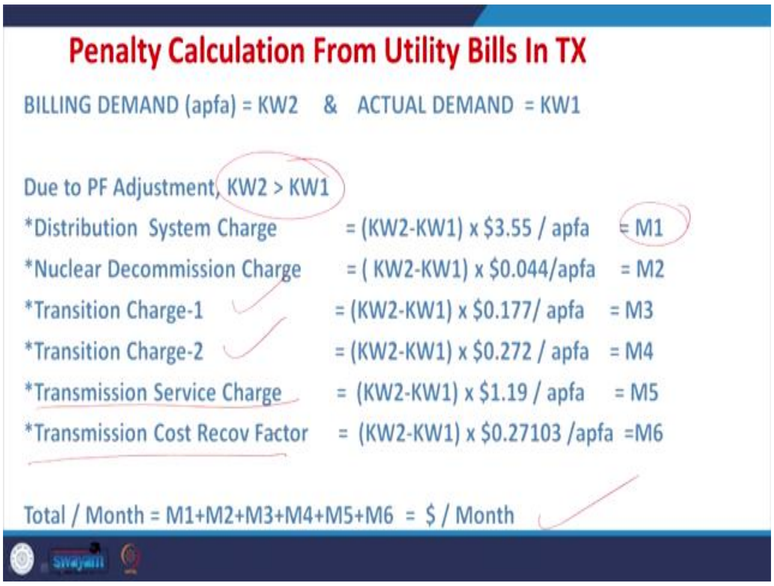

So, this is the penalties that has been discussing. So, due to the PF adjustment from kilowatt 2 to kilowatt 1 and distribution charges for the machine 1, nuclear decommission charges. And overall cost you have to bear that is the total by month M 1, M 2, M 6 by the, it is rupee or dollar whatever maybe ultimately phenomena is same. So, you have a transmission charges, you have a transition charges, there are transmission service charges, transmission cost recover factor this all come into the picture. And ultimately you required to calculate those values and you will be metered accordingly.

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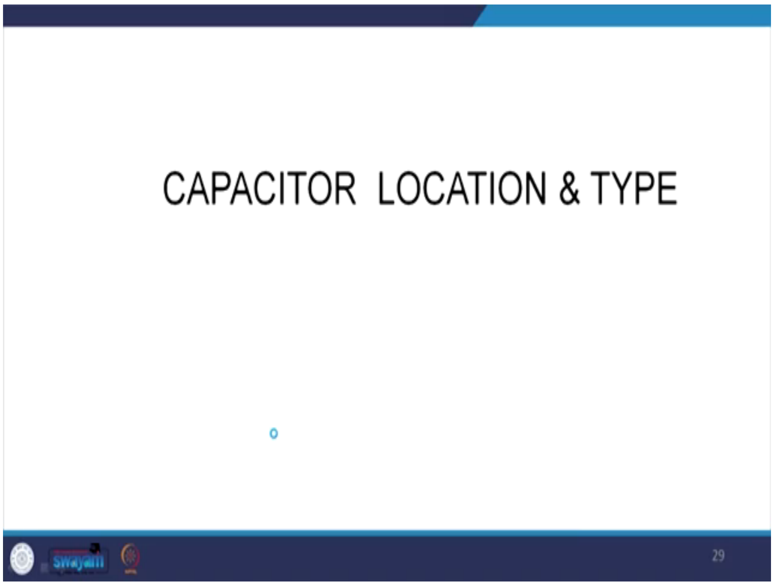

So, what is very important now? The placing of the capacitor and its type. So, I have told you in little early that, you have to have a variable capacitor. Because you have some harmonic sources and that may corrupt this capacitor.

