Course Name: Power Electronics Applications in Power Systems

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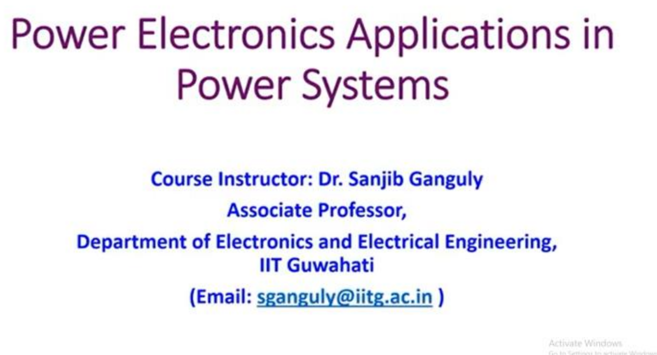
Week: 01

Lecture: 02

Lec 2: Basic Concepts of reactive power compensation



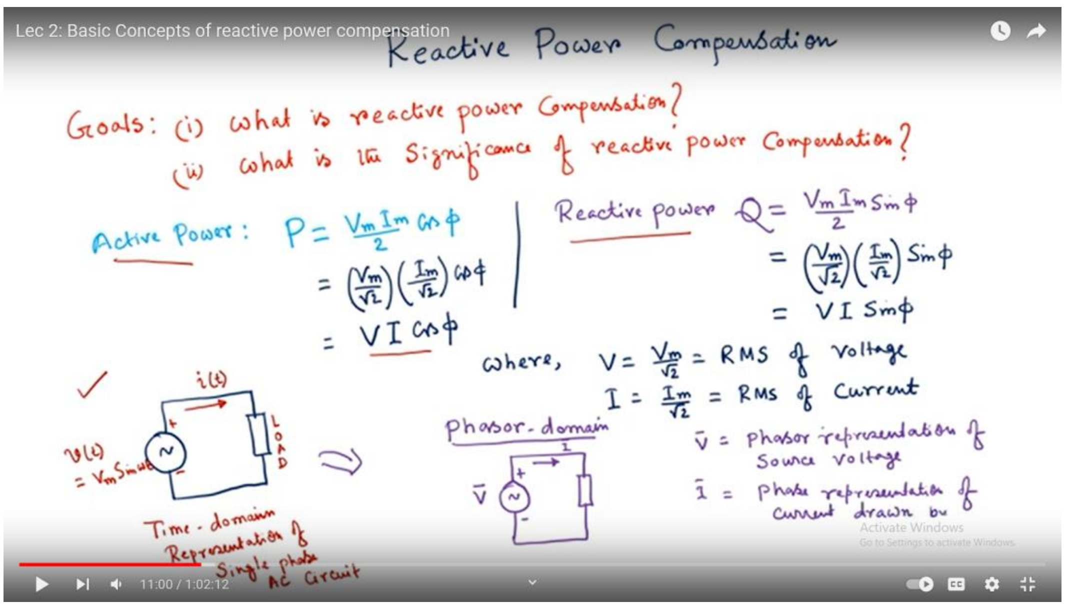
Welcome again in my course power electronics application in power system. In the last lecture, I discussed what is the basic concept of active and reactive power of AC electric circuit. Now, in this lecture, I will discuss what is reactive power compensation and what is the significance of reactive power compensation in power systems. So, in this lecture, we will learn what is reactive power compensation. So the goals of this lecture is number 1 to learn what is reactive power compensator and what is the significance of reactive power compensation. So this we will try to understand.

So if I summarize what we learned in the last lecture that in a single-page AC circuit, if you take the average of the instantaneous power, then whatever you will get that is defined as the active power. And, this active power always is either 0 or positive. So, it cannot be negative. Whereas, in the concept of reactive power is that it is the peak value of the pulsating component p2.

So, in the last class, we discussed that the instantaneous power, if we just derive its equation, we will have two components. One is p1, another is p2. And the peak value of the p2 is defined as the reactive power. So, in this lecture we will learn what is the significance of reactive power. The significance of active power is already discussed in the last lecture.

It is the useful power which is being converted to some other form of energy. For example, if your load is an electric motor, so the active power is the power the motor consumes to convert it to mechanical work. Now what is the significance of reactive power? That is what we will discuss in this lecture. So in this lecture, in the previous lecture we have two expressions of this active and reactive power. I will rewrite this again.

