Pulsewidth Modulation for Power Electronic Converters
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Lecture - 07
Applications of voltage source converter - II

Good morning. Welcome back to this lecture on lecture series on Pulsewidth Modulation for Power Electronic Converters. So, we have so far been focusing on power electronic converters, you have discussed several kinds of power electronic converters like starting from DC to DC converters and DC to AC converters where we saw, but voltage source inverters and current source inverters. And we also discussed about multi level converters and different ways of realizing multi level converters such as the neutral point clamped or the diode clamped inverters the flame capacitor inverters and hybrid certainly inverters, etcetera.

Now, we are supposed to start with pulsewidth modulation before that what we have been looking at is we are looking at certain applications of a voltage source convertor now. So, you are looking at certain applications of voltage source converters before we launch on to pulsewidth modulation of such converters in another lecture or so now.

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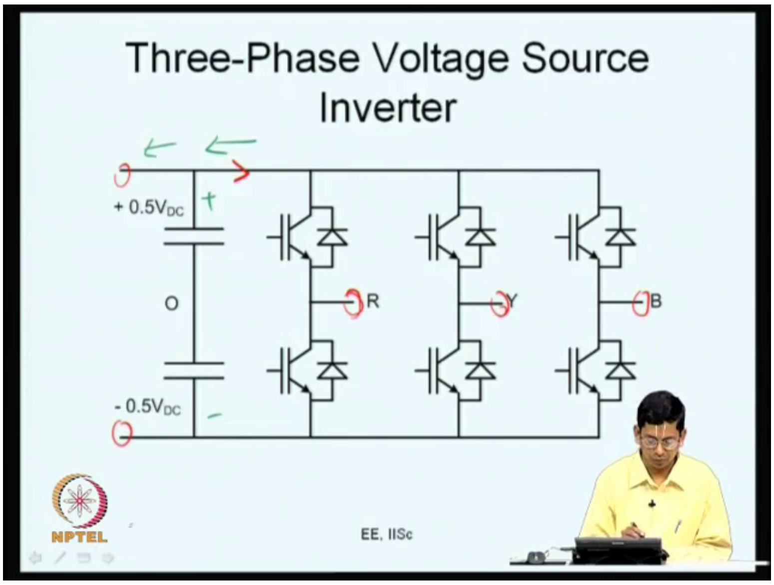

So, there are numerous applications as we saw the last class and we dealt with one of them which is basically more a drive. Now we look at another application which is basically the active PWM rectifier in this lecture in some detail. Now this is backed over three-phase voltage source inverter and there is DC these are the DC terminals here the DC terminals here and you have the AC terminals here. So, the DC supply could be connected between these 2 terminals and the three-phase loads can be connected a to BC terminals R, Y and B right.

So, if there can be an inversion now. So, this is DC can be a DC supply or in or battery bank you know ups; it is typically a battery bank and it can be a DC power supply, it can be another converter which gives DC whatever way. So, you can feed an AC load here as we observe the other day itself this converter has a bidirectional power flow capability. So, current can actually flow in this direction as indicated by the red arrow or it can also flow in the opposite direction as indicated by the green arrow.

The voltage polarity remains the same the voltage polarity remains the same, but the current flow direction can reverse. So, average current once it reverses you know the power flow direction reverses now and if you look at it correspondingly on the line side it would you know what happens is the phase difference between the voltage and the current waveforms now. So, when the voltage and the current waveforms are they different phase only within plus 90 to minus 90 degree power flow is in a particular direction if it is beyond 90 degrees or it is close to 180 degree. Let me say the power flow is really in the opposite direction now. So, as we saw earlier this is our actually is a bidirectional converter now.

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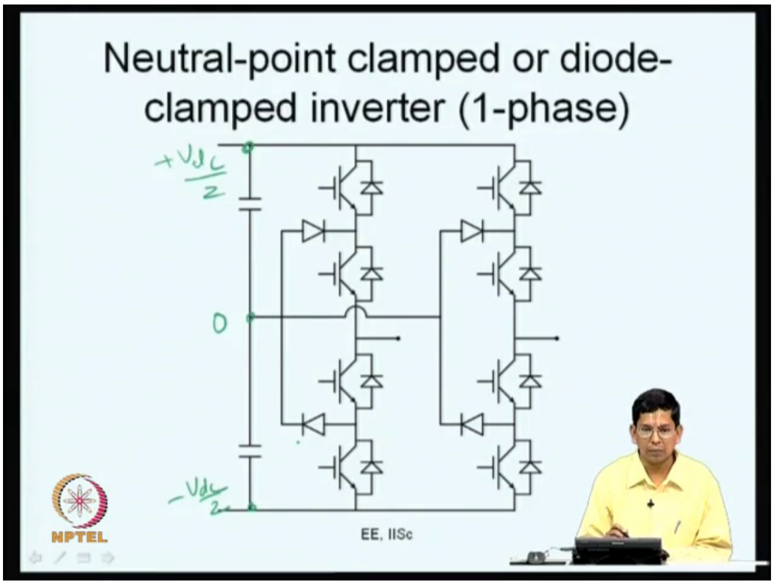

So, this is the three-phase voltage source inverter that was a 2 level one this is a 3 level inverter now as we saw the pole voltages can be 3 different levels that is plus Vdc by 2 or this is plus Vdc by 2, this is 0 this is minus Vdc by 2. So, you have this point O which is taken as the reference and you have plus Vdc by 2 here and you have minus Vdc by 2 here and this pole can be connected to any of the 3 throws. So, namely a plus Vdc by 2 0 or minus Vdc by 2 that was our i, you know that is what we had been looking at

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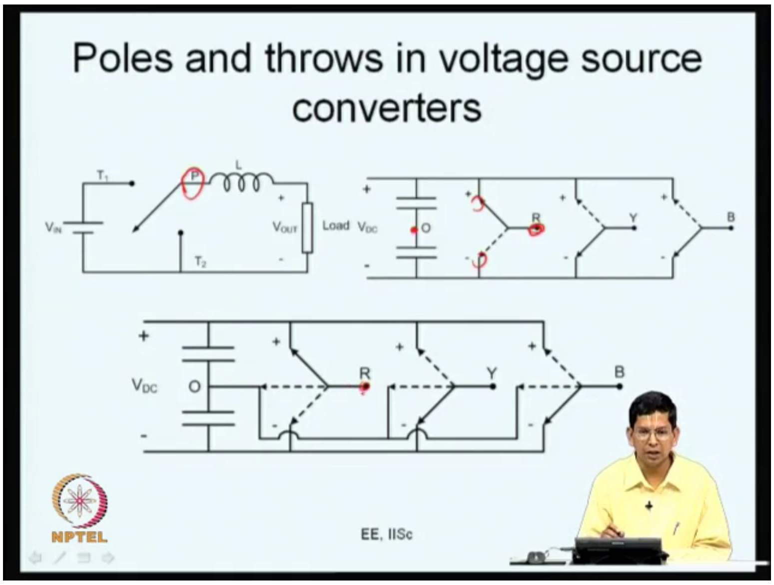

So, you look at all the power converters if you take the DC to DC converter or you know it is a simple buck converter here, here what you have is you have a single pole double throw switch is connected here you have a single pole double throw switch here you have a single pole double throw switch here excuse me. Then if you take a three-phase voltage source converter once again every leg is a single pole double throw switch if you take a multi level converter or a or a 3 level voltage source inverter every leg is now a single pole triple throw switch.

Now, what we do here is essentially control these pole voltages or rather the average pole voltage. Now if let us say I want to control this average pole voltage this is the pole, I apply some you know the pole is either connected to T 1 or T 2. So, the voltage up right at the pole is either VDC or 0 in the case of a buck converter.

So, what would be the average voltage at the pole it would be some weighted average of the voltage at throw T 1 and the voltage at throw T 2 . So, the average pole voltage will be some value that is in between the voltages at T 1 and T 2 which is incidentally VDC and 0 or V in and 0.

Now, similarly you take this pole voltage the average pole voltage can be anywhere between the pole voltage of the top, I mean the voltage at the top throw and the voltage at the bottom throw. So, that is anywhere between plus VDC by 2 and minus VDC by 2 measured with respect to the DC bus neutral if you take a multi-level converter or a 3 level converter to be precise once again you have this pole this pole is connected to any of the 3 throws now. So, what you have is you know the average you know the time average of all the 3 voltages typically in a switching interval you might not connect this pole to all the 3 throws you might connect only to 2 of the throws maybe 2 plus 1 0 or 0 1 minus and you will get an average which is either between plus 1 0 or I mean plus VDC by 2 1 0 or 0 1 minus VDC by to add this potential now.

So, what we do essentially is basically we control, when you look at the power converter you know power converter has several switches if you look at a power converter like this you have switches, it is a question of generating gating signals for turning on and turning off. These devices the converters can be viewed a little differently can be viewed in terms of switches as shown in this particular slide when you use this way you can say that what you are trying to do is you are basically trying to control the average pole voltages that is all that we are trying to do now.

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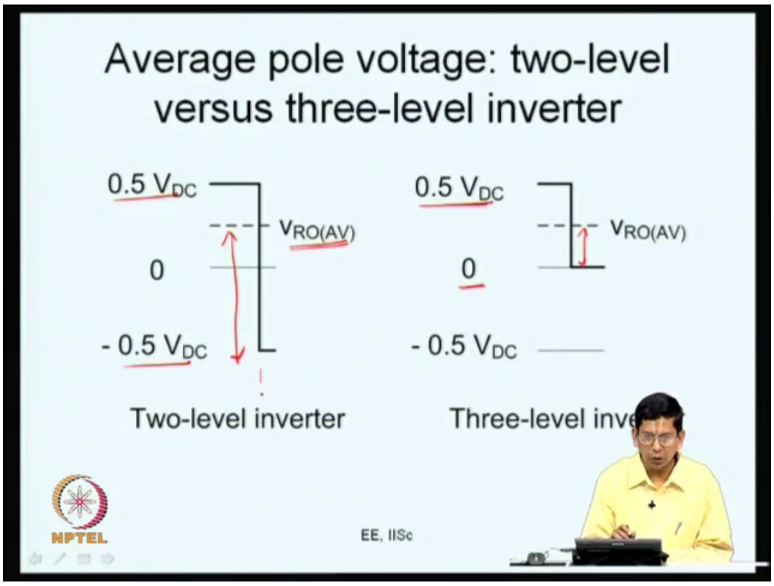

How is the average pole voltage controlled you know this is how more about how an average pole voltage is was realized as I just mentioned in a 2 level converter you apply plus 0.5 VDC for certain amount of time and minus 0.5 VDC for remaining amount of time and you get an average voltage which is indicated as VRO average here now.