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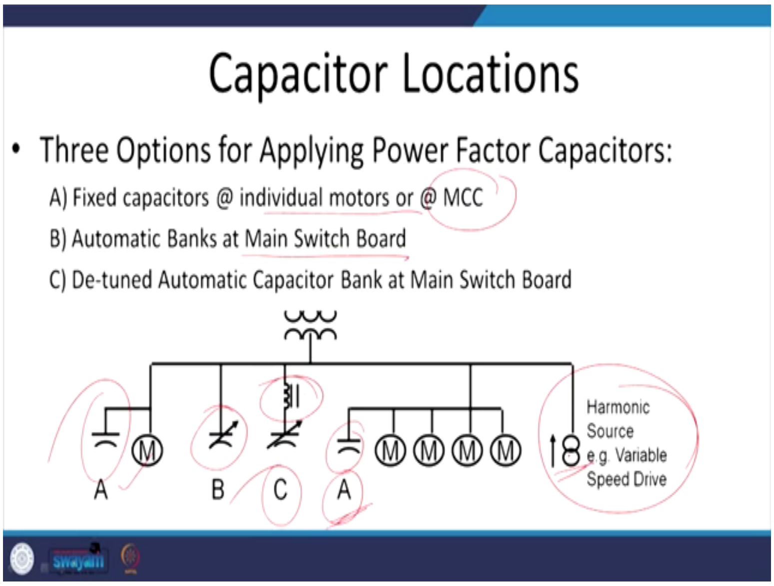

And thus, generally what happen? This is a three options applying a power factor capacitor: A. a fixed capacitor individual motor of the motor rating these this one. And another may be the B. the automatic bank at main switch board, so we can switch it on according to the loading and de-tuned automatic bank that is C. because you may cause a resonance with it with the main switch board. And of course, this is A. and this is also A. So, it has its own advantage and disadvantage which you have understood from our discussions. Generally, this is been used, so that it does not have a resonance with your power supply. Since it is a fixed, you know there is no point of control. So that sometime it may take the capacitive VAR also. So for this reason, this is the inferior solutions.

Next since you can switch it on, for this reason this is little bit superior solution because according to the load, you can turn on these capacitors. And the best solution is a solution C. where you can also de-tune this capacitor. So, that it does not cause resonance with the adjustable power supply.

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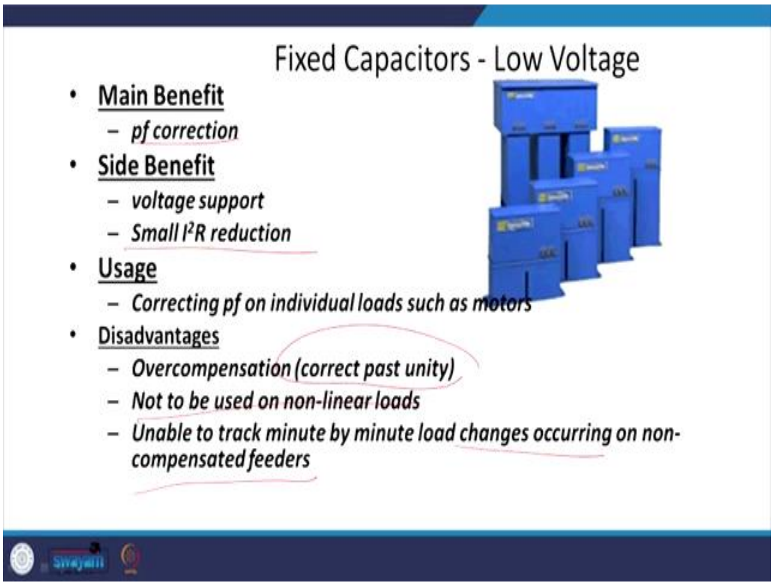

So, just wrap up. So, main intension is a power factor corrections. Side benefit, it recovers the sag. Because if you terminate the capacitor, so it will recovers the voltage sags and smaller I square R drop, corrections of the individual loads and the motors. But disadvantage is that overcompensations. If sometime if you have a fixed capacitor then you may have over compensate, you may have a capacitive VAR. Not to be use for the non-linear load, because you may cause a damage of the capacitor and may cause a resonance of the capacitor. Unable to track minutes by minutes loading change occurring for the non-linear feeders. So, we required to have a proper data to de-tune it, that is sometime always not possible and thus you may lead to the resonance. And so, these are the capacitor bank, this is the courtesy of the Schneider.