So active power is equal to P, capital P, which is equal to Vm Im divided by 2 cos phi. And reactive power we got expression that is capital Q is equal to V m I m by 2 sin phi. Now what is V m and I m? V m is the peak value of the voltage. It is a sinusoidally varying voltage we consider. So, Vm is the peak value of the sinusoidally varying voltage.



And Im is the peak value of the sinusoidally varying current which is drawn by the single phase load. Now, this we know that this can be written as Vm divided by root 2 multiplied by Im divided by root 2 cos phi. Similarly, this can be written as V m that is reactive power is equal to V m divided by root 2 multiplied by I m divided by root 2 sin phi right. Now, this Vm divided by root 2 is the rms value of the voltage. We know that it is the RMS value.

We represent it with capital V, simple capital V. And Im divided by root 2 is basically the rms value of the current. So, we represent with capital I. So, the whole expression becomes Vi cos phi. Here also the expression becomes V i sin phi where V is equal to V m divided by root 2 which is r m s of voltage.

I hope you are comfortable with the RMS value of the voltage that is taught in basic electrical engineering course. Similarly, capital I is equal to Im divided by root 2 which is equal to rms of current. Now, also you remember that in the last lecture, I mainly discussed a time domain relationship of voltage and current of a single-page and later on of a three-page system. Here also we will discuss a similar concept but the representation would be different. So in the last lecture I discussed in time domain representation, now we will discuss a different representation. That representation is called frequency domain or phasor domain representation. So if if my time domain circuit is something like this, which I discussed in the last class, where this is representing the instantaneous voltage V t, which we considered as V m. sin omega t and for this polarity, if the direction of current is somewhere here, then this is the instantaneous component of the current and this is what the load. So, this representation, this representation is time domain representation of single-phase AC circuit. Now, this expression what we get as active power and reactive power, this expression we get with the analysis of this time domain representation of single-phase AC circuit.

Now, in this lecture, we will also see or recap this idea of phasor domain representation. Where this same circuit will represent in a phasor domain. So this is the voltage source, this is the load. So now we will represent this voltage with the RMS voltage and this V bar, it represents the phasor representation of source voltage. Now, for this polarity of this voltage, suppose current flowing through this is represented by I, then this I is basically the phasor representation of current drawn by the load.

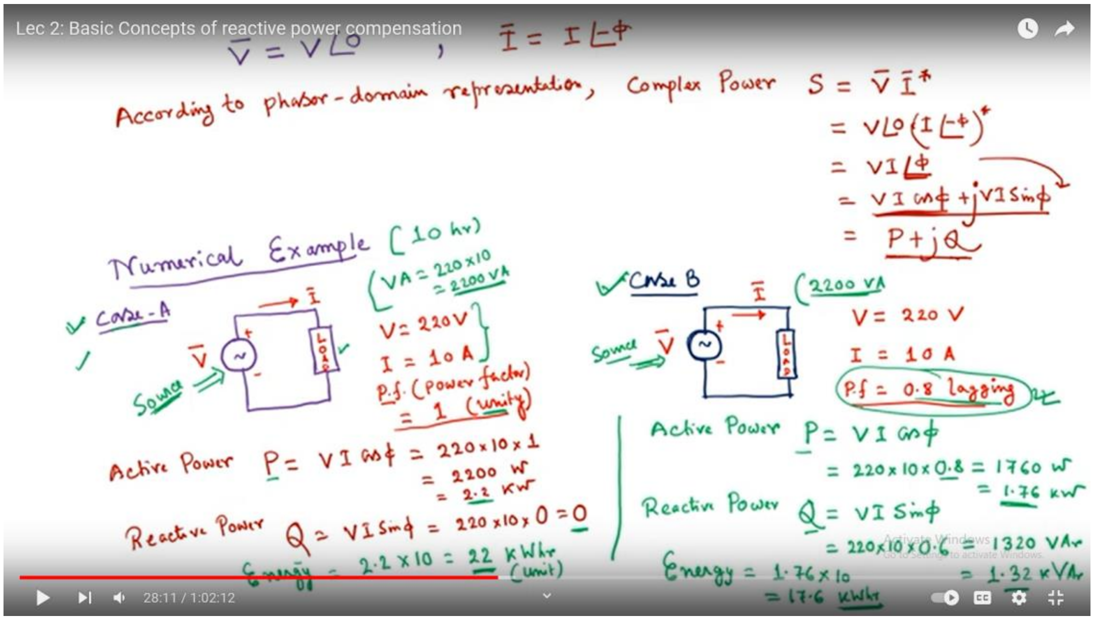
Remember, this is the load which is drawing this amount of current and this bar, V bar and I bar. These represent the phasor quantities. It means that they have some magnitude and they also have some phase angle. Now, in order to relate this phasor domain representation with this time domain representation, what we will do is that we will draw a phasor diagram and we will also see that, whether this phasor domain representation actually represents the expression of active and reactive power that we derived in the last lecture. Suppose if we consider V that is the source voltage, it will have some RMS value of magnitude and it will have some phase which is represented by 0.