Now, this VRO average turns to be positive if you want a negative VRO average, you must apply plus 0.5 VDC for shorter duration than for minus 0.5, then you apply minus 0.5 VDC. So, you can get various values of average VRO average can be anywhere between plus 0.5 VDC and minus 0.5 VDC VRO average will be equal to plus 0.5 VDC if the pole is connected to the top throw throughout the switching interval. On the other hand if VRO average is connected to the bottom throw throughout the switching interval it is going to be minus 0.5 VDC.

So, what you typically do is connected for some time for the top throw and some time to the bottom throw and so you get a kind of a weighted average of these 2, 0.5 VDC and minus 0.5 VDC and you will get some voltage between the two. Now here incidentally this voltage is something like 0.25 VDC if you consider a similar voltage of say 0.5 VDC in a 3 level inverter you will realize that by time averaging of plus 0.5 VDC and 0, you do not have to apply minus 0.5 VDC you apply 0.5 VDC for roughly half the switching interval and 0 for another half; the remaining half of the switching interval to get an average pole voltage something like 0.25 VDC. So, the difference as we pointed out earlier is that in a 3 level inverter you are able to realize certain average voltage by applying instantaneous voltages which are closer to the average voltage design.

So, the worst case error between the actual applied voltage and the average voltage is much higher here is pretty high here, whereas it is low here that is the difference that you are getting here. So, this leads to better performance in terms of harmonic distortion in terms of the waveform the quality of the waveform that is synthesized now.

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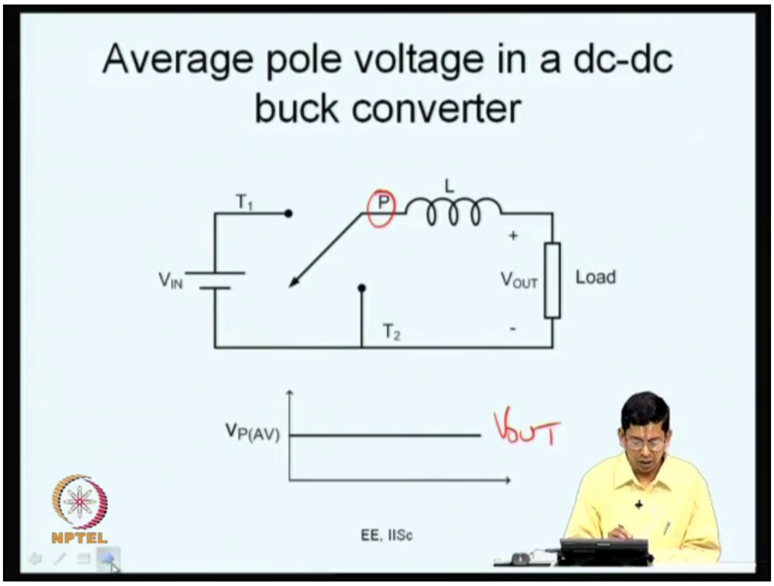

So, if you move on this is what you do in one switching interval what you do over several switching intervals if you are talking off a buck converter as I mentioned in the previous lecture, you control the average pole voltage here such that it is always constant I am talking about steady state you always maintain that as constant. So, this VP average is constant and this VP average. In fact, is equal to the output voltage the average output voltage because the average voltage across the inductor is 0 this is what we saw. So, how should be average pole voltage be controlled in a buck converter, it should be controlled to remain a constant it must remain constant and equal to the output voltage.

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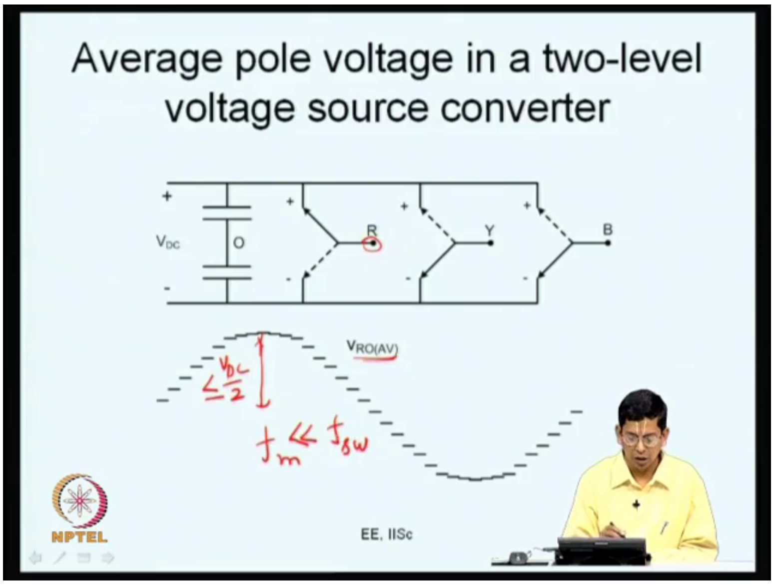

Whereas instead of a buck converter DC; DC buck converter if you take a three-phase voltage source inverter how should this average pole voltage be con control this is R r is being measured with respect to O. Therefore, you call it VRO and this VRO is averaged over one switching interval. And therefore, we call this VRO average now how does this VR or average vary it can be varied in several fashions. Usually, we will tend to vary it in a sinusoidal fashion as I mentioned it is also possible to vary it, you know in some sinusoidal plus certain harmonic current ripple frequency harmonics added to that, but we will come to that in a in a much later class.

But typically what we can try to do is what we look to apply on the load this sinusoidal voltage. So, you want to apply sinusoidal voltages. So, one easy way to do that this control R VRO average itself to be sinusoidal now. So, VRO average can be controlled to be a sinusoid as shown here, it has a sinusoidal variation over a entire lies line cycle and as I mentioned in the previous class. This frequency can be easily controlled and also the amplitude can be controlled the maximum amplitude as I said was VDC by 2, it cannot be greater than VDC by 2 this amplitude will be less than or equal to VDC by 2 within that we can control this voltage.

So, it is possible to control the amplitude such that this VRO averages peak value does not exceed VDC by 2 and the frequency can be varied over a wide range, but this line frequency are the modulating frequency let me call this fm is used to be lower than whatever switching frequency. In fact, I would say it is typically much much lower than the switching frequency of the inverter those are the conditions now.

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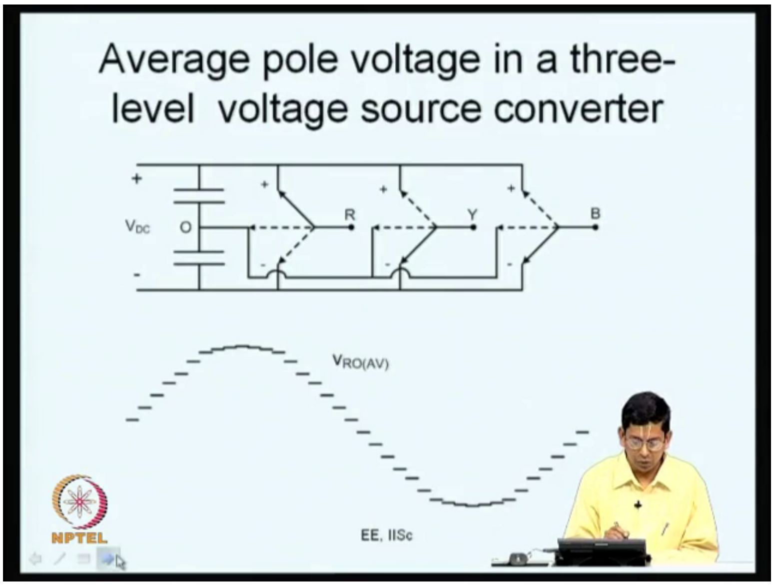

Instead of a 2 level inverter if you take a 3 level inverter and once again VRO average is typically modulated in a sinusoidal fashion, but as I mentioned the way a particular average voltage is realized its different within a switching interval the instantaneous error voltage is lower now that is what results in a better quality waveform here.

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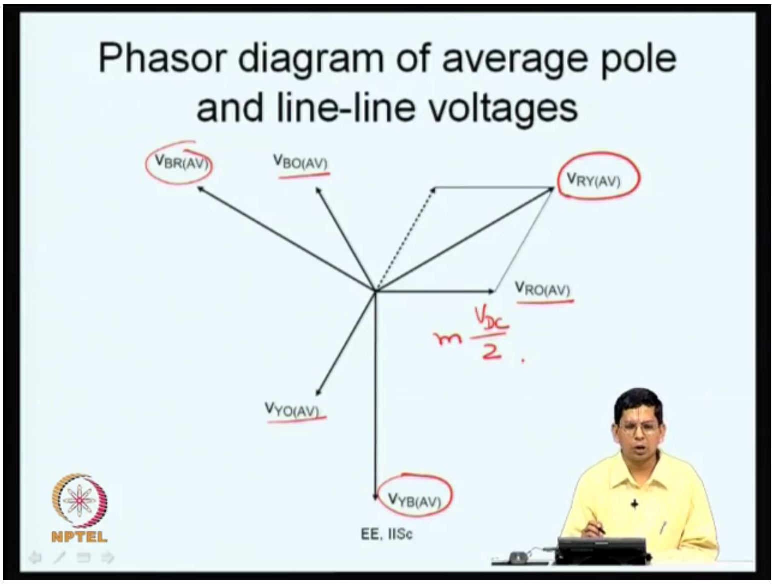

So, if you have the 3 average line to line voltages you know whether you talk of 2 level inverter or a 3 level inverter you have VRO average and we VO average and VBO average which are sinusoidal now and VRO average minus VBO average gives you VRY average and VYO average minus VBO average gives you VYB average. Similarly VBO average minus VRO average gives you VBR average. So, these are the 3 line to line voltages that you apply.

So, you get you know sinusoidal voltages ignoring the harmonics of course, you get sinusoidal voltages that are applied here now you are able to control both the frequency and the amplitude of this as I mentioned this this can have an amplitude of VDC by 2, let us call it m VDC by 2 where m is what is called usually called as a modulation index or depth of modulation and m can vary between 0 and 1. So, you can have you know something as low as 0 or some minimum value right up to VDC by 2 you can control that.

So, it is possible for you to control the amplitude of the voltage, it is also possible for you to control the frequency of the applied rotation.

