Pulsewidth Modulation for Power Electronic Converters
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Lecture - 06
Applications of voltage source converter - I

So, welcome back to this lecture series on Pulsewidth Modulation for Power Electronic Converters now. So, we have been looking at various power electronic converters here.

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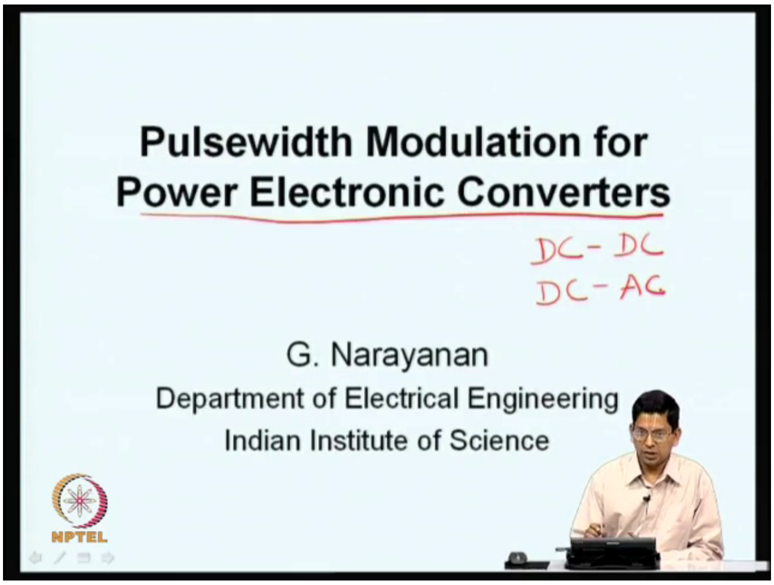

So, we started off with we started looking at various power electronic converters, we started off with DC to DC converters and from then we moved on to DC to AC converters. In DC to AC converters we looked at basically both the voltage source and the current source converters and in the voltage source we looked at both the 2-level inverter and as well as the so called multi level inverter now.

So, today, what we will be doing is, we are actually supposed to be looking at the applications of voltage source converters. It is basically a kind of an overview of various applications, so, you may not find too much of details here, but there are certain amount of overview that we will get here. And as far as the details of these applications are concerned you will certainly have there are other courses, where you will have quite a few mean quite a lot of details of these applications might be available now here.

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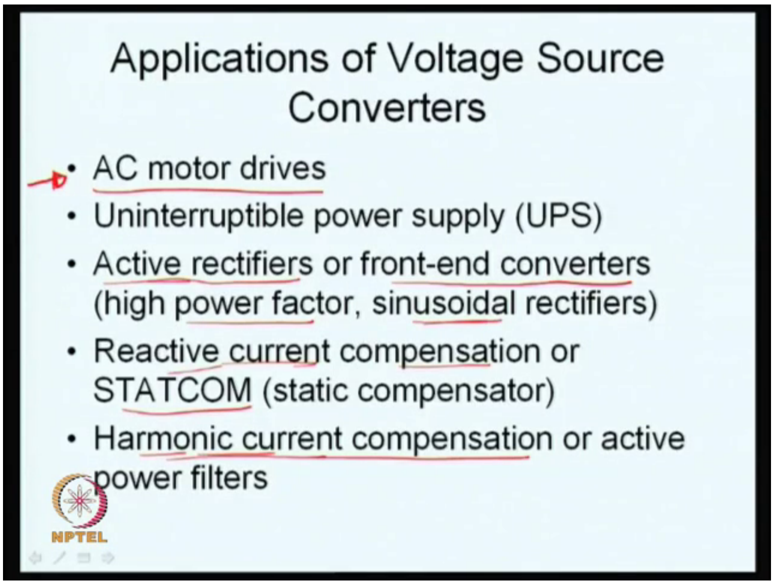

Before you know when we look at what exactly are these applications of voltage source converters, some indicative applications are given here. Please you know, this is more indicative and it is kind of not certainly exhaustive now. So, you have voltage source converters what all you can do with the voltage source converters is kind of a question now. So, one of the applications is AC motor drive. You have various induction motors and such kind of we have induction motors which are very rugged now and what you do is, you basically control the induction motor. You try to control the speed of an induction motor by using a inverter now.

An inverter is capable of giving you AC voltage; AC of what amplitude, of what frequency? That is kind of programmable. So, you can control you can get what voltage, what amplitude you want, what frequency you want and that is what is required in the motor drive as we will be seeing shortly today. And today, in fact, our emphasis will be really on AC motor drives. There are also other applications of voltage source convertor. Everybody knows that a voltage source converter or inverters they are applied in uninterruptible power supplies.

So, what you will have in an uninterruptible power supply is you will have a battery bank, whenever there is no power supply available in the mains, no power supply is available for the utility, what you do is to invert this battery power and feed your AC loads. So, you use an inverter there now and this battery itself is charged from the mains whenever power supply is available. That is what typically happens in an uninterruptible power supply.