Similarly, if we go back and check this expression of this current, so this current we considered in the last lecture. I t was equal to Im sin omega t minus phi. If Vt is equal to this, we consider Im is equal to that. So, what we know that, that if Vm is our reference voltage or reference phasor, then Im will lag with respect to this reference voltage at an angle phi, where this phi is called power factor angle. So, we will represent I, that is the phasor current is equal to the RMS value of the current at an angle minus pi.

Now, according to the definition that in phasor domain that we have a relationship of active and reactive power with this phasor voltage and current. What is that relationship? So, according to phasor domain representation, we know that complex power S is equal to V phasor I phasor conjugate. Now if we put this V phasor and I phasor expression over here, so this will be v at an angle 0. So i conjugate means this is i multiplied by i at an angle minus phi and the conjugate of that. So this will become v i at an angle phi.

So which is equal to v i cos phi plus v i sin phi. So if I convert this, that is this expression to this expression, this expression is in polar form. If we convert it to Cartesian form, we will have this expression. Now if we look at the expression of active and reactive power that we derived from this time domain expression, then we can write that this is, there would be some complex operator j over here because it is a complex quantity. So, this will be p plus j cube.

where P is our active power and Q is our reactive power. So, you can see that this time domain representation actually set the foundation of the concept of active and reactive power and that is being transferred to phasor domain representation to directly find out the relationship of active and reactive power. Now, coming back to the main goal that what I have said in this course that what is reactive power compensation. So, in order to understand that, let us take an example. Let us take a numerical example.



In this numerical example, suppose I have same circuit, same voltage source, but we have different types of the loads. So, suppose this is case A in which I have a voltage source connected to a load; load is represented by a rectangular box and we will consider the voltage here at V and for this polarity the current drawn by the load is I. So what we will consider here as V is equal to RMS value of this V is equal to 220 volt, okay and I is equal to the RMS value of the current is equal to 10 ampere and the power factor which is represented by this P stop f that is power factor of the load is equal to 1 that is unity. Now, we will take another case that is case B. We will have the same circuit.

So this is the rectangular box which represents the load. and this one is sinusoidal voltage source. And this voltage is also equal to V and for this polarity of the voltage current drawn by the load is equal to I. So, this is load that was also load. Now, here V is same the RMS value of voltage is same as that of case A that is 220 volt.

I is also same that is RMS value of the current is also same that is 10 ampere. However, this power factor of the load is a different it is 0.8 lagging. So, only difference of this case and this case A is that the power factor are different in both the cases. In one case the load is having unity power factor and another case load is having a power factor of 0.8 lagging. Now what we will do is that we will determine the active and reactive power for this type of load. So, first of all active power consumption for this case P is equal to as we know the expression P is equal to V i cos phi from here. So, this is V i cos phi. So, this is equal to 220 volt multiplied by 10 and power factor is unity here, so this is 1, so that is equal to 2200 Watts or 2.2 kilowatts and reactive power for this case is Q is equal to Vi sin phi which is equal to 2 to 0 multiplied by 10.

If cos phi is equal to 1, the sin phi will be 0, so that is 0. Now, for case B also we will determine active power. So, active power for case B, which is having a load of a power factor 0.8 lagging. So, this active power will be equal to P is equal to VI cos phi, which is equal to 220 multiplied by 10 multiplied by 0.8, which is equal to 1760 watt. or 1.76 kilowatt and the reactive power Q will be equal to Vi sin phi which is equal to 220 multiplied by 10. Now if cos phi is equal to 0.8 then sin phi would be equal to 0.6. So, this will be equal to 1320 volt ampere reactive or 1.32 kVAr. So, that is what the two cases, in one case we have a load which is having unity power In another case, we have a load of 0.8 power factor. You look at, due to this power factor, both the cases having different active and reactive power consumption. In case A, active power consumption was 2 kilowatts. In case B, it was, it is 1.76 kilowatts. Whereas in case A, reactive power consumption is 0. In case B, reactive power consumption is non-zero which is equal to 1.32 kVR. Now what we can conclude from this? What we can observe from these two case studies? Let me put this into like this.