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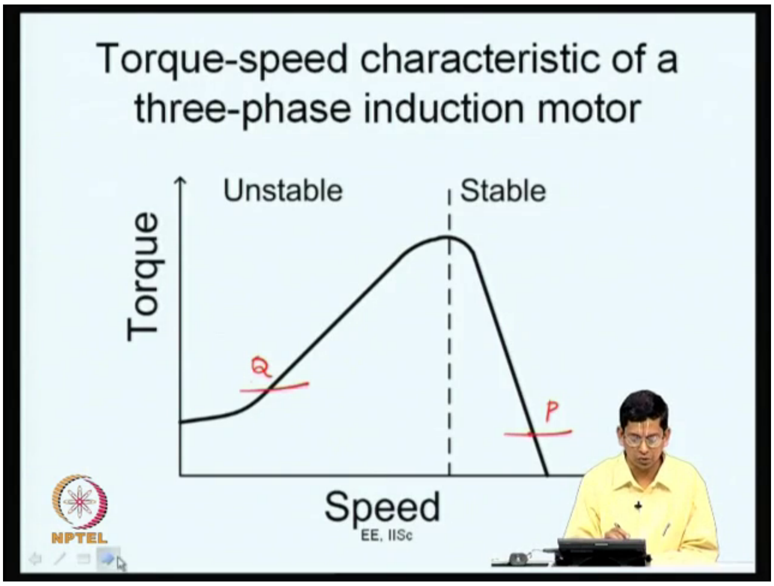

Therefore what you can do is you can do some exercise certain amount of control on the operation of an induction motor. Now let us look at the torque speed characteristic of an induction motor quickly as we saw the other class this is an unstable operating point and this this region is the stable operating point very simple, you can consider 2 operating points here and perturb these points you will find this point P, if there is a small perturbation the operating point will return there, if you perturb it at the point Q, if there is a small disturbance, it will not return to that point.

Therefore, you call this stable operating point unstable operating point the set of all stable operating points give you the so called stable operating region and the set of all unstable points give you the unstable operating region which is something that from your very first course on an induction motors now.

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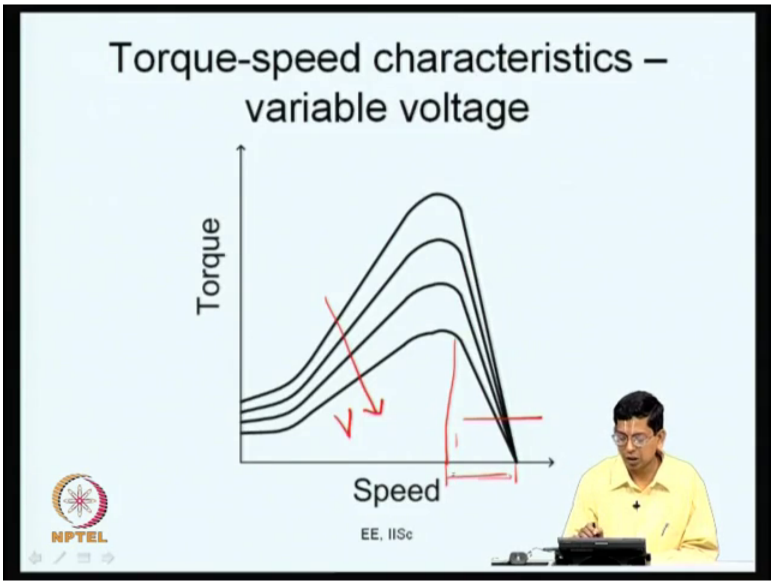

See if with a voltage source inverter you are capable of varying the amplitude and you know applying a variable amplitude on your motor. So, as V decreases your torque speed characteristic reduces changes like this for a higher V the torque peak torque is high for a lower V the peak torque is low. So, the characteristics roughly look like this now.

So, there are certain amount of speed control that can be exercised as we saw in the previous class if you have a load torque, I mean if the torque speed characteristic of a load is a flat line like this the point at which it intersects no changes with your applied voltage with change in applied voltage the torque speed characteristic of the motor changes. And therefore, the point at which in it intersects with the load torque changes and you can exercise speed control of the motor, but over as only a small range its only over a small range of speed, there is all that you can exit control over now.

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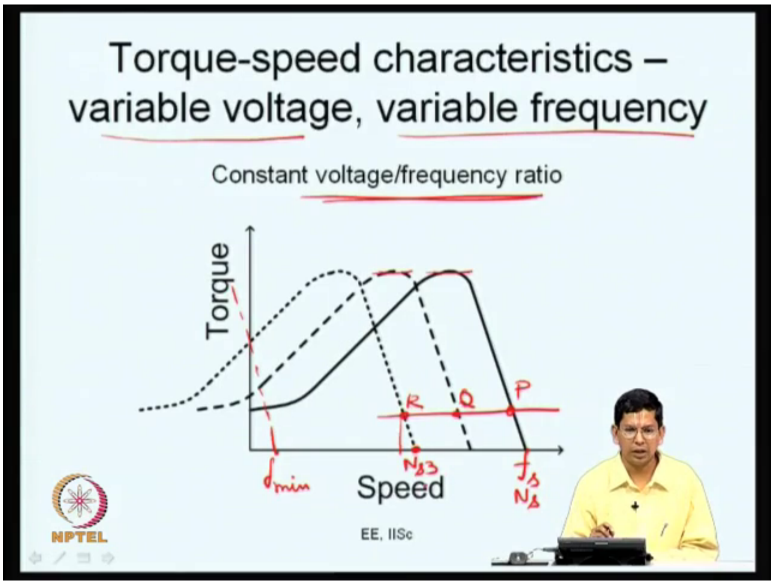

If you want to do better than that if you want to exercise control over a large range of speed what you can do is you can vary the voltage and also vary the frequency what is the effect of varying the frequency, once you vary the supply frequency the stator frequency voltage frequency. Then you know the stator voltage frequency is what decides the revolving magnetic field the frequency at which the magnetic field revolves you are going to apply a faster one and you are going to apply a slower one. So, if it is at 50 hertz, it is going to revolve at certain frequency the magnetic field, if you reduce it to 25 hertz the rotating magnetic field is now going to rotate at half the original frequency.

So, you use that to control that. So, this is your synchronous frequency the synchronous frequency is varied or this is actually the synchronous speed Ns an Ns and fs are directly proportional to one another and they are related in terms of the number of poles that the machine has now for a given number of poles there is a fixed relationship between the two. So, if you want to vary the speed control one way you do that is you reduce the frequency of the revolving magnetic field that you know how do you do that you reduce the frequency of the applied voltage now.

If you reduce the frequency of the applied voltage, it is possible that the strength of the magnetic field comes lower. So, what you do is you maintain the voltage to frequency ratio constant if you maintain the voltage to frequency ratio constant then the peak torque is practically unaffected the peak torque, if you can see there is practically unaffected now this is fairly valid as long as you come to lower value of speeds now. So, or lower frequencies now at lower frequencies what you do is you boost up the voltage the voltage is kept a little higher than what is dictated by the rated will be of ratio. So, you can make up for the reduction in the; you know the magnetic field strength by doing that.

Well, ignoring that you know you have a; if you maintain a constant voltage to frequency ratio it is possible. Now let us say if we have a load characteristic as indicated by the red line here you may operate it if your voltage and frequency are such that you are following this solid line; the characteristic with solid line you are operating at P.

Then let us say the voltages in the frequency are changed and the characteristic of the motors are shown by the dashed line. So, now, the operating point will shift to q then if it is further reduced if the frequency is further reducing the voltage is reduced correspondingly it may shift to this point R. So, you see that you can operate over an entire range; you can operate it over an entire range. So, that is what we saw and you know you can at starting what we will do is we will typically apply a very very low frequency very low frequency such that the starting torque itself is fairly high. And then you go about once you apply the small amount of frequency let me call this as f minimum. And then you gradually increase this f minimum all the way to what you need to apply this is what is called a slow start in constant V by f induction modern drives.

of course, you are other things are there, there as this is an open loop drive, you can have several closed loop drives in with constant V by f also you can have slip regulation what is called a slip regulation you can compensate for that see for example, in this case this is your synchronous speed let me call this as Ns 3, whereas the actual speed is here now there is a difference between that.

So, your frequency that you applied to the machine is kind of proportional to Ns 3, but should also have a small variation you know that that they should be slip should be added to that now. So, if this is the rotor speed that you want if this is the rotor speed that you want here now to that you will have to add the component that corresponds to slip to get whatever is your Ns 3 now. So, there is something called slip regulation that is what I am trying to say is let us say the machine is being run at you know, it is a 400 volt 1500 rpm machine.

If it is depending on the load it may run you know if it is no load; it is going to run close to 1500 rpm that does not happen in a practical machine. There is always certain amount of load on that as you go on loading the machine speed drops that is what is indicated by this curve you go on slightly increasing the load the machine speed goes on dropping and that is what you call as a slip now.

Let us say you want to operate the machine at 750 hertz now. So, at 750 hertz; what you do is you can say that you have to reduce your frequency to half if you reduce the frequency to half it will be operating at a synchronous speed of 750 rpm, but the actual speed will be little lower than 750 rpm may be 720 or 730 or 740 or something in between depending on what the exact load is

So, there is something called slip compensation that you can do which will make sure that the machine can really run at 750 rpm. So, the machine will be running at a synchronous speed you know the synchronous speed of the machine will be equal to the actual speed at which it should run plus the. So, called slip speed. So, that is called you know it is I mean V by f drive with slip regulation now and also you have several closed loop drive schemes which are as I mentioned in the previous class.

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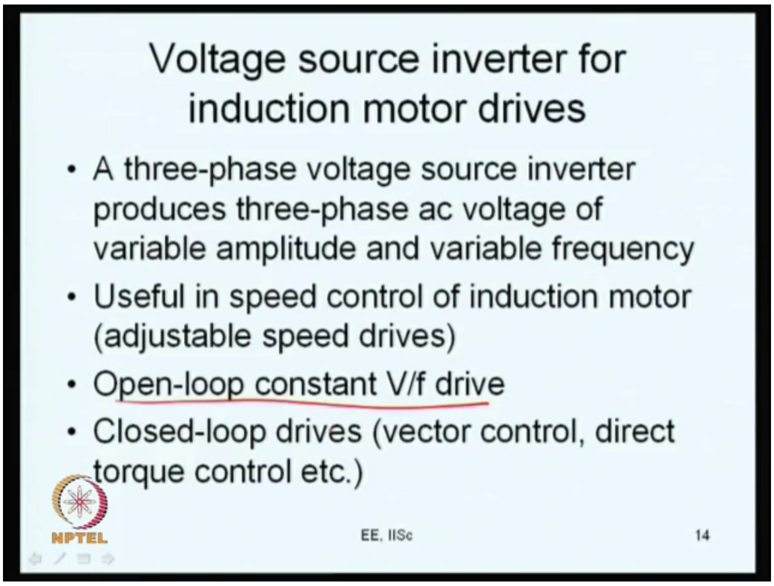

We will be dealt within our dealt with in some other NPTEL courses or exclusively on the subject of motor drives you know that is an involved subject.

So, for example, if you want how high dynamic performance you have you know drive schemes called vector control or field oriented control and direct torque control etcetera these require and understanding of how you model the machine for dynamic operation and how you go about controlling them. And in the different frames of reference etcetera. So, you can find you know you can develop good understanding by following courses which are in the area of motor drives in this case now.

So, what we are going to look at is we are now confining ourselves to open loop constant V by f drive here and closed loop is dealt with in other courses now we are able to vary both the a frequency in amplitude. And therefore, we use an adjustable speed drive and we call it open loop constant V by f drives. So, this is one application that we will be invoking in most of our most of this course.