Then you also have the so called active rectifiers or front-end converters now. So, what do we mean by this active rectifiers we look at this in detail in the next lecture; however, we will just look at a few things. What do you mean by rectifier? Well, a rectifier is you know that it converts AC into DC as we know, and what we mean by active rectifier? We typically may have diode bridge rectifier and these diode bridge rectifiers, they are actually non-linear elements. They draw non sinusoidal current, pulsating current from the AC mains. Typically, these diode bridge rectifiers will have a capacitance on the DC output and they draw pulsed current and which is not sinusoidal at all now.

So, there the current waveform is not sinusoidal and also the power factor is very poor. So, what we try to doing is, we try making use of voltage source converters to perform this rectification to perform this AC to DC conversion and those are what are actually called as active rectifiers. And this you can actually achieve a high power factor and you can draw almost near sinusoidal currents from the mains. So, these are necessary things that you want now. These active rectifiers are sometimes also called front end converters because an AC motor drive is basically an inverter feeding an induction motor. So, now, that inverter requires a DC supply and that DC supply is provided by such an active rectifier and therefore, it is also called a front-end converter at times now.

Then you have the other application what I have called as a reactive current compensation. Many a times you know reactive power is being drawn by many of overloads now and that is not very good; the utility wants us typically to maintain the power factor better than some level like 0.8 or something like that. And also, there are some tariffs if you go lower than that you may have to pay penalty etcetera now. So, there is certain amount of reactive power may have to be injected into the utility at times and because of the loads in basically lagging loads which are already connected to the grid now. So, you need what is called as a reactive current compensation, actually voltage source converter can be used for this reactive current compensation also. Quite often it is called static compensator which is abbreviated by this name STATCOM as given here now.

This is yet another application of this. So, in case of an active rectifier what it do is, you draw near sinusoidal current from the grid almost at unity power factor at very close to unity power factor. In case of reactive current compensation what you do is, you once again draw near sinusoidal current from the mains, but at a power factor which is kind of close to 0 leading. So, that is what we try doing here now. So, that there is certain amount of power is reactive power is supplied into the mains current. Then like you know it is not only reactive current, this may be reactive current lot of reactive current is being drawn by various other loads in the plant and we are using a converter to supply a part of that reactive power.

Now, we may also have loads which are actually drawing harmonic currents. That diode bridge rectifier itself is such a load. So, it draws quite lot of harmonic currents now and these harmonic currents have to be compensated for what you can do is, you can use voltage source converters to provide such harmonic currents to these non-linear loads. So, that the non-linear loads such as a diode bridge do not draw the non sinusoidal parts or the harmonic components from the mains. So, if you have a non-linear load; the non-linear load draws non sinusoidal current which has a fundamental component which is a sinusoidal component at line frequency and also harmonic component. So, the fundamental component can be drawn from the mains, but the harmonic components of that can be supplied by another voltage source converter just what is called as harmonic current compensation.

Again, we look at the same detail in our next lecture now this is also called active power filtering. So, these are the various applications of voltage source converters, but as I told you while back or focus today will be on AC motor drives, and even in AC motor drives you know before we get onto AC motor drives we will have a quick recap and basically review whatever we did in the in terms of converters in the previous classes because that is now quite necessary right.

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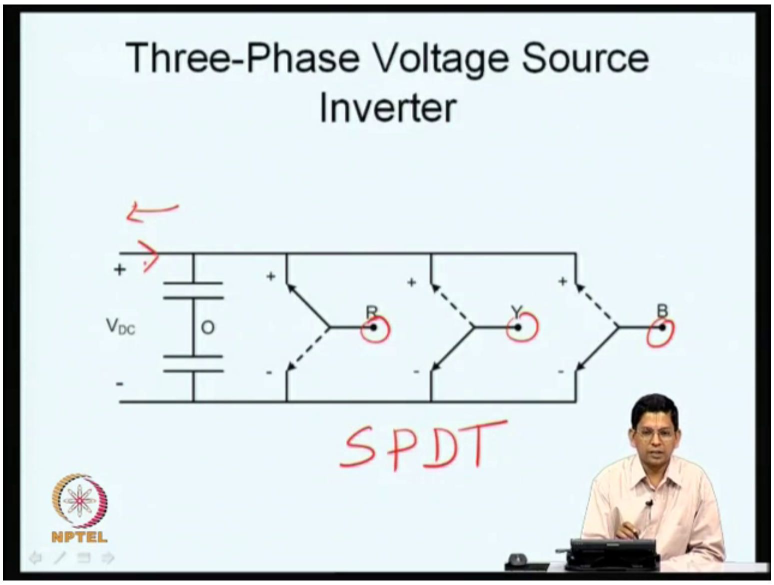

So, let us take a quick look at what we have been doing in what we did in the last lecture. So, this is basically a three-phase voltage source inverter which is been shown in terms of single pole double throw switches. You have 3 single pole double throw switches here and these are the load terminals R, Y and B and DC power is fed from here now. So, DC current can flow through this. In this case there is a DC to AC conversion and current can also flow in the opposite direction. It is also possible that current can flow in the opposite direction in which case it means that the power is flowing from the AC side to the DC side. If it is flowing from the AC side to the DC side, the power factor here though between the voltage and current will be greater than 90 degrees or will be closer to 180 degree so to say that power can flow on. So, it is a really a bi-directional power flow convertor.