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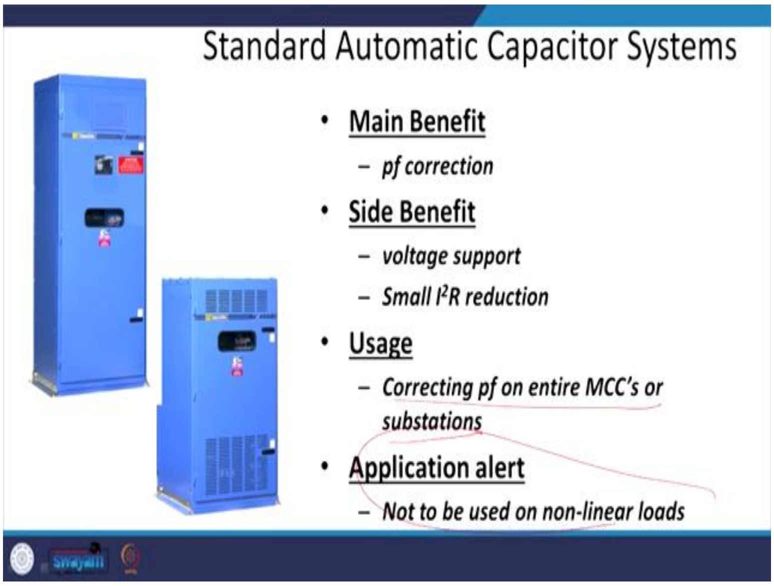

So, main benefit the we have talked about all those things and corrections of the entire MCC and the substations and applications alert, not to be used for the non-linear load. That is something we require to keep in mind. If the non-linear load is quite high then capacitor bank, correction with the capacitor bank will not work.

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So, for this reason we require the anti-resonant automatic capacitor bank which the C type. This is this pictures courtesy to the same Schneider. The automatic capacitor bank where with a reactor in series and it is been tune to just below the 5th harmonic 4.2 to 4.4 hertz, uses where non-linear load is less than 50 percent of the total load.

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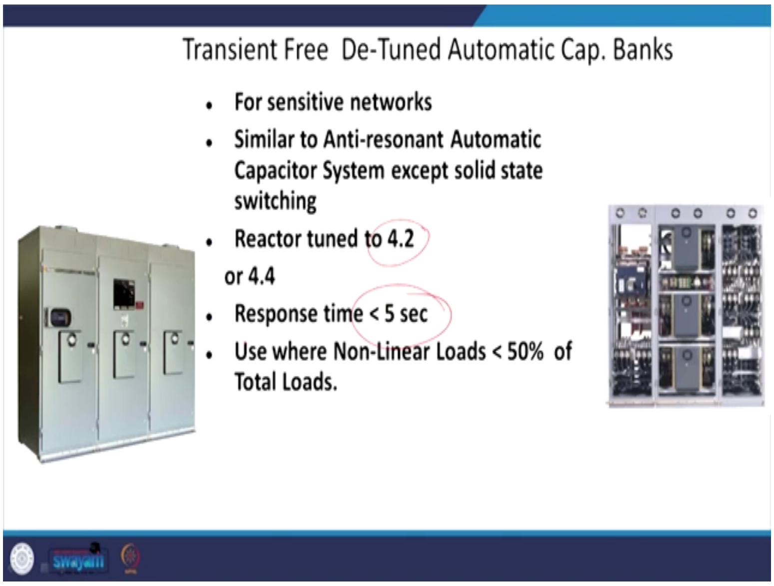

And transient free detuned automatic banks for very sensitive networks, similar to the anti resonant capacitor. It is same. It is been detuned to the harmonic of 4.2 to 4.4 and it has a response time of less than 5 second, where non-linear load is more than 50 percent.