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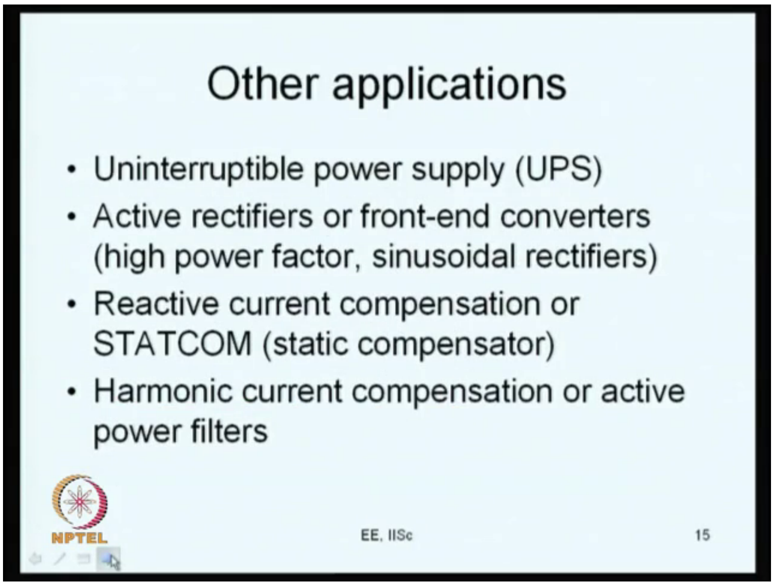

So, there are other applications as we mentioned one is an uninterruptible power supply what do you do this here you have a battery bank essentially when there is no power supply available in the mains the energy stored in the battery bank is what you used to supply the AC load now. So, you use an inverter. So, battery bank whatever you know you through an inverter you feed AC loads there is the output frequency is always 50 hertz or so.

So, you know you do not vary the frequency there. So, you only control that and again you know as I said the battery requires to be charged. So, whenever the mains voltage is available the battery gets charged and whenever the mains voltage is not up to the mark, I mean its quality is not up to the mark if the voltage is a little higher than what is expected or lower than what is expected. For example, once again you know it the load is not directly fed from the mains, but it is fed through the inverter you rectify and then you invert and you feed the load now.

So, that is what we saw what an uninterruptible power supply now, then the main application that we are focusing today is basically active rectifiers or front end converters now. So, here we are going to shortly see what are the issues with diode bridge rectifiers and why we need active rectifiers and how do you realize such active rectifiers now and once you are in a position to reply you know to realize an active rectifier as we will soon see it is possible for us to compensate for reactive current also. So, these are 2 issues we which will see shortly today and harmonic compensation little later.

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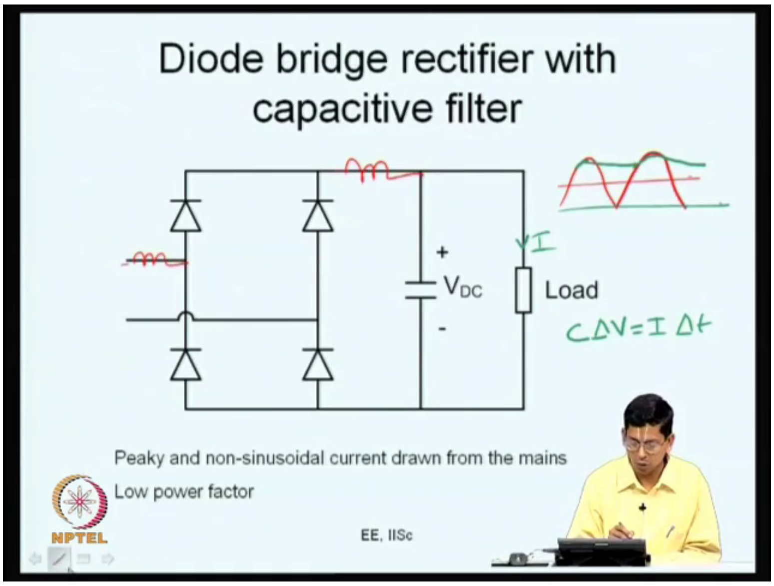

So, now let us say you want rectification the best known rectifier is a diode bridge rectifier and in mostly in power supply applications you will have a capacitance on this side why. Let us say if we have a diode bridge rectifier if you use a resistive load this would be the output voltage waveform will be what is called as a rectified sign now.

Now, you can see very well that this rectified sign has a lot of ripple, it has certain average voltage, but there is a lot of ripple this is the average that you might want there is a lot of ripple on top of it now. So, what you need is such a high amount of ripple is unacceptable. So, the minimum filtering that you do is to put a capacitance here of course, there are additional filtering that you can do in terms of having let us say an inductance here or an inductance here, but as I said the minimum filtering that you do is a capacitance here now.

So, what happens because you have a capacitance here let us say, then you have a capacitance like this the capacitance gets charged over a short interval of time and you discharges like this it charges up and it discharges like this the voltage waveform becomes something unlike as I have indicated in green ink now. So, you can see that the ripple in the output voltage is now much reduced which is what you want it is basically a power supply ideally it should have a flat voltage without any ripple which is not possible. So, you reduce the ripple to what to an acceptable level that is what you do and you put a begin of capacitance effectively to realize this now.

In fact, the capacitance sizing can really be done by this you will have to look at the load current and the time between 2 charging intervals for this load current and the product of the 2 gives you the extent of discharging of the capacitor. So, if you have an acceptable ripple delta V then you can say that now that gives you basically the capacitance that you want now like basically what I am trying to say is c times delta V is some I into delta T now delta T is the interval between 2 successive charging intervals of the capacitor now

During that time in if the capacitor is getting discharged by the load current I that it needs to flow now and let us say this delta V is what is the acceptable ripple voltage now. So, you need a big enough capacitance that has to keep the voltage small enough. So, that is what we are trying to look at now this is how you basically choose a capacitance as you all would know very well.

Now, let me go back to this problem of putting this here. Now the problem we are looking at this what is wrong with this converter if at all there is anything wrong with this converter what is wrong here that is what we are looking at now right. So, what could be wrong.

Let me say what is the nature of current here let me also take away this let me also take away this inductor let me say that you have only the capacitor filtering now; now I want to look at this current I which is being drawn here .

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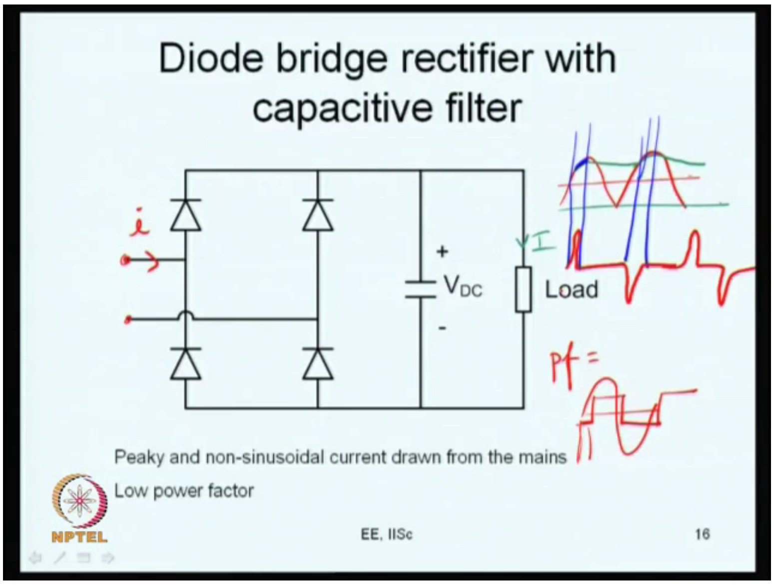

This current I which is being drawn here is this continuous no why you can very easily see that only during that time that this is being charged that is let us say only during this interval of time when it is being charged there is a current flow during the remaining interval of time there is practically no current flow here only during this instance there is current is flowing through this the other times the diode is not conducting it is only the capacitance that is getting discharged through this load the capacitance kind of continues to supply the load and it is getting discharged now.

So, how does the current waveform look like the current waveform looks something like this something like this and in the other half cycle it will be something like this. So, the nature of the current waveform would be something like this why is this like this the diodes will be reversed by asked for most part of the time why, because the output capacitance voltage is greater than the input AC voltage for most part of the line cycle for most part of the line cycle you take the input voltage or its rectified form and you take the capacitance voltage the capacitance voltage is greater than that the capacitance voltage is given by the green ink here and the rectified input voltage is given by the red ink here.

You can see that the voltage that shown in the green ink that is the capacitance voltage e is greater than that for most part of the time and there is no connection and it gets charged only during a short interval of time when this green ink and the red ink are overlapping it is only during that time there is a conduction now and there is kind of current pulses are being drawn here now.

So, what is good and what is bad about this when current pulses are being drawn you can see that this is not sinusoidal current at all this is an nonlinear. It is an example of a non-linear load which we will discuss again in in slightly greater detail a little later. So, it is not a; we ideally we want every load to draw sinusoidal current it is being fed with a sinusoidal voltage ideally it should be drawing a sinusoidal current, but now it is a peaky current well we can partly rectify this problem by having some inductive filtering either on the DC side or on the AC side and different kind of ways of doing it and design of induction itself is a subject and you this is dealt with in certain other courses as well here.

So, we are not going to deal the design of inductors here we are simply looking at this capacitor case now. So, what you want is ideally you want a sinusoidal current which is not happening here that is one reason why we would like to look at an active rectifier rather than such a passive rectifier using diodes we want to use active devices and see whether you can come up with a rectifier which can draw sinusoidal current.

Now, how about the power factor the power factor is also poor this power factor is a product of what is called as the distortion factor and there is something called as you know the displacement factor. So, even you know if you have a continuous current here if it a; if you have a highly inductive load and such that the load can be replaced by a current source the input waveform will become a square waveform a square waveform. In some sense is better than peak current waveform in terms of the current shape it is probably a little closer tier there is something called. But, nevertheless you know what I am trying to say is the voltage waveform could be like this and the corresponding current waveform could be something like this it is possible that you can come up with this in a different scenario I am talking of a different scenario where you do not have a you know I am not talking of capacitance, but I am talking of a highly inductive load. So, that the current is maintained continuous and it is almost consumed in this case now.

So, here what do you have is if you look at this square wave current waveform the square wave waveform is distorted. So, that distortion is given by what is called as the discussion factor. And then there is certain phase displacement between the sinusoidal wave form and the square wave form and the cosine of that angle is what is called as the displacement factor here. So, what I am like to what like to point out is you consider this case of capacitive filtering you consider this capacitive filtering in capacitive filtering the distortion is very high. Therefore, you know the distortion factor if you look at it, it is very poor the discussion factor is essentially; what is the fundamental current the ratio of the fundamental current to excuse me.