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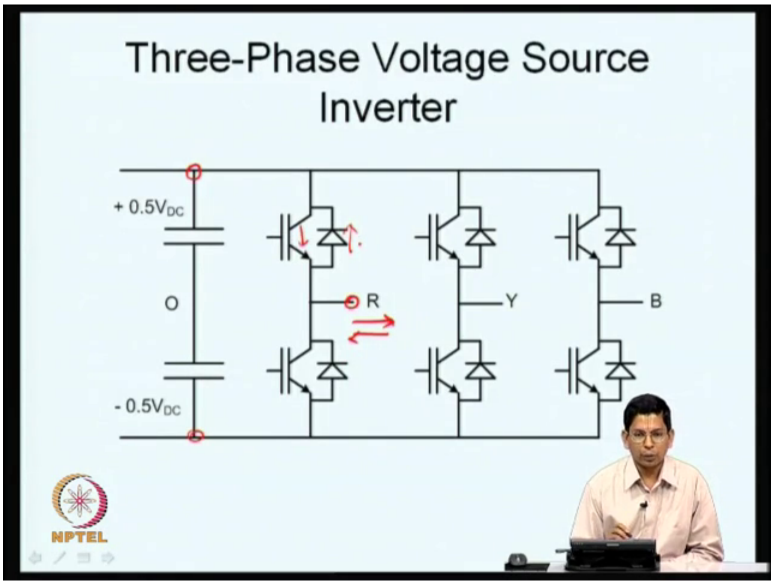

And the actual switches are realised like this now. So, to restate whatever I said this is the pole of a single pole double throw switch. At this pole we can apply either this potential which is plus 0.5 V DC or minus 0.5 V DC, by turning on either the top device or the bottom device, but not both we can apply this potential either plus 0.5 V DC or minus 0.5 V DC irrespective of the direction of the current. The current can be flowing in this direction or it can be flowing in the opposite direction. Irrespective of the direction of the current flow we can apply this voltage level now.

So, depending on the direction of the current and depending on the let us say the top device is on, if the current is as indicated by this arrow mark then current may flow in this direction. If the current is really in the opposite direction, then the current will flow through the diode now. So, these are bidirectional current carrying switches as we saw now. So, what you can really have is between R, Y and B is actually the three-phase load connected and we presume that the load is inductive.

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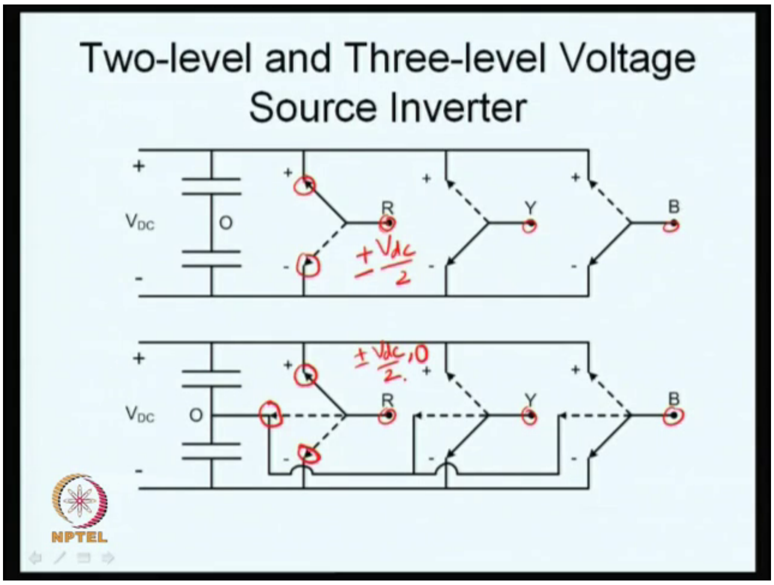

Now, this is we looked at a 2 level and a 3 level voltage source inverter. In case of a 2 level voltage source inverter, both the inverters you have the same three-phase load connected. In case of a 2-level inverter, you have only 2 poles; one of them connected to the positive DC bus and the other is connected to the negative DC bus.