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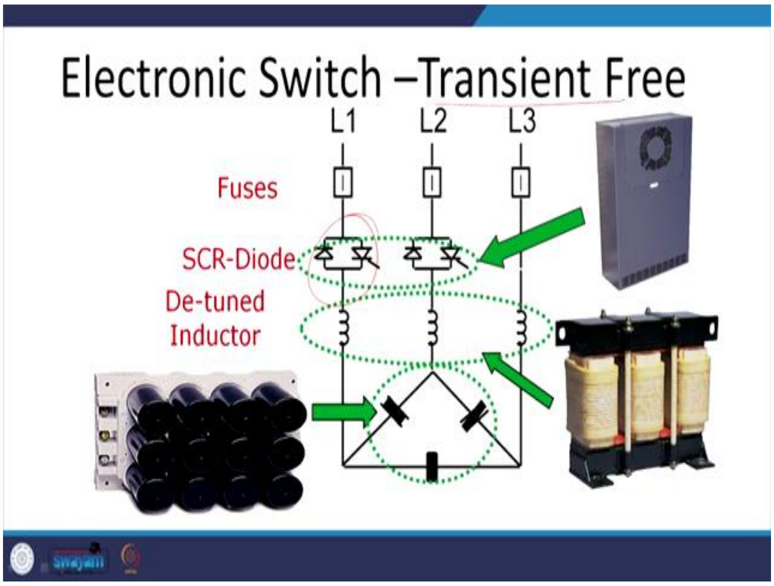

So, this is the way to put it, the electronic transient free. Ultimately you have a thyristors. So that will turn on and turn off thyristors and diode combinations, and you have a inductor and they have a capacitor bank. This is for the electronic switch transient free operation. I request the student to refer to the, my facts devices courses, these entities are been discussed in detail.

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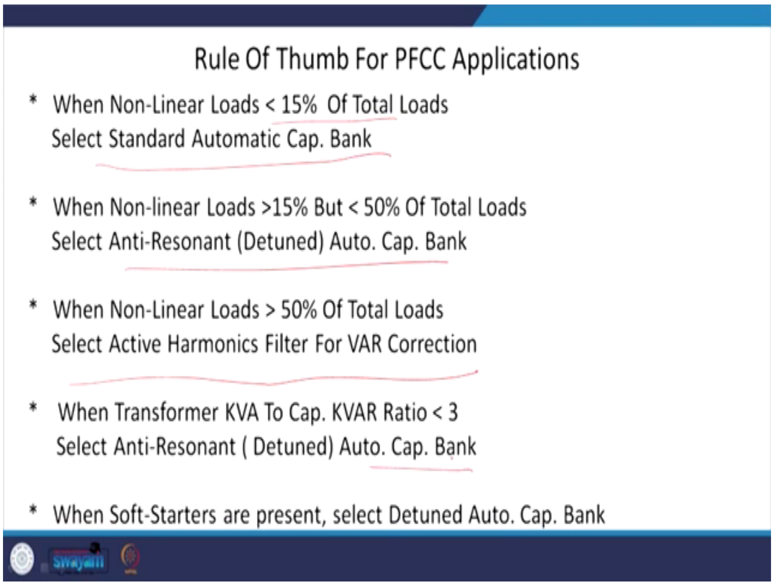

So, role of this, role of thumb of the power factor correction. When non-linear load is less than 15 percent select the standard automatic capacitor, when non-linear load is above 15 percent to 50 percent select the detuned anti resonant capacitor, when load is more than 50 percent select active harmonic filter of the VAR corrections. When transformer KVA or capacitor is around 3 percent select anti-resonant or detuned capacitor, when soft starters are present select detuned auto cap.

So, thus I conclude my discussions here and these are the few case studies which we will be discussing later. Thank you for attention. So, we have discussed the problem of the power factor corrections and it’s mitigation for power quality issues.

Thank you.