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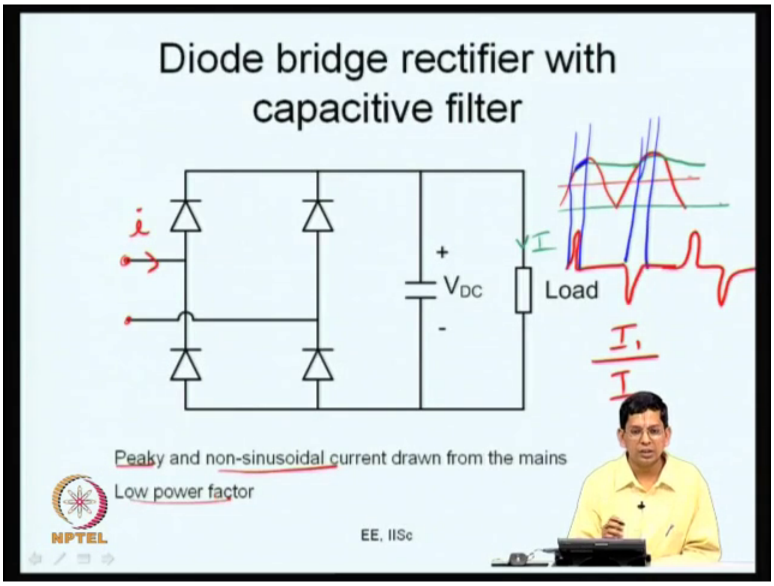

The ratio of fundamental current to the RMS current, this is very very low and the power factor is proportional to that hence it is at a very poor power factor.

Again ideally we expect loads to draw power at a fairly high power factor if not unity something close to unity poor power factor is usually discouraged by the utility because it results in very poor utilization of the transmission lines and the capacity of those you know the transmission and distribution system.

So, you know the customers are discouraged from drawing power at high I mean at low power factor and they are encouraged to draw power at high power factors through various you know penalties and agreements and many other issues like that. So, this is how you get that and you search. So, you see that you get peaky and non-sinusoidal current from the mains and the power factor is pretty low these are reasons why you do not want that now.

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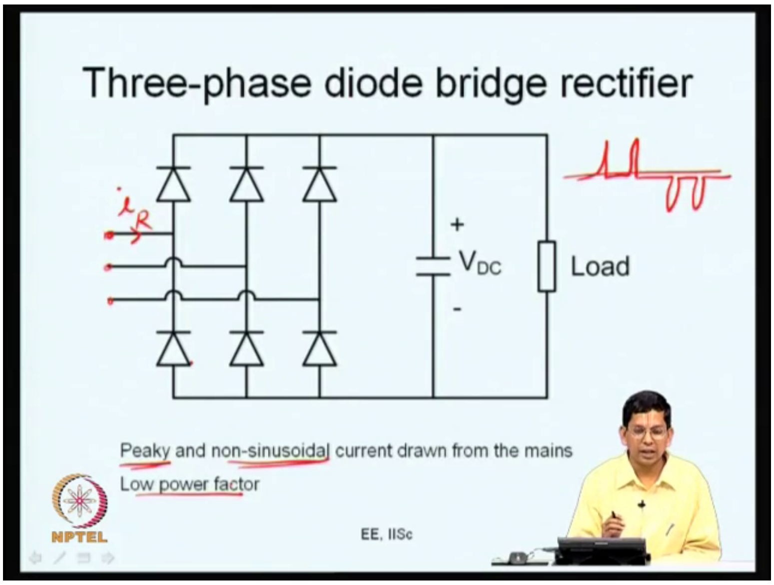

Let us say instead of a single phase you have a three-phase diode bridge rectifier; what is the difference. Now the story is still the same except that you are now feeding; it from three-phase mains now. So, if you look at this current this current will conduct there will be some current let me call this is iR; there will be current flowing through this whenever the R phase top diode or the bottom diode conducts one of the 2 diodes conducts now

So, this will happen whenever R phase is most positive and this diode will conduct whenever R phase is most negative. So, you will have this will happen you know again a couple of times R phase and Y phase can conduct and again R phase and B phase can conduct

So, in the earlier case we found that there was conduction only when the mains voltage was very close to its peak now what you have is in the single phase case there is only one line to line voltage here you have 3 line to line voltages. So, whenever a particular line to line voltage is close to its peak either positive peak or negative peak there will be conduction.

So, let us say VRY is close to its positive peak or VRY is close to its negative peak you will find some conduction here that is R phase current. Similarly, VBR is close to its positive peak or VBR is close to its negative peak you will again find conduction here now.

So, what you will see is you will basically see 2 pulses like this in a half cycle and another 2 pulses like this in a half cycle this would be your nature of your current waveform that you will find here now. So, its once again distorted it is once again peaky it is distorted and it is not comparable to sinusoidal now and this has a very very poor power factor. So, these are again reasons which we do not want and we want to do something better than that that is why we are looking at can we see an active PWM rectifier.

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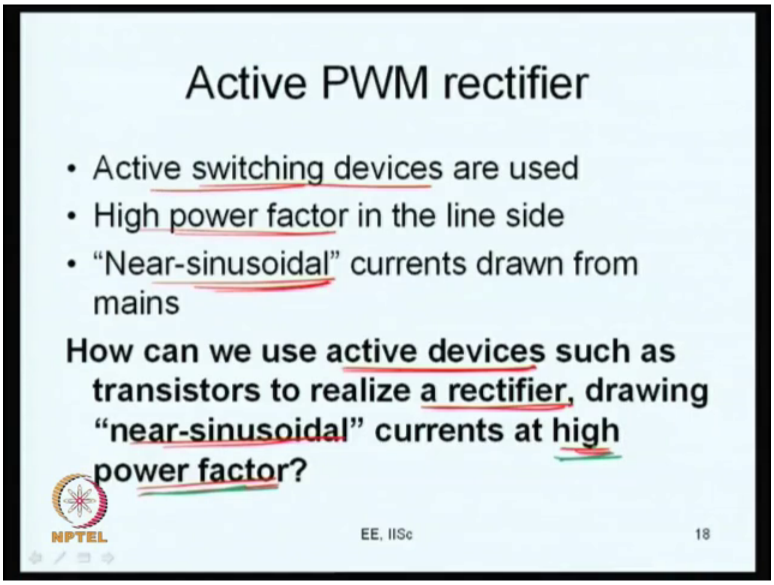

So, what do you do an active PWM rectifier uses active switching devices such as transistors now.

then it draws power from the grid from the mains at a high power factor not a very low power factor at high power factor and the current drawn the wave shape of the current drawn is almost sinusoidal is very close to sinusoid. So, you want these are the attributes high power factor and sinusoidal currents are the main attributes now. So, the question is how can we use active devices such as transistors to realize a rectifier which draws near sinusoidal currents at high power factor this is the question now.

So, what will be first we will focus on this in the next few minutes. So, the first 2 focus will be on high power factor how do you first ensure high power factor here that is what we are going to look at now, right.

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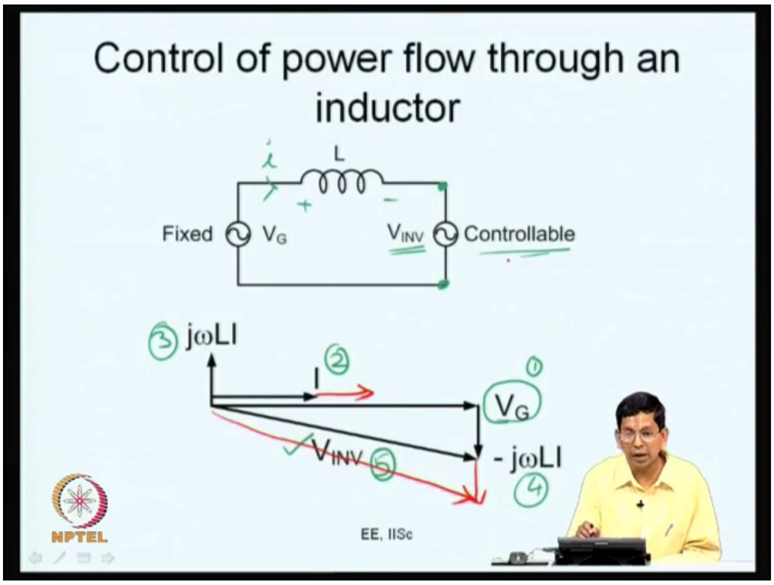

Let us say you want to control and have an inductor, let us say we have an inductor like this. So, the inductor was supplied to the mains voltage it is a good idea to connect an inductance in series of the mains voltage, because you have certain current being drawn from the mains you want this current to be smooth. And inductor has this property of smoothening the current inductor does not let the instantaneous current change at some faster rate capacitance has this property of smoothening the voltage inductor has the property of smoothening the current.

So, if you want to draw fairly smooth currents from the mains one idea is you use an inductor even and diode bridge rectifiers many a times you may have some inductive filters on the AC side as well, let us say you have an inductor. Now on the other side of the inductor let us say you apply some voltage which is controllable. Now the power flow actually depends on what you have applied here it is given by this phasor diagram this is very similar to your power flow through a transmission line that you would have studied in your power systems course.

So, there is something called sending end power there is something there is something called sending end there is something called receiving end this is sending end voltage and receiving end voltage now the power flow through the transmission line which is modeled as an inductor depends on sending end voltage and the receiving end voltage . So, now, for us here the sending end voltage we can say is VG which is a grid voltage which is a fixed value and the receiving end voltage which we call as V inverter that is the inverters terminal voltage and that is controllable.

Now, what I am going to do is I have this VG which is fixed I have this VG we just fix it in this term now next what I want to do is I want to draw this is my first next what I want to do is I want to draw certain current I at unity power factor you can see that I am drawing this current at unity power factor if I were to draw this current at unity power factor then there is certain drop across this inductor and this is a reactive drop we are talking of any AC situation now.

So, the is this reactive drop of the inductor this year now this is going to be small, because this inductor is typically going to be small I mean the size of the inductor is usually in terms of per units basically in mean per unit term. And basically what we mean is we look at how much of voltage what percentage of the voltage is dropped by the inductor the what percentage of the mains voltage is dropped by the inductor it could be typically a 10 percent or 10 percent or so; so this j omega L I could be something like 10 percent or 10 percent or so.

What we do now is you subtract this j omega L I from VG to get your invertor voltage. So, this is your third; now what you do is you subtract that this is your fourth phasor in the diagram. Finally, you get your V inverter. So, if you apply this V inverter I shown here on this side you will be able to control the power flow to the inductor you will be able to draw a current I equal to of this decide amplitude and decide phase incidentally which is you know at unity power factor which is the same phase as the grid voltage here you are able to do that that is the philosophy now.

We can if you can control this voltage here appropriately apply this voltage V in I mean V inverter you can draw this amount of current now you may have a small question now somebody may ask; let us say I want to draw a unity power factor current, but which is slightly higher in amplitude like this. So, what do I do nothing what happens is this minus j omega L I increases now. So, what you do is the V inverter changes like this. If you apply another V inverter as shown here the amplitude can easily be controlled we have firstly worried about the control of the amplitude if the phase of the current can also be controlled as you will see a little later now.