Whereas, if you look at the 3 level voltage source inverter you have 3 poles; one of them is connected to the positive terminal, other one is connected to the DC bus midpoint and the third is connected to the negative DC bus. So, in addition to 2 of this one connected to the positive and one connected to the negative, you have a third one or the middle one which is connected to the DC bus midpoint and that is why we call this as a 3 level voltage source inverter.

Here, if you take a 2 levels voltage source inverter VRO can be only plus V dc by 2 or minus V dc by 2 as I mentioned the other day. If you take VRO over here it can be either plus V dc by 2 minus V dc by 2 or it can also be 0 in a 3-level inverter. There are 2 different voltage levels here and there are 3 different voltage levels in a 3-level inverter. Hence you get the name 3 level voltage source inverter now.

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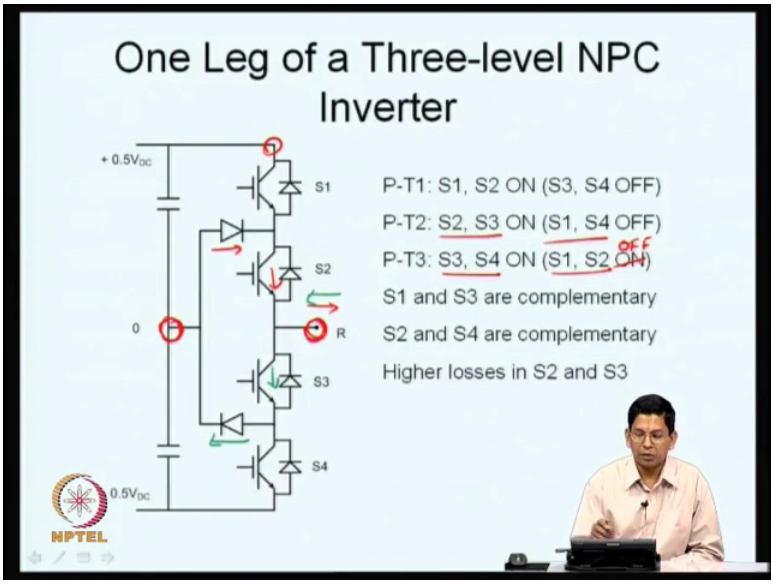

So, the realization of a 3 level voltage source inverter also we saw. It is a single pole triple throw switch now. So, either the top 2 devices are on or the bottoms 2 are off. So, in that case in the top 2 are on, this pole is connected to the top throw or the positive DC bus now. Again, you may have a situation where the middle 2 are turned on S2 and S3 are turned on and; that means, S1 and S4 are turned off.

These S1 and S4 the extreme switches are turned off. In that case the same pole is connected to the midpoint here and the direction of current depends on if this is the direction of current then you will have current flowing through the diode on the transistor. If the direction of current is different let us say it is in the opposite direction as shown by the other colour ink, then it can actually flow in this direction through this transistor and through this diode back here.

So, you can also think of there is also the other state where the pole was connected to the bottom throw S3 and S4 are on and S1 and S2 are off. So, now, what we have here is if this was the same mistake as in the last slide, this should be off here. So, these are S1 and S2 are off now. So, you can connect the pole to either of the 3 voltage levels. This is the exact realization of a 3 level voltage source inverter and you know the pole can be connected to the DC bus neutral hence it is also called Neutral Point Clamped inverter or NPC inverter.

You use diodes to do this connection therefore; it is also called diode clamp inverter as we mentioned the other day; these switches S1 and S3 act in a complementary fashion and S2 and S4 act in a complementary fashion.

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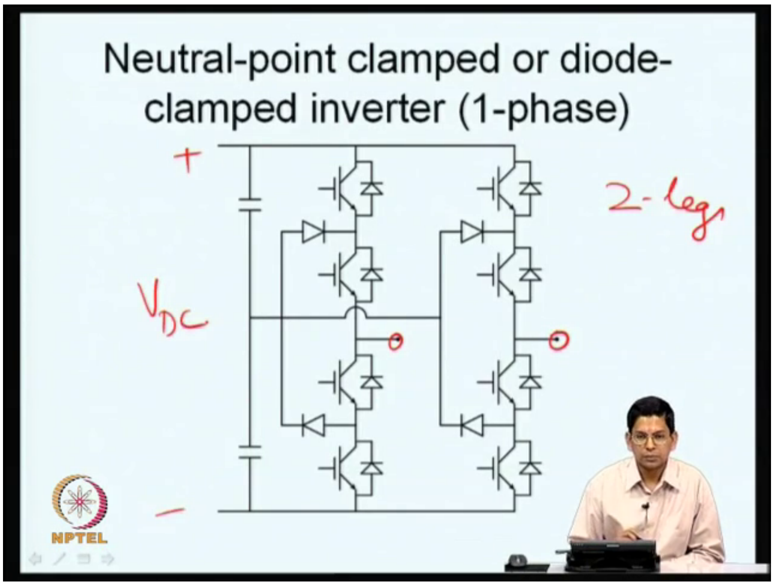

So, this is how you did what we saw earlier was a single leg now you have 2 legs here, and these 2 legs you can have a single phase load connected between these 2 terminals and this is your DC bus voltage being fed here.