Suppose this is the source of this particular circuit. This is also the source of this particular circuit and normally the source of the electric circuit in our home, we are a domestic customer, so for us the source is the power supplied by the electric utility. Now in this particular case, the source which is representing this electric utility is sending this Volt-Ampere of 220 multiplied by 10 that is 2200 Volt-Ampere. So that is what the power it is sending by the source. Here also for this particular case, the source is also sending that 2200 Volt-Ampere from the source end.

However, in case A, the active power consumption is 2.2 kilowatts. And in case B, the active power consumption is 1.76, which is much lesser than this 2.2. So, what we can observe from this is, in case A and also in the case B, in both the cases, the source is sending same amount of volt ampere. So, if the source is our electric utility, then electric utility is sending same amount of volt ampere. However, due to the different types of the load, case A is consuming, case A is basically consuming 2.2 kilowatt, but case B is consuming lower, that is 1.76 kilowatt. This primarily happens due to this power factor. Now we all know that this electric utility sells us the power and we the consumer we consume the power and according to our consumption the electric utility sets the billing. And if you look at, for domestic customers, the electricity billing will depend upon how much active power you have consumed multiplied by the time. So, it is basically based upon the amount of energy that we are consuming. Now, how can we get this energy value? This energy is nothing but that how much active power we are consuming multiplied by the duration.

Now, of course, from one duration to another duration active power consumption gets changed. So, for every hour, for example, if we consider that active power consumption remains same, then what we do is that to find out this net energy consumption, what we do is we multiply hourly active power multiplied by this duration and sum up. So obviously, suppose this situation sustains for 10 hours, suppose, then for this particular case, the energy consumption will be 2.2 kilowatt multiplied by 10 hours, so that is 22 kilowatt hour of energy. Often we call it as units of energy. So, it will consume 22 units of energy. Whereas for this case B, the energy consumption was this active power that is 1.76 multiplied by this 10 which is equal to 17.6 kilowatt hour of energy or 17.6 units of energy, which is lower than this. So, if you compare these two cases, case A and case B, in both the cases, source is sending same amount of Volt-Ampere. Ultimately, when the source is going to build the electricity consumption of the load, in case A, it is getting the price of 22 kilowatt-hour, whereas in case B, it will be getting a price of 17.6 kilowatt-hour, so which would be lower than this. And this primarily happens because of this power factor which is non-unity. So, when we have a non-unity power factor load, so the total energy consumption would be less than the unity power factor load.

So, accordingly this electric utility will get lower revenue due to this non-unity type of the load. But of course, what type of load we will be using being a customer that will be not decided by the electric utility. So, that will be in our hand. So, therefore, due to our specific nature of this electricity consumption, the electric utility will get lower revenue if the load is of significantly of lower power factor. So, that is the point I want to raise over here. Now, if we want to keep the summary of our observation. Number one observation will be in both cases the source is sending same Volt-Ampere; VA represents Volt-Ampere. However, the energy consumption of case A is higher, since in case B, the load power factor is of non-unity. So, third summary is that thus the electricity supplier will earn less revenue when the load power factor is non-unity.

Now look at this both the cases. Here the rating of this generator for this case A and rating of this generator in case B are identical. So that means the electric utility who is supplying power needs to set same amount of infrastructure for both the cases in order to supply power in case A as well as in case B. However, by setting identical infrastructure, it is getting less revenue when the load power factor is non-unity. Load power factor is non-unity and it is lagging in nature. So here is the concept of this significance of the reactive power consumption of the load.

In one case load due to this non-unity of this load power factor the electricity supplier earns less revenue in spite of setting same amount of infrastructure for both the cases. So that is what the point I want to establish here. So that is what in fact the difference. This is one point I want to establish. Another point is that here if you look at in case A, its reactive power consumption of the load is 0.

So, therefore, this load due to its unity power factor is not consuming any reactive power. So, the generator for this case A need not to provide any reactive power by the source. Whereas in case B, since we have a significantly high reactive power is consumed by the load, due to the non-unity power factor. And who will supply this reactive power? There is no one except the source to supply this reactive power. So therefore this source has to supply both active power and reactive power.

