Power Quality Improvement Technique
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Lecture - 11
Passive Filter Design

Welcome to our NPTEL lectures on the Power Quality Improvement Technique. We have introduced and discussed the concept of the passive power filter. Today we will discuss about the Design of the Passive Filter in detail. Now one aspect we require to understand is the sharpness of the resonance which you have studied in your fundamental courses of the power electronics that plays an important role in the filter design.

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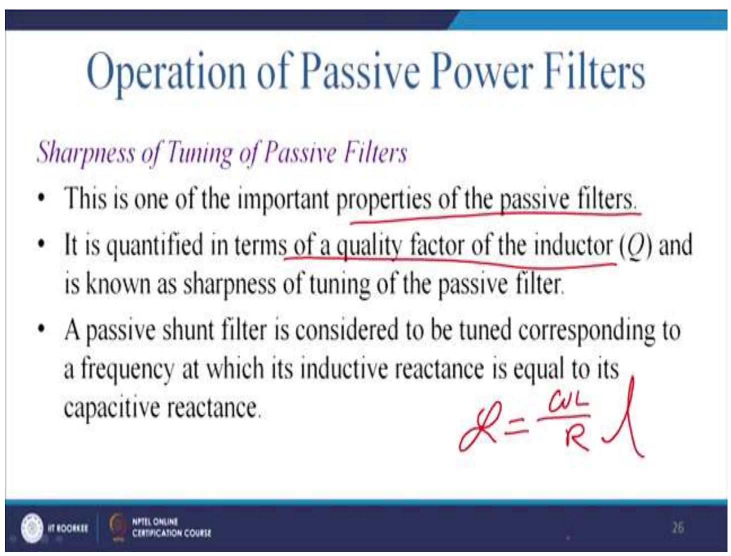

So, this is one of the important properties of the passive filters. How you design the sharpness? What is its bandwidth? It is quantified in terms of the quality factors of the inductor, and it is known as the sharpness of tuning of the passive filter. As you know $Q = \frac{\omega L}{R}$, this ratio. The passive filter is considered to be tuned corresponding to a frequency (we want notch kind of compensation, thus this Q required to be quite high) at which its inductive reactance is equal to its capacitive reactance.

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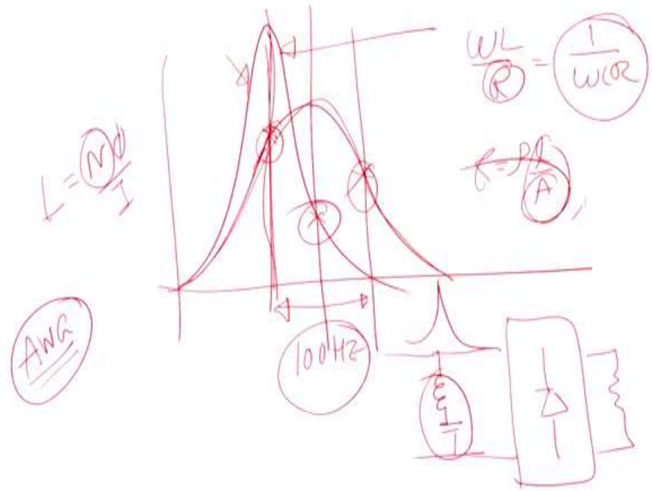

And also, it should have a characteristic, something like this you know. You are connecting a passive filter here. Thereafter, I am drawing the single line diagram. Thereafter you may have a diode bridge rectifier for single phase let us say. Now, this has to be tuned if it is compensating for the third harmonic. So, the response should be like this. So, you can design the filter such a way so that third harmonic is 150. So, it has a component of the 150, so something like this.

And again, you have an option. You know that you have a problem of the third and fifth. So, you can take little bit of flattened option and something like this. This will be the response. And there this is third and this one is your fifth let us say. So, both will be compensated by this. Where flattening can be less. So, here band width can be more of the 100 Hertz, considering the 50 Hertz system, this is a third harmonic 150 Hertz and 250 Hertz. And, accordingly you can eliminate fifth and third or if you have a problem only on the third, then you can take this kind of response and you can eliminate.

Thus, this is essentially a band pass filter here. And, this is a notch filter because it is passive and it will eliminate the filtering. So, a passive filter is considered to be tuned corresponding to the frequency (or may not be tune and you can increase the Q and you require to suppress the fifth and 7th, or third and fifth, you can tune it in a different way and thus you can get the desirable characteristic to some extend and it is a compromise solution) at which the inductive reactance is equal to the capacitive reactance.