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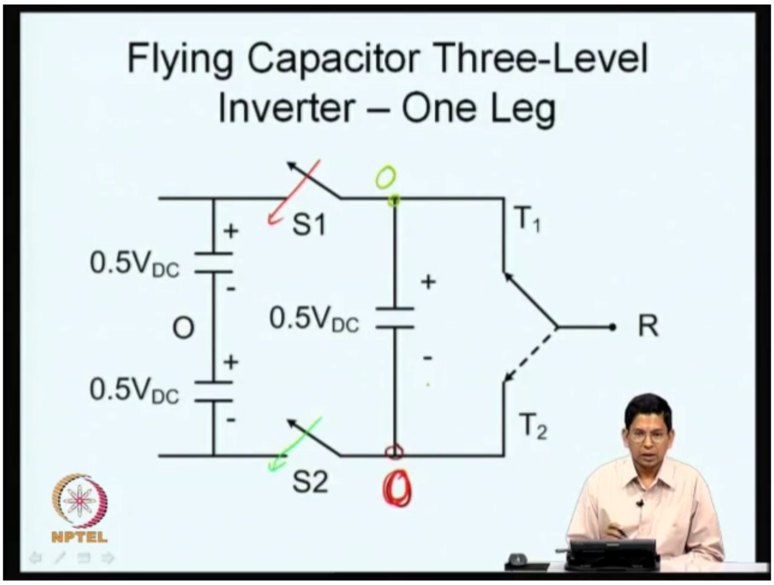

So, this is the other alternative that we looked at is a flying capacitor converter now. So, you use a capacitor which is charged to 0.5 V DC just like other capacitors and you can connect this in series or in parallel I mean in series and with one polarity or in series with another polarity. For example if S1 is closed, then this gets connected in series with these capacitors in a particular polarity or alternate like S1 can be closed. That is one possibility.

So, then the other possibility for example, is S2 is closed and S1 is open. In such a scenario they again this is connected in series, but the polarity of that of this is reversed now. So, in this case if you have connected here you will have this O is basically equal to you get this potential at O for if let us say the top is turned on, so, this is plus minus and you have plus and minus and this is where you get the potential of O. So, let us should make it red colour. So, this is where you get O now, whereas if you do the connection is as shown by the green ink, this S2 is closed in S1 is open and in this case this point is equal to potential O. So, this is how you get this and you have a single pole triple throw switch here and all these switches have to be capable of conducting in both the directions.

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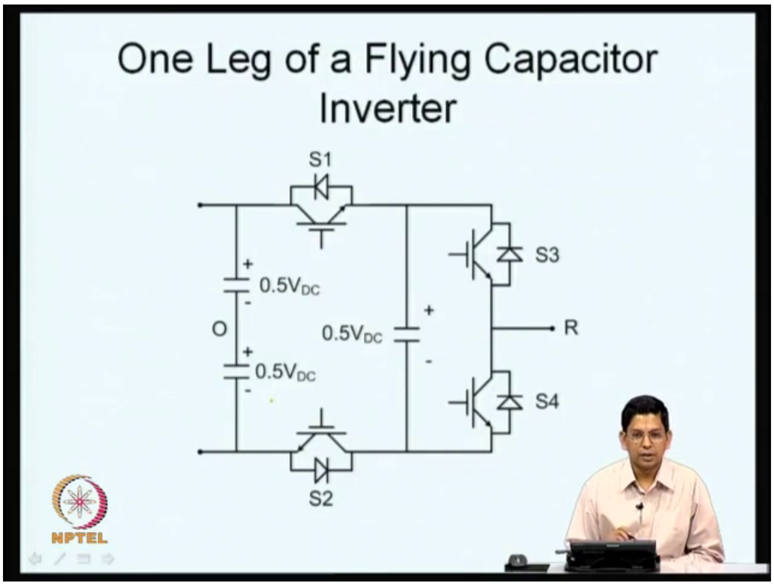

And you have this was the realization that we saw now. Basically, with all these, what we would aim at doing is to realize certain average voltage. That is what we will be looking at shortly from now on.