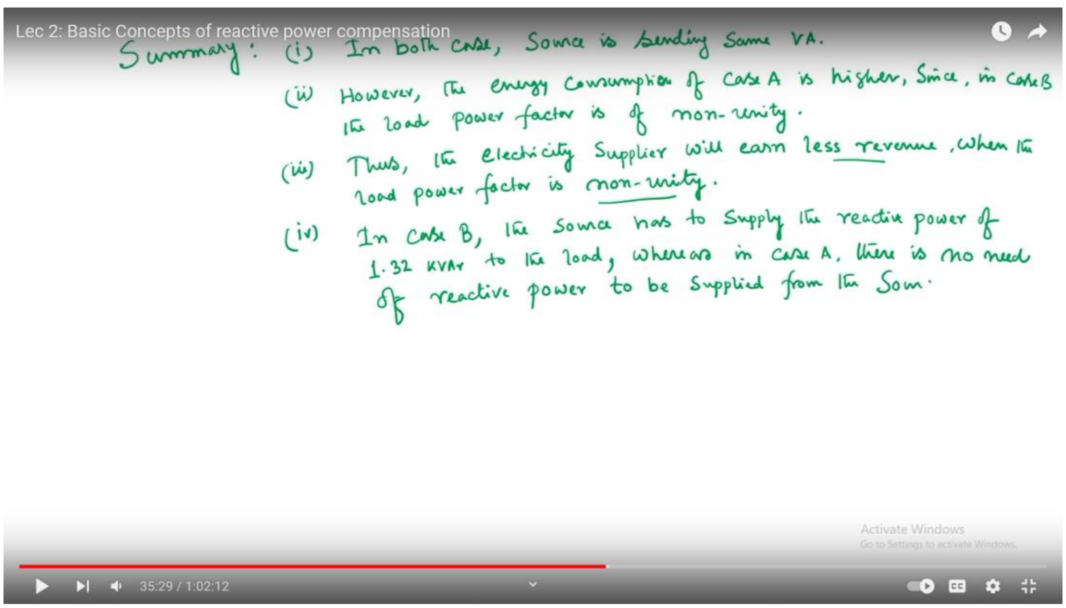
And since it is supplying both the power, its active power, you know, this energy revenue due to this active power consumption is reduced. And that is what the another point that we can find over here. So, if we write it here, so in case B, the generator, the source or the generator has to supply the reactive power of that is 1.32 kVAr to the load. Or whereas, in case A, the source is relieved, it does not require to supply or you should write it here, whereas in case A, there is no need of reactive power, there is no need of reactive power to be supplied from the source.

That is what important observation that we can find. So, generator in case B or the source in case B is overburdened to supply both active and reactive power. Whereas, in case A, the generator is relieved to supply any sort of reactive power and that is beneficial in terms of this energy consumption, energy consumption for which normally the billing depends; electricity price depends for domestic customer I am talking about. So this is what another important observation. So in both the cases, we have a difference of the consumption pattern primarily because of the type of this nature of the load. But in reality, in practical scenario every generator or every source is designed in such a way that it is it can be operated to supply certain amount of reactive power.

So it is the electric utility, they know that this reactive power supply would be required for every type of load which are having a non-unity power factor, and primarily loads are of inductive. So, that is what the important point I want to raise over here, and that is what one of the significance of the consideration of reactive power over here. So, here although in the last class or in the last lecture, I discussed that if you look at this expression of this p2 which we derived from the instantaneous power its average is 0 means one half cycle;