But in that case, you may tune to the fourth harmonic. So peak maybe fourth harmonic, but you can tune third and fifth both. So, then to some extent you mitigate fifth harmonic as well as the third harmonic. Here your peak should be attenuated and it is a notch kind of filter and there will be a sharp cut off for the third and you can see that in fifth that attenuation is not up to such a level that you will be able to accept.

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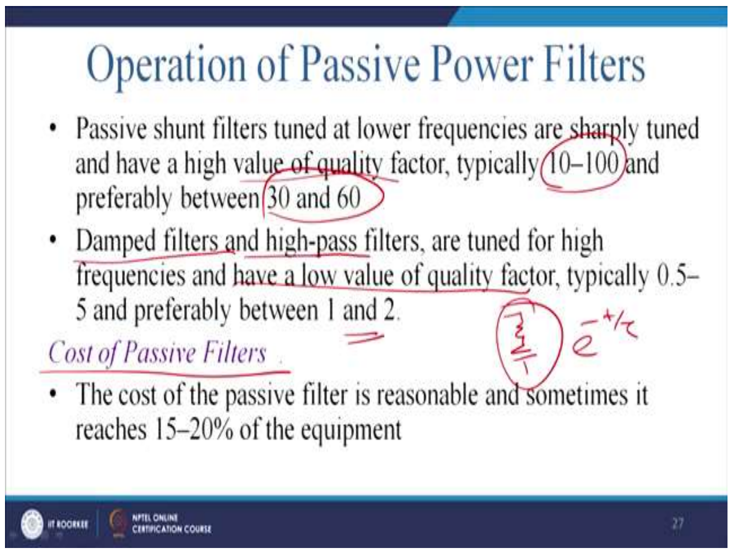

Now, the passive shunt filter is tuned at lower frequencies are sharply tuned to have quality factor, typically 10 to 100, and preferably between 30 to 60. Please understand there is a challenge involved. For this you know having a very sharp $\frac{\omega L}{R}$ or that equal to $\frac{1}{\omega CR}$ whatever may be. So, here value of the resistance required to be very less, and thus you have to increase the $R = \rho \frac{l}{A}$.

And if you are not connecting an external resistance, then ultimately cross-sectional area of the wire and the length of the wire counts because you cannot play anything with the L. Essentially inductor is linked with the L. Here, $L = \frac{N\phi}{I}$. So, N is linked to the length. For this reason, N will be to some extent is a function of L.

So, ultimately to increase the quality factor, you essentially have to play with the cross-sectional area. So, to have a high-quality factor, you require to choose (we have a table called AWG) conductor or gauge generally AWG. So, you require to choose the higher

AWG close to 60 quality factor. And if you want this kind of thing, you require to reduce the cross-sectional area. But here problem is something else.

Since it is a passive filter it does not matter, but having a higher cross-sectional area essentially this employs the more costs to this solution. Damping: I will take out a separate entity and it is not totally restricted to the shunt active power filter or the passive filter. It is required when you are connected to grid connected system. So, damped filters and high pass filters are tuned for the high frequencies and have low value of the Q factors. Essentially you have R and c.

It is essentially a damping. So, you have a term of $e^{-t/\tau}$ where $\tau = \text{RC}$. Essentially it will have a damp. Generally, when you have a LC then it is a second order system. So, you have a flexibility of the under damped, over damped. All those entities can be there. But here once you have the high pass only, it is just a damping and you require to keep the value of RC close to yours switching frequency.

Now, of course, cost depends on various parameter as I told you. The Q is to some extent depend on not only the current rating. One of the advantages of the passive filter is that it does not see the total rating. It only sees the voltage rating. Of course you require to choose the capacitor of higher voltage rating, but since current will be very low the power rating of those passive filters connected in a shunt path is low and for this reason we prefer to connect them in the shunt path also.

The cost of the passive filter is reasonable and sometime it reaches 15-20% of the equipment. Why? You see where the problem lies. let us go to the white page again and take a fresh white page.