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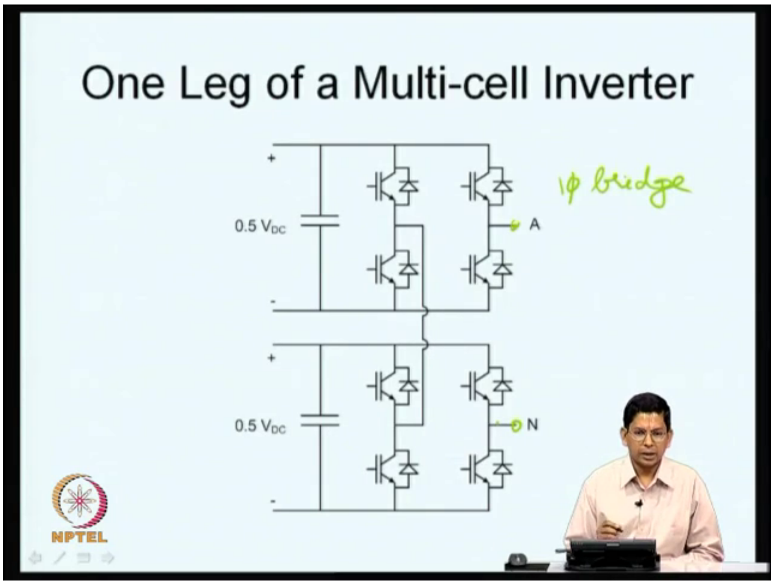

So, this is another one leg of what is called as a multi-cell inverter now. If you need different voltage levels between A and N what you try to doing here is, you use one simple single phase bridge you use. So, this is a single phase bridge you can connect 2 of them and you can make a connection like this and. So, between these 2 points you can have various voltage levels. It can be V DC it can be 0.5 V DC, it can be 0 or it can be minus 0.5 V DC or it can be minus V DC.

So, though different voltage levels are possible here and this is where you know you can connect one of the phases of the load across these 2 terminals. There is again one leg of a multi-cell inverter now. So, these are various topologies for realizing you know what are called as multi level what is really a multi level inverter.

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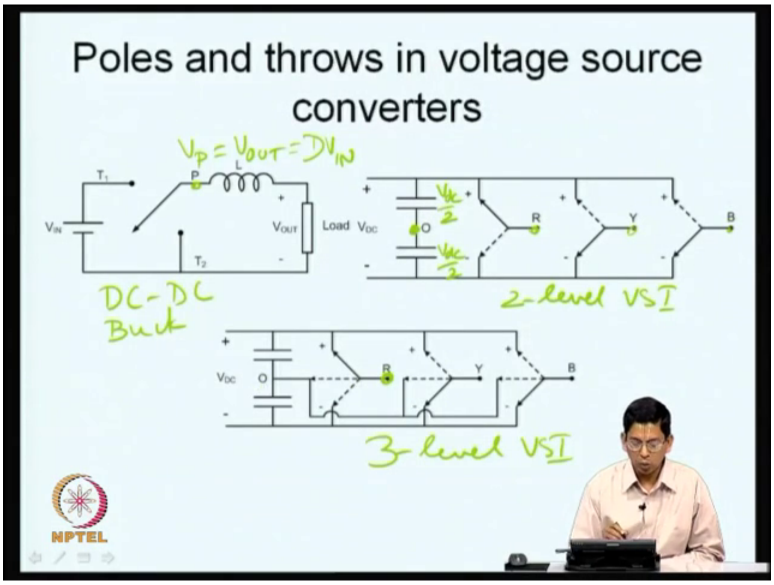

So, if you just look at what we are going to be primarily concerned is this is about DC to DC converter. What you have is a DC to DC buck converter. In this you have a single single pole double throw switch and there is certain potential at the pole now. What is that potential at the pole? That potential at the pole is essentially the voltage output voltage and how is it related to the input voltage. It is related to the input voltage as certain duty ratio times V IN. The duty ratio meaning like you know you connect P to T1 for some time and P to T2 for some other time. So, you keep on doing it in a cyclic periodic fashion.

So, the time for which you connected to T1 divided by the total switching time is the duty ratio as we defined now. So, you get this is a duty ratio times V IN now. So, you get some potential at the pole which is lower than V IN. So, what you are doing is you are this is the pole there are 2 throws now and you are controlling the potential at this pole.

In case of a 2 level voltage source inverter; this is a 2 level voltage source inverter, as you can very clearly recognize. So, this is a 2 level voltage source inverter. So, now, let us take the point of reference as this midpoint O. Now, if you want to main R, what you are going to do is you look at this potential V RO, at any instant it can be either plus 0.5 V dc, this potential is V dc by 2 and this is another V dc by 2. So, the potential at R at any instant can be either plus V dc by 2 or minus V dc by 2. On what you will do is, you will do on averaging. You will connect it to the top throw for some time and the bottom throw for some time. So, the average potential at R will be somewhere between plus V dc by 2 on minus V dc by 2.