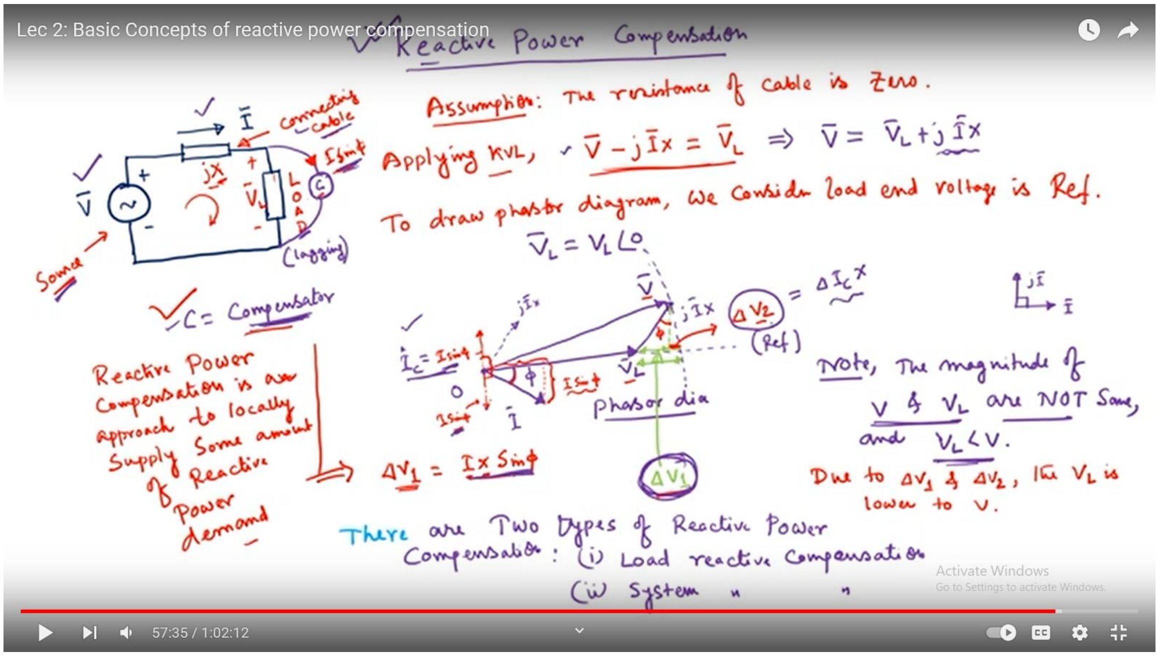
it is coming; if it is coming from the source another half cycle it is returning back to the source. So, one may think of that why, what is the significance of reactive power then, why should we bother because it is having zero average. But here you can see that for this in case B, for non-unity power factor load, whenever it demands the reactive power, the system or the source has to supply.

And that is what the significance of the reactive power. Now this phenomena would be more predominant when we will go for higher load demand. So, here we consider a very you know nominal load demand of that 1.76 kilowatt or something like that. Suppose if you visit industry, a process industry in which a large number of motors are running with significant ratings, then you will see that the overall power factor of the load will be much lower. So in those cases, this source or the utility need to supply a huge amount of reactive power.



So this is one thing that one needs to understand. Now in the next part what we will discuss is what do you mean by reactive power compensation and how it can be done in order to discuss this. So, we will take an another example in order to establish this; let us take an another example; let us consider we have a source also we have a load that is consuming both active and reactive power that is something similar to a non-unit lagging type of load. And we also have a connecting cable. So, let us draw this. We have a source. We have a connecting cable. The connecting cable is represented by a rectangular box, we have a load over here. And we will represent it as a phasor domain representation. So, this RMS value of the voltage is V and for this polarity the current drawn by the load is I.

They are phasor quantities. That is why I put bar on the top of this V and I. Let us consider that this is connecting cable and we assume that it is simply represented by its model by this X, J X and this is what our load, this is what our source. So this is the source and this is the load which are connected through a connecting cable and this connected cable will model with simply J X. So when I do so, so automatically we take an assumption that, the resistance of cable is 0. And the voltage at this load end, suppose it is VL, voltage at this load end is VL. Now, what we will do is that in order to analyze this system, we will apply KVL at this loop, we will apply this KVL at this loop.



So, applying KVL, what we will get? We will get this V minus this voltage drop in the cable, which is minus j I multiplied by x is equal to the load end voltage that is VL. Here V and I are phasor. I hope that all of you are comfortable with phasor diagram. So, to develop the phasor diagram, what we need? We need to first consider someone as a reference and we need to develop the algebraic equation by using KVL or KCL.

So, here already we have developed this algebraic equation. What we need to do in order to draw this, to draw this phasor, we consider load and voltage as reference. So, therefore, we will consider VL is equal to its rms value at an angle 0. So, to draw the phasor diagram, first we have to draw the reference which is VL. And as we know this load is lagging in nature, we already considered load which is lagging and most of the practical loads are lagging in nature. So, the current will lag with respect to this voltage by some angle. Let us consider this angle is phi. So this is our reference phasor. This is our current phasor. From these two, we can find out the phasor of the source voltage. How can we find out?