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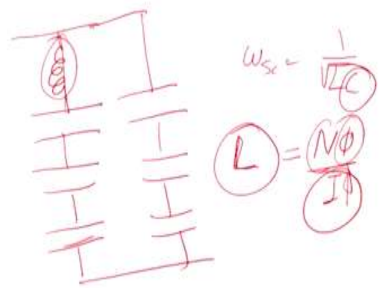

You already have a bank of the capacitor to compensate your power factor. Now, what you want in between, you wanted to put an inductor here. So, since it has to compensate the reactive power at fundamental frequency, the current that it will offer to pass may be quite high, and that $\omega_{5C} = \frac{1}{\sqrt{LC}}$ so 'C' is already fixed and now you have to calculate the value of L.

Once you calculate the value of L, it has to bear the high current unnecessarily if you are retrofitting. If you are not retrofitting and you are designing for the fifth harmonic, that is a different issue. So, it has to bear this amount of the fundamental current unnecessarily. You know that these value of $L = \frac{N\phi}{I}$.

Since value of the I can be very high, and thus the value of the inductance can be low, and you require to meet that inductance and for this reason you have to meet the higher value of the flux and number of turns. Generally, this amount is constant and if current value is increased you have to play with the number of turns. Hence, number of turns can be higher and since number of turns is higher it leads to the higher costs.

And, for this reason we now consider retrofitting this reactive capacity in bank. Can we convert it to the passive filter? That is fine, but it initiates a higher cost and it has to be done case to case basis. Clear? Let us go to our discussions. For this reason your component costs will be 15 to 20 percent of the equipment cost.

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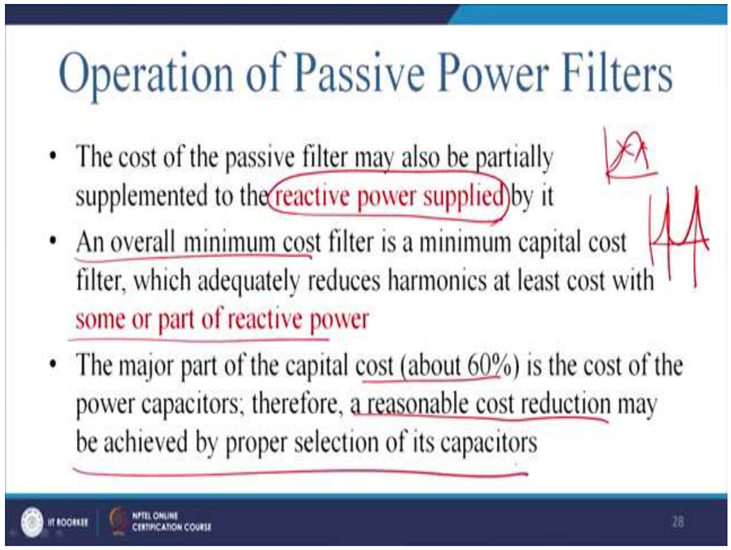

The cost of the passive filter (that is what I was saying in our discussions) may also be partially supplemented to the reactive power supplied by it. So, generally in fundamental frequency it will be reactive, capacitive VAR will be more, and it will give you more reactive compensation, and we will require to optimize it. An overall minimum cost filter is a minimum capital cost filter, which adequately reduces the harmonics at least cost with some part of reactive power. So, it is an optimization technique. You will find many paper on the cost optimization of the hybrid filter nowadays, not the passive filter.

So, ultimately the cost of the reactive power will be there. Whether, if you will be having a band pass kind of things then you can eliminate since most of the cases it is three phase three wire system. So, you can eliminate this fifth and seventh with a single filter or you will take two notches. This is the fifth and 7, so that optimization generally has been done. And we can have best solution for a particular site with the data. Definitely we have to work with the data.

The major part of the capital cost (about 60 percent) is the cost of the power capacitors. As I told you, this has to be connected with the reactive power compensation, and thus it is been connected with the high voltage line in most of the cases or it sees the total voltage. For this reason, voltage rating of this capacitor is quite high, and as I put them in series value of the capacitor goes low. And you want that value of the capacitor that will be switched on, to compensate your reactive power problem and thus you have a quite big cost coming from the value of the capacitor. Therefore, a reasonable cost reduction may be achieved by proper selections of the capacitor.