So, the same story about Y and the same story about B. So, if you look at a 3-level inverter once again you know it has 3 switches, but in a 2 level case it is all single pole double throw here it is a single pole triple throw switch. So, this is a 3-level voltage source inverter you have single pole triple throw switches here. Once again what you do is as you know at this potential R; potential at R with respect to O can be either plus V Dc by 2 minus V dc by 2 are 0. So, and what you can realize is, you can realize any potential that is anywhere between plus V dc by 2 and minus V dc by 2 in an average sense. So, that is what you can do now.

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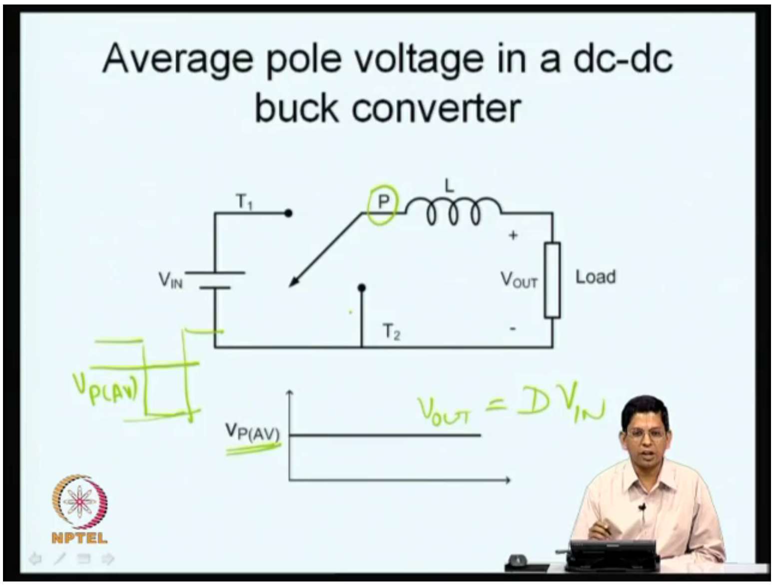

So, let us look at more of this in the following slide. What you want to do in a steady state? At steady state in a DC to DC buck converter is to produce certain output voltage now. This output voltage is nothing, but the DC voltage here. So, if I call this potential at V P and this V P has certain average value. This V P is like plus V in some time and it is equal to 0 some other time. So, it has certain average value. This average value I am calling it as the V P average. Now what does this V P average equal to? This V P average is actually equal to the DC output voltage that we want. This is equal to V OUT and this is equal to D times V IN as I just said a while back. So, the pole voltage cycle by cycle is controlled in such a fashion that the average voltage is the same. The average voltage does not vary, whereas, if you move to an inverter that is going to change now.

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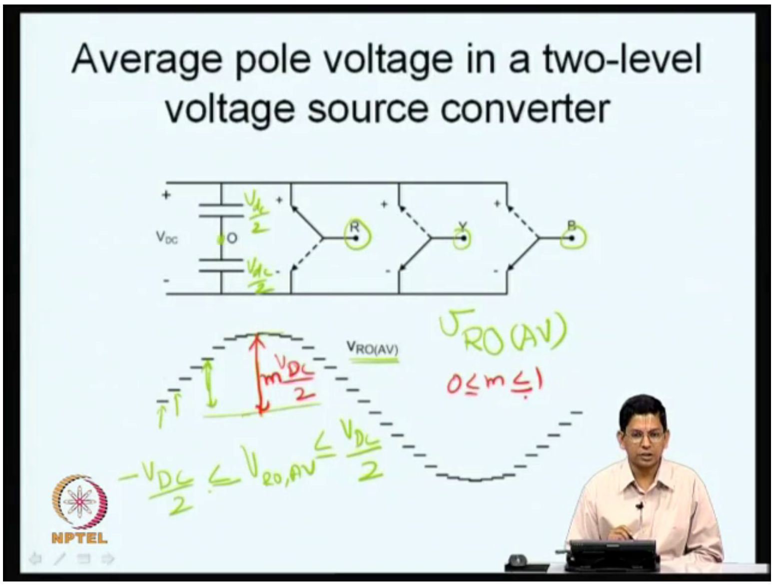

Here also you have this pole voltage pole at R. Now we are measuring it with respect to the midpoint O, V RO and we are looking at this V RO average. What we are looking at is the potential V at the pole R measured with respect to O and the average value this is the instantaneous. We are trying to average this over a switching cycle and what we call it is V RO average now. So, this V RO average can be anywhere between plus V dc by 2 and minus V dc by 2. Because this has a potential V dc by 2, this also has a potential V dc by 2. V RO can be the instantaneous value is either plus V dc by 2 or minus V dc by 2 and it can be averaged that is you can apply plus V dc by 2 for some time and minus V dc by 2 for some other time and therefore, there is a kind of a time averaging that you are doing now.