You see, from this equation, we can write capital V, which is the voltage at this source, is equal to VL plus j i x, where j i x is the voltage drop due to the connecting cable.

So, now where will be the location of this j i x? So, if this is i, when you multiply j operator, suppose this is i, if this is i phasor, then j i phasor will be 90 degree leading with respect to i. This is somewhat known to you. So jIx phasor will be somewhere in this direction jIx. Now if we add these two which is representing jIx then what we will get? What we will get that is the source voltage that is V.

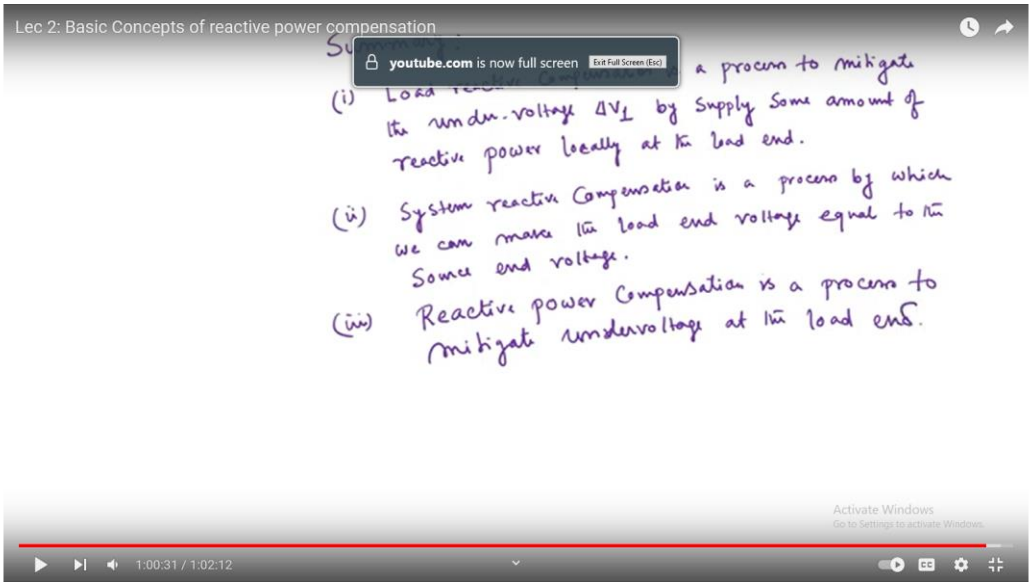
Now what you can see is that note the magnitude of V and VL are not same. So, looking at this phasor diagram, this is the phasor diagram we developed, one can comment that this V and VL, their magnitude are not different and you can see that this VL is lower than V. So, that is happening why it is happening that why this VL and VL is lower than V primarily because there is a voltage drop in the connecting cable. So, this is happening due to the voltage drop in the connecting cable. So, that means that what the voltage the source is supplying the load and voltage is not same of that voltage.

So load and voltage is different to the voltage supplied by the source. So that is visible from this phasor diagram. Now, the question is it is something like that you can imagine on all of our home we are a domestic customer. We need a single-phase AC supply from the electric utility and the rating of this single-phase supply is suppose 230 volt 50 hertz in India. So, what we expect is that in the black point that we have from where we are connecting different devices like fan, light, etcetera, there we have 230 volt 50 hertz supply. But as you know that this our home is normally located far away from the distribution transformer, even distribution transformer is far away from the substation from where the electric utility supply has the power. And due to that, due to the physical distance, this wire or cable either overhead wire or the conduct ground cable the electric utility are using to bring power to our home, there is some voltage drop. So, in order to ensure that in our home there is 230 volt, then at their end the voltage supply would be higher. Or if they supply 230 volt equivalent single page at their location of the substation, then in our home this voltage will be less. And that is happening. And this is primarily happening, one of the reasons is that we have this connecting cable, we have overhead line in which there is some amount of voltage getting dropped. So, and that is why this V and VL are different. Now this reactive power consumption, reactive power compensation is a process to create a condition such that this VL would be equal to V. So load end voltage would be equal to V. How it is possible? By connecting an external compensator near to the load end. So this C represents compensator. Now, what this C will compensate? C will primarily compensate the reactive power. Now, this compensator will primarily compensate the reactive power demand by the load locally at the load end so that VL and V become equal. Now, let us see that why, who is basically responsible for that, you know, unequal values of VL and V. So, if we just take a, suppose this is my origin and this is the supply voltage, if we just by taking the, you know, supply voltage or source voltage as a radius, if we take an arc, if we draw an arc over here, then we can see that there is a this much amount of mismatch of the supply voltage and source voltage. Now this mismatch we can divide into two components.