So, now the first question is well if I can control this V inverter I can control the power flow through that I can control the amplitude and power factor I can draw current of decide amplitude at unity power factor, but how do I get this apply this voltage V inverter is the question I mean the answer is obvious.

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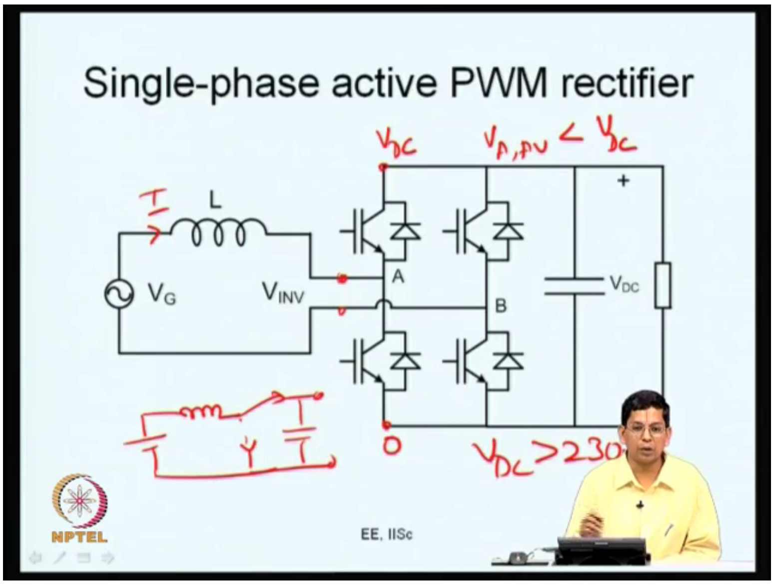

So, you use a voltage source inverter if you have voltage source inverter which has a particular value of V DC which is now steady let us presume that you have an inverter was DC bus voltage is charged now.

So, by switching this inverter appropriately you can produce this voltage V inverter we are looking at only the fundamental component here the sinusoidal component, you can apply certain V in write here now. So, by doing this you are realizing this or rather this is realized by using a voltage source convertor like this. So, use this voltage source convertor to apply the desired V inverter. So, that you get your I of required amplitude and in phase with the current now.

So, this presumes that this capacitance is charged and the voltage is maintained at VDC so; obviously, such a converter requires closed loop operation and the inner loop will be the current loop current control loop on the outer loop will be the voltage control loop once again the control of such converters will be dealt with in great detail in other NPTEL courses on power electronics in the subject of electronics. Here we will just look at the basic operational philosophy and we look at how to design pulsewidth modulation methods for such kind of operation. So, we will focus primarily on the steady state operation of this converter now.

So, this converter is a derivative from the boost converter if you can make all right you can I think you can very easily understand this point because you boost converter what we had was something like this you had voltage source and the series inductance and you had a single pole double throw switch, you had a single pole double throw switch; this is what you had and you had capacitance here you can see the similarity the voltage source except it is not a DC. Now it is an AC source I mean it is a variable source now you once again have an inductance. Now you again have a single pole double throw switch here it at a is the pole and there are 2 throws and you have plus VDC here the same observations can be made about the other one also right.

So, it is a boost converter. So, in a boost converter what happens now this is your pole voltage and let us say and these are your thrown voltages now let us take this negative bus as the DC as the reference now. So, the throw voltage here is 0 on the throw voltage here is VDC. So, your pole voltage at VA right the average value of VA should be somewhere between 0 and VDC because you know the pole is connected to VDC for some time and 0 for the remaining. So, its average value somewhere between VDC and 0 and its value that is the average voltage at a cannot exceed VDC that is what I am trying to say now. So, this VA average certainly has to be less than VDC or VDC is greater than VA average now what is this VA average now it is something very closely related to the mains voltage with only way inductive drop added to that.

So, the moral of the story is the DC bus voltage here has to be greater than the peak value of the mains voltage, if you are talking about 230 volts RMS main. So, 230 in multiplied by root 2 is its peak value and the DC bus voltage has to be greater than VDC has to be greater than 230 into root 2 that this is the lower limit. And this is what you have to ensure now.

So, this is what something that you need to do is it is a boost converter what you want to emphasize this is a boost converter you can call it as a single phase the AC to DC boost converter with power factor correction.

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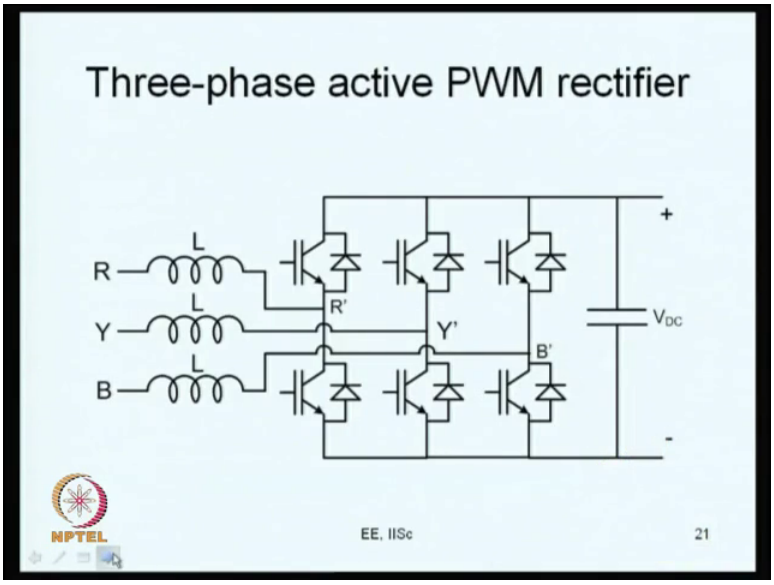

The same thing can also be done in the three-phase case. So, you have a three-phase converter and you have 3 inductors like this and here you can do that now you can connect the lower on the DC side, if we want rectification. In fact, if you are looking for what is called as distributed generation the on the DC side you can really have a DC source such as photovoltaics or you can have a converter which you rectifies the power available in some other source alternate source so and that power can be pumped into the mains through using this converter right.

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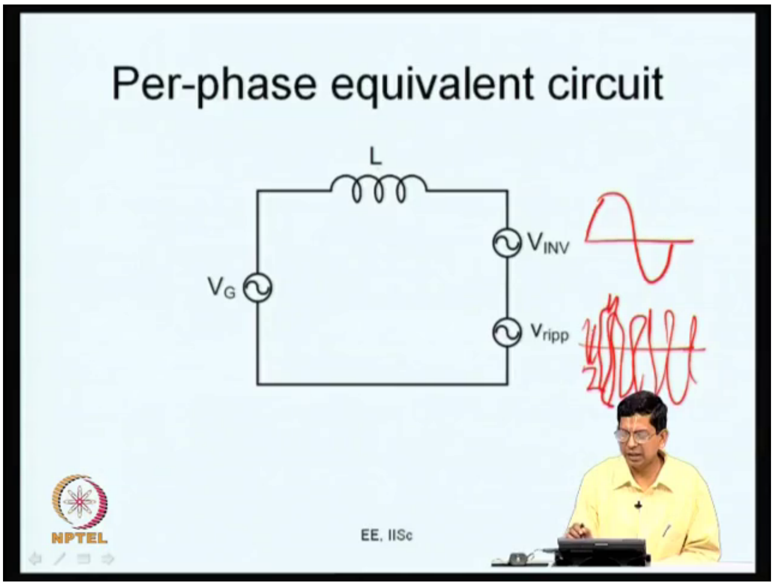

So, it can be either single phase or three-phase if you even if you look at three-phase the per phase is equivalent circuit is something like this what you do is you have the grid voltage this is the per phase grid voltage and this is the per phase inductance now and if you look at the per phase voltage of the inverter it can be decided into 2 one is the sinusoidal component there is a sinusoidal component.

Now the other one is a ripple component we have we have kind of a ripple on this you know you will have you have ripple voltage on this I am not drawing it very very neatly. But, you have some voltage like this is what you have it, basically there stepped waveforms. So, please ignore what I am trying to you know the inaccuracies in the waveforms. So, it is a non-sinusoidal waveform and this is the sinusoidal part. So, the actual waveform minus the sinusoidal part is your ripple voltage, I can split it up into V inverter plus ripple voltage.

So, that is my this is the fundamental part and this is the ripple part; now this is my equivalent circuit. Now I can use this equivalent circuit first to study the fundamental component. Now just I want to see how much fundamental current flows. So, the fundamental equivalent circuit is like this.

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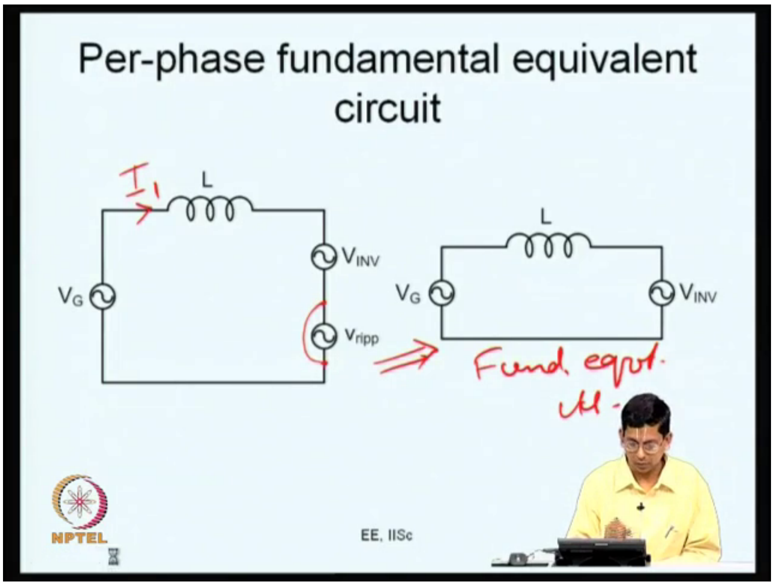

If you want to consider the fundamental equivalent circuit I mean, I want to calculate the fundamental current; the fundamental current I one is not affected by the ripple voltage. So, this is effectively a short here. So, you will be go to this fundamental equivalent circuit this is your fundamental equivalent circuit this is what we have been using all through the phasor diagrams which we explained something back or all really based on this fundamental equivalent circuit.