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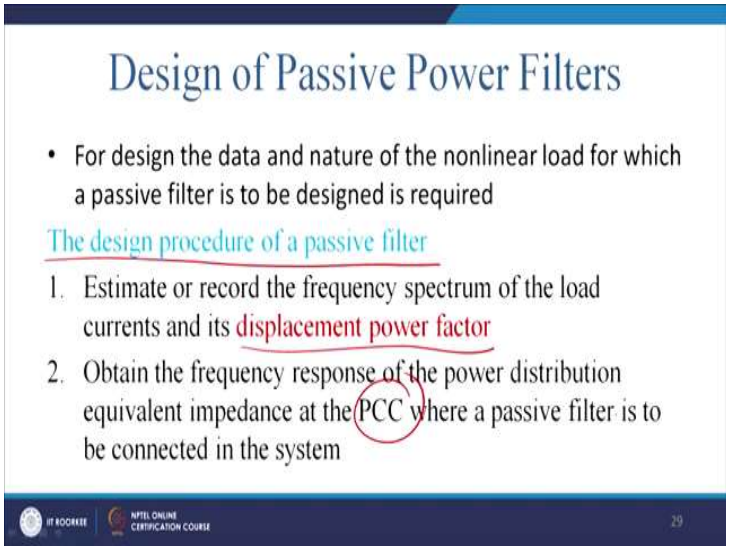

Designing: so now we are coming into the important conclusion of our discussions. For designing the data and nature of the nonlinear load for which a passive filter is to be designed is required by us as a designer. Because if it is a single phase then there is a presence of the third harmonic, fifth harmonic, 7^{th} harmonic. Whether if it is three-phase three-wire system, you will have the harmonics like fifth and 7 and 11 and 13.

In case of a three-phase four-wire system, there will be a third harmonic, fifth, seventh, then 9^{th}. 6^{th} will be absent because it is the even harmonic, so and so on. Ok? Also, you may have a 12-pulse converter. Once you have a 12-pulse converter, we will start with the 11 and 13. So, accordingly the design has to be changed. So, the design procedure of a passive filter. Estimate or record the frequency spectrum of the load. Just collect the sample and do the FFT.

Now, most of the oscilloscope can provide you the FFT and you can get the spectrum of the load current and its displacement power factor. These are the two important entity form there you can calculate the THD, there is a link between displacement power factor and the THD as well. After obtaining the frequency response of the power distribution, equivalent impedance at the PCC (that is point of common coupling) where the passive filter is to be connected. That has to be found out.

And most of the cases we have to add another entity. Now most of the cases, we have a multi-bus system and load is connected to one of the bus and you may have a multiple non-linear load. We generally run the frequency load flow study and thus you get the saddle point. Means in which bus the maximum harmonic contamination is there and you supposed to put it at that bus considering the spectrum of the harmonic content at that bus.

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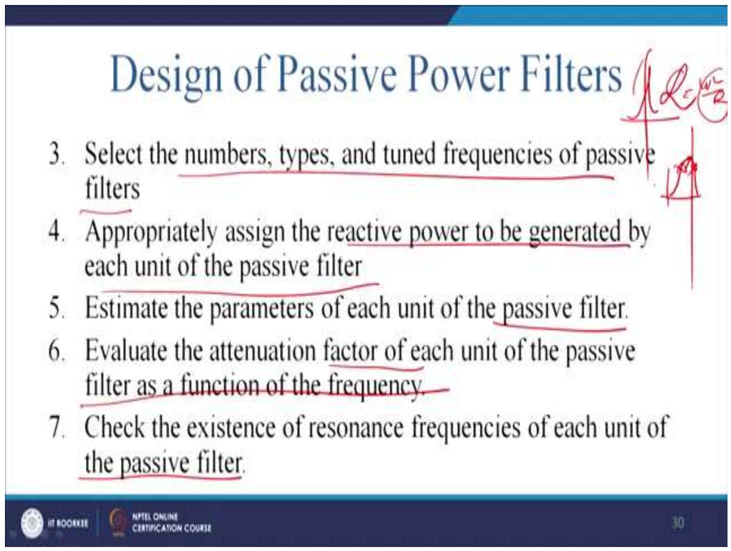

So, now we require to do something. Select the numbers, types and tuned frequencies of the passive filters. So, you can go for band tuning and the notch tuning. If you want first this third harmonic one filter for a single phase, fifth harmonic for the one filter, or fifth and seventh harmonic for one filter, or individual fifth for one filter, and the 7th for the one filter. So, in that way you will decide the number of the filters. But generally, what happen? If you have a very sharp notch, then value of Q required to be higher.