One is this component, another is that component. This component we will consider as del V1. And that component if I draw it in a different color to make it visible, that component if I represent del V2, so that means due to del V1 and del V2, the VL is lower to V, the supply voltage. So, if we can somehow this compensate this del V1 and del V2, then our load end voltage would be equal to the source end voltage. This is exactly done by this reactive power compensator. This is exactly possible to do this reactive power compensator.

Now, let us see that what is this del V1. Now, since this is phi, this angle is phi, so one can find out that angle is also phi. So, basically, this del V1 is basically equal to its magnitude is equal to Ix sin phi, Ix sin phi. Now, here I is the current drawn by the load, x is the reactance of the cable and sin phi you know phi is the power factor angle. Now you can see over here is that if I resolve this capital, this I phasor into two part, one is this part that is called out of phase component or perpendicular component and this is in phase component, then this component is basically equal to I sin phi. So, this I sin phi multiplied by this cable reactance is equal to del V1, which we need to compensate so that the difference between this VL and V can be reduced.

Now, in order to do so, what is usually done is this I sin phi is basically this component of this current. This is I sin phi. If we just arrange this compensator which can draw this i sin phi equivalent component of the current which is we can draw this i sin phi. The equivalent component of the current from at this load end, then this I sin phi and that I sin phi will be nullified and therefore, del V1 can be eliminated. So, the difference of this V and VL would be somewhat reduced, right? And this process is called reactive power compensation.



So, reactive power compensator, I write here, reactive power compensation is an approach or a process we can say to locally supply some amount of some amount of reactive power demand. So, how it is happening? You can see that this compensator will design such that it will draw a i sin phi component of current, but it should be 180 degree phase difference with respect to this I sin phi, so that this I sin phi and the I sin phi drawn by the load can be nullified. So, since the load is of inductive in nature, so this compensator at that moment should act as a 180 degree phase difference of the inductive load. So, which is naturally some kind of leading power factor system or some kind of capacitive system we can consider, you can understand. So, this process is called reactive power compensation. Now, there are two types of reactive power compensation. There are two types of two types of reactive power compensation. One is called load reactive compensation or simply load reactive power compensation. Another is system reactive compensation or system compensation.

So, there are two types of load reactive power compensation. So, by connecting the compensator which will inject that 180 degree out of phase of current component of this load current that is I sin phi, it can mitigate the difference of this del V1. Now, when you mitigate this del V1, that means when you connect a compensator which is also drawing a current, but 180 degree out of phase with respect to this load current or load current this component, then you can mitigate this delta V1. Now, the question is how can we mitigate this delta V2? In order to mitigate this delta V2, this x sin phi will not be, you know, enough to mitigate this delta V1, we need to mitigate something more than this. Suppose if we consider this I sin phi is Ic, then this Ic will not be enough for mitigating both del V1 and del V2.

We have to supply this, we have to design a compensator which can draw a current more than this Ic, okay. Suppose if we consider that that current is del Ic, then it should be del Ic multiplied by this x. Del Ic multiplied by this x, that component of the current, it should draw from the system so that del V2 can be mitigated. And this process is called system compensation. Load reactive compensation and this is called system compensation.

So in summary, we can write from this today's lecture. Load reactive compensation is a process to mitigate the under voltage del V1 by supplying some amount of reactive power, reactive power locally at the load end. And system compensation, system reactive compensation is a process by we can make the load and voltage equal to the source and voltage. Number three is that reactive power compensation is a process to mitigate the under voltage. Reactive power compensation is a process to mitigate undervoltage at the load end.

So this is what the summary of this lecture. So we learned what is reactive power compensation, what is the significance of reactive power. Also we also learned how can we do this reactive power compensation. So reactive power compensation and important approach or important process of the power system to mitigate some kind of under voltage by locally supplying some amount of reactive power. This is one of the task of a compensator which we will be discussing in future in our power electronics based compensators. But this is not only the task of the power electronic based compensator because reactive power compensation is not only done to mitigate the voltage related issues like under voltage or over voltage even, but it is also useful during dynamic condition. Those things we will study in future. So, up to this today.

Thank you for your attention.