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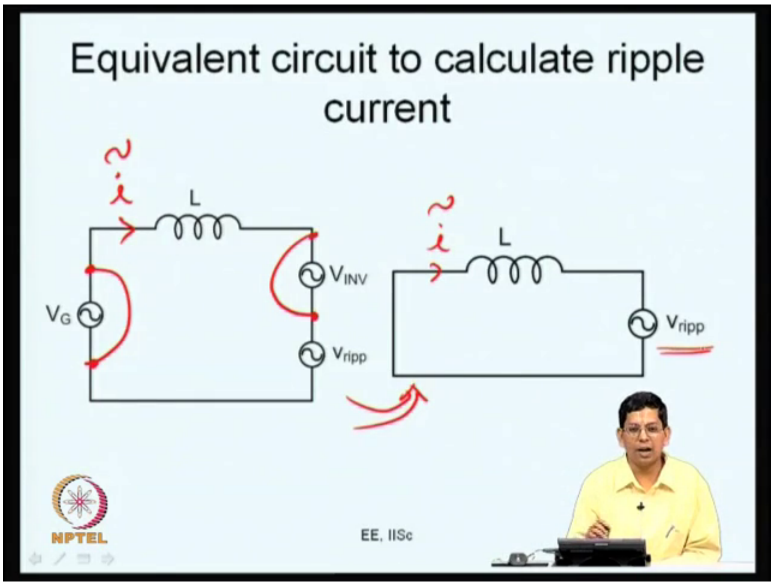

So, if you are looking to calculate the ripple current I am not looking at the fundamental, but I am looking at calculating the ripple current now. So, what do you do the ripple current comprises of all the harmonic currents it is the sum of all the harmonic currents. So, it does not have a fundamental frequency component at all. Therefore, this fundamental voltage is not going to affect the fundamental component of the inverter voltage is not going to affect it act as a shot.

Similarly, the mains voltage is also sinusoidal. So, it does not affect now. So, if you shot these 2 the result you get this here. So, this is; what is your equivalent circuit to calculate ripple. So, if you consider the fundamental component you need to use this equivalent circuit where you have the mains voltage and we have the line inductance and the mains voltage on the other side is you know the power flow is checked are controlled by the applied voltage the fundamental component of the inverter voltage. And if you look at the ripple there is no triple in the mains voltage I mean we are assuming the mains to be sinusoidal the mains itself can have some sinusoidal component, but we are ignoring it now we are assuming it to be sinusoidal or at least its sinusoidal component in the non-sinusoidal component the main. So, it is very low.

So, in that case VG is sinusoidal it does not affect the; you know amplitudes of any of the harmonics. So, it does not affect the ripple current again the inverter voltage has a fundamental component the ripple component the fundamental component does not influence the ripple current flow. So, to study the ripple current we can have this as the equivalent circuit now.

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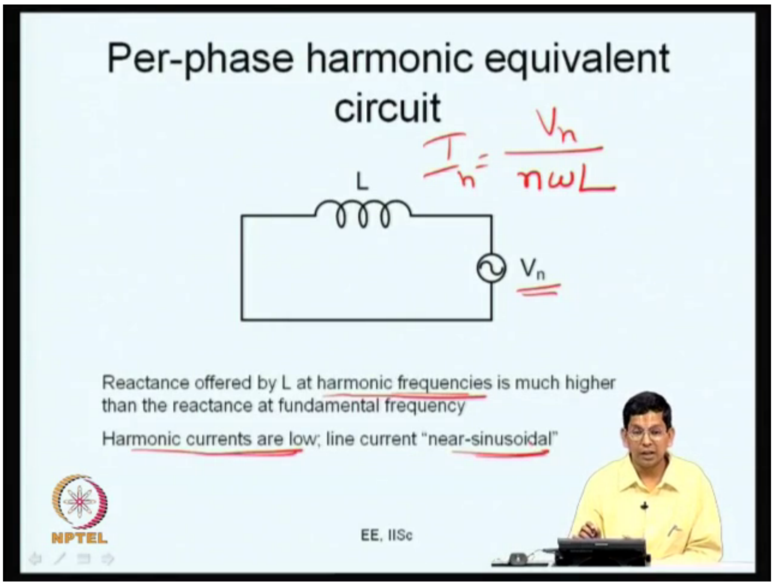

So, this ripple is basically the sum of all harmonic currents, let us say a specific harmonic let us say Vn is the nth harmonic voltage by nth harmonic we mean the harmonic frequency is n times the fundamental frequency, it has the same inductance l, but the reactance offered by this is n times omega L where omega is the fundamental frequency, if you are talking of the fundamental component the fundamental component sees reactance of simply omega L, but the harmonic voltage sees a reactance of n times omega L the reactance offered by L at harmonic frequencies therefore, is much higher than the reactance seen by the fundamental component. So, n could be very high. So, L I mean fundamental frequency can be 50 hertz, but the harmonic frequency can be 1050 hertz, let us say or 950 hertz. So, you are n is 1050 by 50 it is something like 21. So, your; the reactance the harmonic reactance is no 21 times the fundamental.

So, what happens you may have considerable harmonic voltages in the terminal voltage, but the higher harmonic voltage is particularly, but the harmonic voltages are all at higher frequencies the harmonic voltages are all at higher frequencies because of this the reactance seen by them is much higher. And therefore, the corresponding harmonic current is very low what would be the harmonic current it is I can say it is n times omega L and Vn upon n times omega L this is the if Vn is the RMS value of the harmonic voltage of a specific nth harmonic voltage is corresponding nth harmonic current is here you can see that as n is high I n is going to be very low.

Therefore this has a very good effect of filtering the harmonic voltages get filtered and the harmonic currents will be quite low and the line current will be near sinusoidal that is all we achieve our objectives. So, earlier we just saw in this case, we just saw how to control the power factor how to achieve a high power factor this is the principle and this is how you really do it in the single phase case this is how you do it in a three-phase case. And then when you analyze the per phase equivalent circuit and break it up into the fundamental equivalent circuit and the harmonic equivalent circuit it becomes clear that the harmonic currents are going to be much less significant than the fundamental current and therefore, you draw near sinusoidal currents here now.

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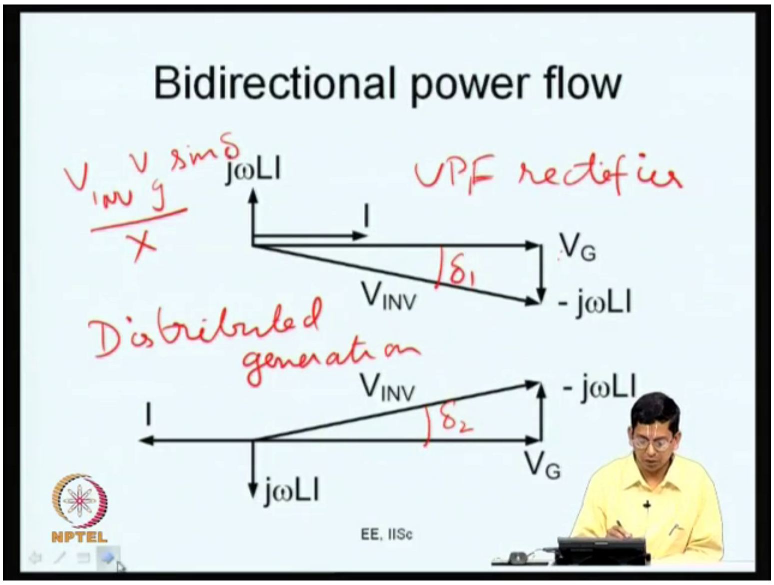

So, now what I am going to say is you are you also have bidirectional power flow; here you can also have bidirectional power, it is not necessary that the current is drawn at unity power factor this is what we saw let us say power is available on the DC side and needs to be pumped back into the mains now which is what you will have. Let us say you have a photovoltaics cell well some DC voltage is available and that has to be pumped back into the mains.

So, what do you do is you now try to how control your current such that the current is at an angle of 180 degrees with respect to the grid voltage right. So, its j omega L is here you subtracted here your inverter voltage is now on this side. So, this is a case of a unity power factor rectifier; what you are doing is you are converting AC to DC and power flows from the AC side to the DC side and the power is being drawn at unity power factor. So, you can call this as a unity power factor rectifier. And this is typically the case in a distributed generation like you can have photovoltaics or you can have several other alternate sources which may directly give you some DC voltage or which can be rectified into a DC voltage this DC voltage can once again be inverted and the power available can be pumped in to the mains through a voltage source converter; now like the one that we just discussed.

So, we can do this simply by controlling this power factor now. So, here the observation is what is different between these 2 phasor diagrams the VG is same the amplitude of I is also the same roughly and what I am indicating here it is at a phase difference is 0 and here the phase difference is 180 degree because of that what happens the reactance drop the direction changes.

So, now here you have this V inverter here you have this if you look at the first case VG that is the grid voltage is leading we inverted by certain angle delta if you look at the next case here, we inverter is leading let me call this delta 1 let me call this is delta 2 there will be equal if you consider the same reactance same grid voltage and current etcetera anyway.

So, you find that grid voltage is leading inverter voltage; so the powers actually flowing from the grid to the inverter voltage now and if you are looking at the next case power swaying from the inverter to the grid voltage. Now the inverter voltage is leading the grid voltage. So, just to recall what you would have studied in you know power flow through transmission lines the sending end voltage and the receiving end voltage the power flow through the transmission line which is modeled as an inductance is proportional to the amplitude of the sending end voltage it is also proportional to the amplitude of the receiving end voltage. And it is inversely proportional to the reactance of the transmission line and it is proportional to the sin of the angle between these 2.

So, the power flow is basically V inverter multiplied by V grid multiplied by sin delta divided by x; so the sin delta. So, that the delta is positive or negative determines the direction of powerful if delta is positive sin delta is positive and power flow is in a particular direction in this case it is from the grid to the mains if delta is negative then what you have is it is in the opposite direction. Now we let us say here delta is always measured as VG as the reference. So, you know the power flow is now in the opposite direction.

So, the relative phase off this VG and AV inverter decides you know how power whether power is drawn from the mains or you know is pumped into the mains now. So, this is what you do at high power factor rectifiers and this is what you try doing in case of distributed generation.

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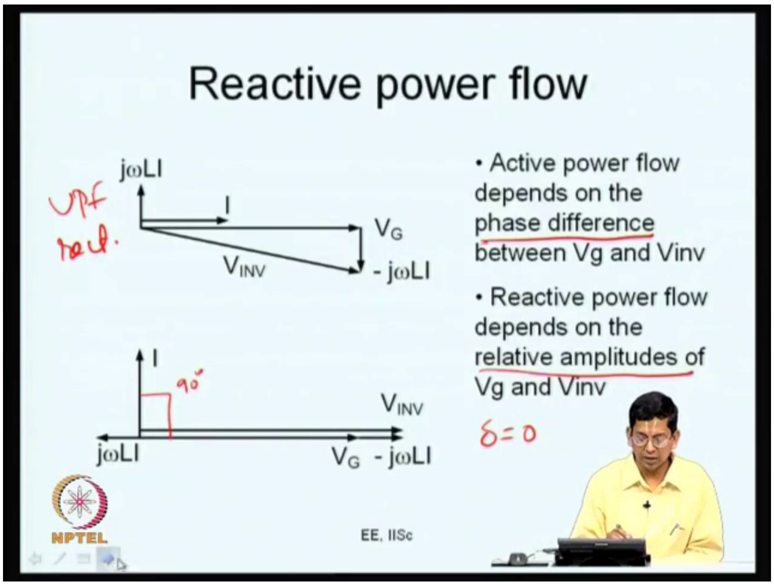

Now, let us say how do you control reactive power flow the you know here we found that the current can be either at unity power factor or at 180 degree phase difference it can get any arbitrary phase angle and one thing that is of interest for us is to see how you can do it at you know at 90 degree leading. So, the current is 90 degree leading in the first case this is what we saw in the case of a UPF rectifier UPF rectifier now you want to pump reactive current into the mains now.