If the value of the Q required to be higher, then $\frac{\omega L}{R}$ this value will come, and thus you require to reduce the value of the resistance. Since you cannot do anything with the value of the inductance and already capacitor value is fixed, so we required to take a higher gauge wire. And for this reason, we generally try to compensate like there. It is to some extent the optimize solution.

Approximately, assign the reactive power to be generated by each unit of the passive filter. So, you know those entity at the fundamental frequency and you have already know that history, then what is its reactive power handling capability, and since you have put an inductor that will also add a negative VAR, but ultimately you have a knowledge how much reactive VAR will be compensated by it.

Estimate the parameters of each unit of the passive filters. So, Q, L, C. Thereafter, the resistance comes from the ECR as well as the ECL. So effective series resistance of the capacitor and the effective series resistance of the inductor. So, evaluate the attenuation factor of each unit of the passive filter as a function of frequency. You can run a program. Generally, we prefer to write a program depending on the data and from there we can find it out the tuning.

Check the existence of the resonance frequencies of each unit of the passive filter. So that it is been close to the Q point or not. This one, it is matching. But its Q point, it is not matching because it may be tuned to the 6th harmonic, if you want to compensate fifth and seventh.

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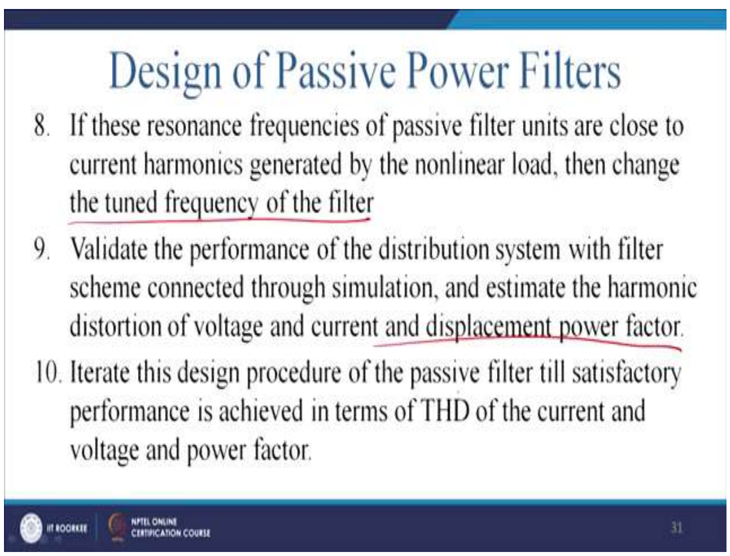

If the resonance frequencies of passive filter units are close to current harmonics generated by the nonlinear load, then change the tuned frequency of the filter. Then we require to run an iterative loop. Validate the performance of the distribution system with filter scheme connected through simulation and estimate the harmonic distortion, (that is THD) of voltage and current and displacement power factor and see that whether there is an improvement or not.

Sometimes you know it is challenging. You can improve the power factor source inductor, for example, you have seen source inductance increases improves the displacement power factor, and thus directly it reduces the value of the THD, but on the other hand it will degrade the power factor. So, for this reason we may have some conflicting combinations.

Once you want to compensate the high reactive power, then value of the capacitor required to be some value and unfortunately which you may not be able to provide. Thus, that kind of sharpness may not be achievable, and thus you may not be able to get the IEEE 519 standard by your designing. Then you have to increase the value of the inductor and that will require extra costs. So that is what I was saying, that you have to iterate and converge it.

Iterate this design procedure of the passive filter. Generally, we write a MATLAB code and run with the simulations in a MATLAB Simulink, and find the optimal value which is require to be placed. You have to take realistically the values of the ECRs and the series inductance value. Generally, it is not been damped and some time it required to be damped. I will show you later. Why we require to damp. So otherwise it may cause a resonance once there is a step change.

Once there is a step change of the load fifth and seventh harmonic will also increase with the fundamental. If there is a resonance, then that will also propagate. So, all those things required to be damped out. System may be stable, but we require to also analysis its dynamic performance. We are fortunate that active power filter can actively damp your oscillation, but in case of the passive we may required to put a damping resistance. But that again deteriorates your THD. Iterate the design procedure of the passive filter till satisfactory performance is achieved in terms of THD of the current, voltage and power factor.

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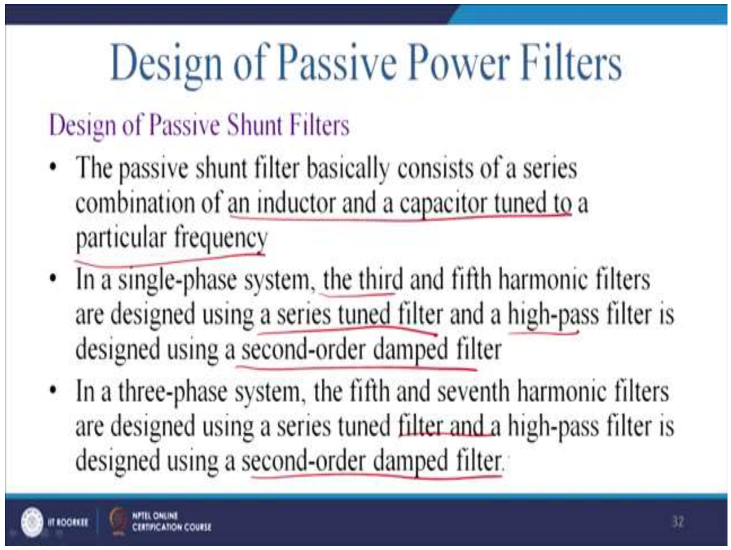

Now, the passive filter basically consists of a series combination of an inductor and a capacitor tuned to a particular frequency. In a single-phase system, the third and the fifth harmonic filters are designing using series tuned filter. There is a reason behind that. Because see high current has to flow and for this reason, we want it to be a series tuned filter. Please refer to my previous lectures of shunt series all those combinations and C-filter. And a high-pass filter is designed using a second-order damped filter.

Why? You know, if you connect R and C it is always damped. We do not want that otherwise response will be sluggish. We want L and C and we put a critical resistance and thus it is critically damped or very close to the critically damped. So, the response is not sluggish and also you get damping. Because first order never gives you that control, you always get a damping.

So, second order system for this required to choose a small L and C with the R. Now there is a concept nowadays, instead of this resistance that is passive damping you can have a current control and active damping. In a three-phase system the fifth and seventh harmonic filters are designed using the series tune filters and a high-pass filter is designing using a second order damped filter.

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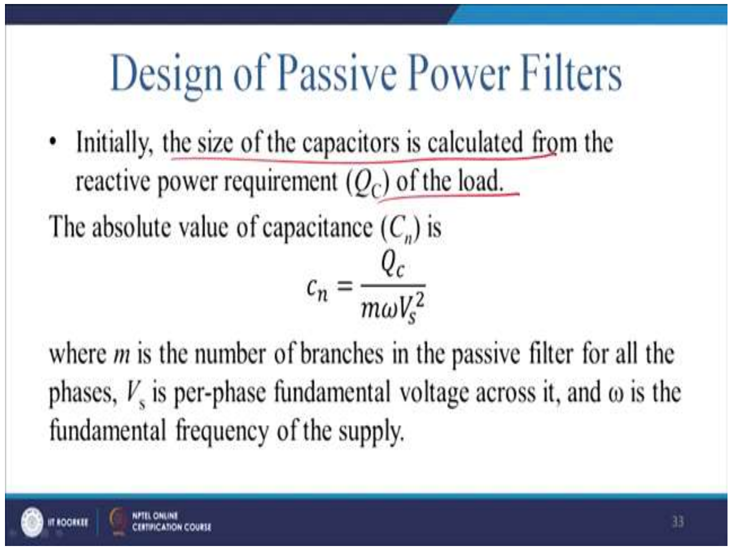

So, initially the size of the capacitor is calculated and most of the cases it is been placed and that value is available to you for a site if you visit the site from the reactive power requirement, but we have to take the derating effect of it. Generally, if it is placed 10 years ago that value of the capacitance will not be same, we have to de-rate the value. Hence the size of the capacitor is calculated from the power requirement of the equipment (Q_C) of the load and historically you find it out how it does the compensation, so your derating should be matched.

The absolute value of the capacitance of the Cn is, $C_n = \frac{Q_C}{m\omega {V_s}^2}$, where you can have a multiple branch of the capacitor. Where m is a number of branches in the passive filter. So that you get a higher value of it and you have to put some value in series, but it will reduce the value of the capacitor. Ultimately the combination of the capacitor bank will come for all the phases. And Vs is a per phase fundamental voltage across it, and 'ω' is the fundamental frequency of the supply.

So, thank you for your attention. I will continue to design the passive filter also in the next class.

Thank you.