So, what you do is you want your current to be leading the grid voltage by 90 degrees. So, the corresponding j omega L is indicated here and minus j omega L is indicated here and you have your V inverter and VG of the same phase, but V inverter is greater than V g. So, what you find here is there is no phase difference that is delta is 0 that is the active power flow is 0 here.

So, how about the reactive power flow the reactive power actually flows from you know the end where the amplitude is higher to the end where the amplitude is lower. So, if there is a power flow from V inverter to VG that fine. So, you are able to pump reactive power flow now. So, the active power flow depends on the phase difference between VG and V inverter the reactive power flow depends on the relative amplitudes of VG and V inverter now.

So, you can also actually know this is a case of supplying an active power if you want you can also draw a reactive power from the mains, but that is not what you normally want to do you want to supply reactive power to the mains. So, that you know the overall power factor of a particular facility or something is improved by such an equipment and this is what we call as the reactive current compensation now.

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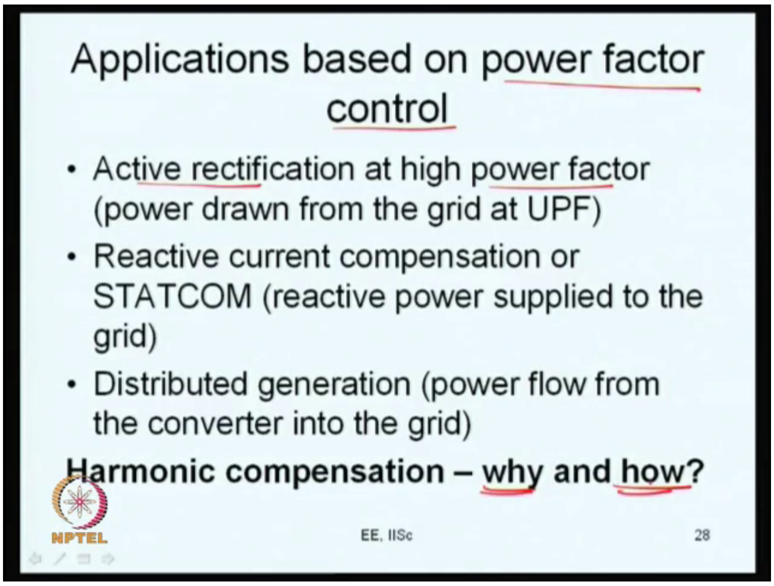

So, from whatever we saw now it is possible for you to you know control the power factor at which current is being drawn now that power factor can be unity that can be are very close to unity the phase difference can be very minimal between the current drawn and the grid voltage. So, this is what happens in active rectification at high power factor you draw power from the grid at unity power factor at very close to unity power factor.

Sometimes you pump reactive current into that or you pump reactive power into the grid you maintain that the current to be leading the grid voltage by 90 degrees now. So, this is what you do here now and in the case of distributed generation is yet another application where you want the power to flow from the DC side to the AC side or to the grid.

So, the grid voltage and the grid current will have a phase difference roughly equal to 180 degrees. So, that power flows in that particular direction now. So, you can see that all these are possible by controlling the power factor that is what we are essentially trying to do. So, the active rectifier is very closely related to reactive current compensation and distributed generation in terms of the control philosophy.

The next issue is about harmonic compensation we have to see why we need harmonic composition and how we will can achieve harmonic current compensation now.

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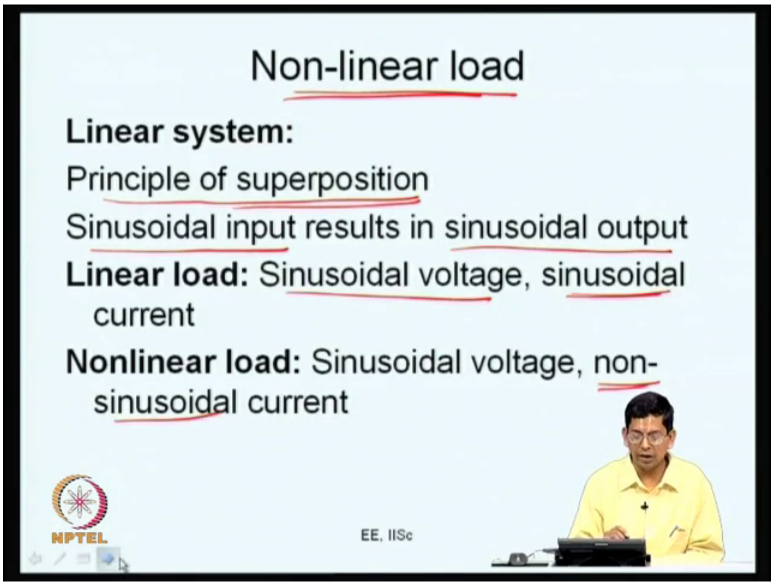

So, the idea about this harmonic compensation is why it is necessary is because we are non-linear loads now.

So, here we need to find out why or what is a non-linear load or rather we will start with what do you mean by linear system as we know a linear system is one that obeys this principle of superposition you have an input u 1 it will produce an input Y 1 if you have an input u 2 it will produce an output Y 2 if you add u 1 plus u 2 will result in an output Y 1 plus Y 2 if u is scaled Y will be scaled correspondingly. And that is what you call as superposition now. So, it obeys the principle of superposition this is when you talk about it in the time domain you talk of time varying signals as the input and output now.

You can also look at it in the sinusoidal you know or the frequency domain. So, if the system is linear if you apply a sinusoidal input the sinusoidal input should result in a sinusoidal output of the same frequency the output wave shape should also be sinusoidal if it is non sinusoidal it means it is not one frequency, it is several other frequencies. So, a non-sinusoidal periodic waveform has several frequency components going by series now.

So, the output should also be sinusoidal and of the same frequency only the amplitude and the phase will change. So, such a system can be characterized by its gain and phase at any given frequency. So, that is a linear system should for sinusoidal input it should have sinusoidal output and going by that what do you mean by linear load for a sinusoidal voltage which you normally have it must draw sinusoidal current. Then, it is linear if it draws non sinusoidal current then the load is non-linear and an example of a non-linear load is what we started our discussion with; namely a diode bridge there is draws currents which are peaky as we just saw this is not sinusoidal.

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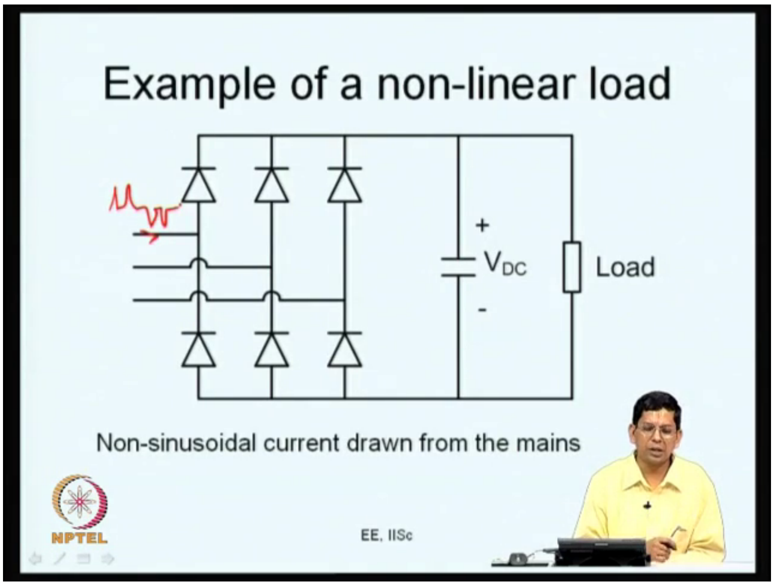

So, this is an example of a non-linear load all the computers that we have are typically non-linear loads because they have internally power supplies where some kind of a rectification like this is done and those power supplies very rarely draw a sinusoidal current they almost drawn non sinusoidal current. So, most computers typically are non non-linear loads and you have a facility with lot of computers connected you will see that the mains voltage itself is distorted see.

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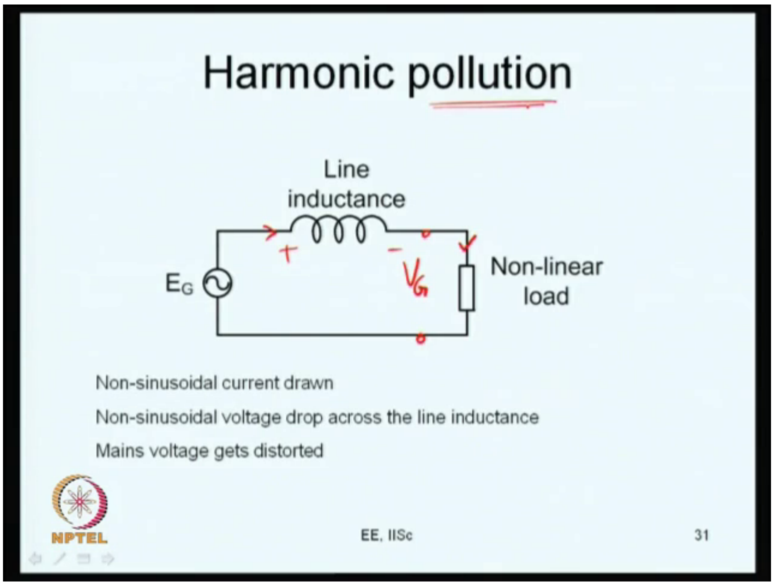

The problem here is what is called as harmonic pollution which we will discuss again in our next class now.

Because of the non-sinusoidal current drawn by the non-linear load the non-sinusoidal current also flows through the line inductance this is the model this is your grid voltage now the grid can be modeled as a series voltage source and an inductance now. So, the non-sinusoidal current drawn by the non-linear load results in a non-sinusoidal voltage drop across the inductor, and therefore the mains voltage is non sinusoidal. This is what is called as harmonic pollution during non-linear Luhan's.

We will discuss in detail in the next lecture. And we will also decide discuss about how to compensate for this which is called harmonic or a current compensation. So, thank you very much for your patience and your interest hope you found this useful and hope you will find the other future lectures also useful.

Thank you very much.