Due to this time averaging you can realize any value, that is, anywhere between plus V dc by 2 and minus V dc by 2 and what you do here is, this average voltage is varied now in a sinusoidal fashion. Since you want sinusoidal output voltages one simple thing for you to do is to vary the average pole voltage in a sinusoidal fashion as I have shown here. Now for example, the small switching cycle and this is the average voltage that I am applying, now in the next switching cycle I am applying a slightly higher voltage and it goes on increasing as I have shown now and it takes a sinusoidal nature.

So, this is what you can end up doing now. So, here there is a question now. If V RO average is modulated like that how should V YO average be modulated? In a similar fashion, in a similar sinusoidal fashion, but phase shifted by 120 degrees. Again, how should B phase be modulated? In a similar sinusoidal fashion, but phase shifted by 240 degrees from R phase. So, in this way you can get three-phase sinusoidal outputs now.

So, you look at this voltage now let me say this value from 0, this is the average voltage now. This average voltage can be anywhere between minus V DC by 2 to V RO average can be anywhere between minus V DC by 2 on plus V DC by 2. So, now if you look at this, what is the highest voltage that I can get here? Let me use red ink here. So, this is, what is the highest value that I can have? The highest value that I can have is V DC by 2. This is the highest possible value. Now, I can, that is what I am trying to say is the pole voltage is controlled in such a fashion that, its average value averaged over a switching cycle varies in a sinusoidal fashion and you can you can control it in such a fashion that the peak value of the sinusoid is V DC by 2.

So, this is the highest amplitude of average sinusoid that you can produce V RO average, if you look at it and if you want to modulate V RO average as a sinusoid, the peak value of the sine and the amplitude of the sine cannot exit V DC by 2. So, this is the highest amount of voltage that this inverter can produce with such a sinusoidal modulation. It is not necessary that V RO has to be modulated in a sinusoidal fashion.

For example; it can also be as a sinusoid with some triplen harmonics added to it etcetera which we will see in a few classes later, a few lectures later, now, but you take it as sinusoid. This is a limit on this. If you really want very high voltage what you need to do is, you need to go in for a square wave operation. But, if you are looking at sinusoidal modulation, this is, the highest value of V DC by 2 that you can get now. You can get any value, let me call this as m V DC by 2, where m, is anywhere between 0 and 1.

So, you can with the voltage source inverter with a DC bus voltage V DC and the average pole voltage is modulated in a sinusoidal fashion, it is possible for you to get a peak phase voltage up to V DC by 2, some m times V DC by 2, where m is a fraction anywhere between 0 and 1. So, it is possible for you to control the amplitude. It is also possible for you to control the frequency now. So, the rate at which the average voltage varies it can be controlled now. So, both the voltage and frequency can be controlled here.

If you look at a 3-level inverter what is the story there? Again, here also if you look at the average pole voltage, unlike in a DC, in a DC to DC converter the average pole voltage is maintained constant at steady state. In a 2-level inverter like it is maintained constant in a buck converter it is maintained constant here.

In a 2-level inverter, the average pole voltage is now varied in a sinusoidal fashion. Please, realize that you know the average voltage is never greater than plus V DC by 2 or minus V DC by 2. So, this is also what is called as a buck derived topology. Now if you say, if you take this, here, again the average pole voltage can be only anywhere between plus V DC by 2 and minus V DC by 2.

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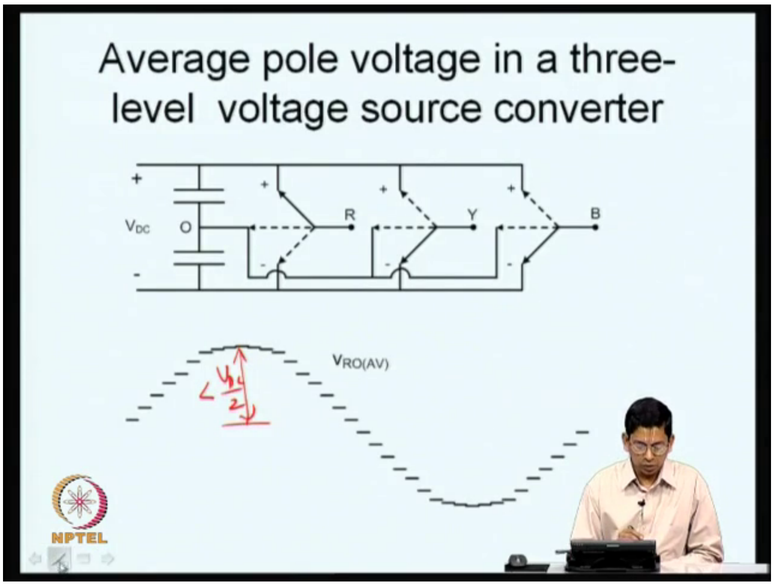

So, here also you can vary it in a similar sinusoidal fashion now. So, in this sense it is similar now, that is, once again you can modulate and what is the peak value that you can get here? The peak value that you can get here, if you are modulating it in this fashion is like V DC by 2, this is something that you can get here.

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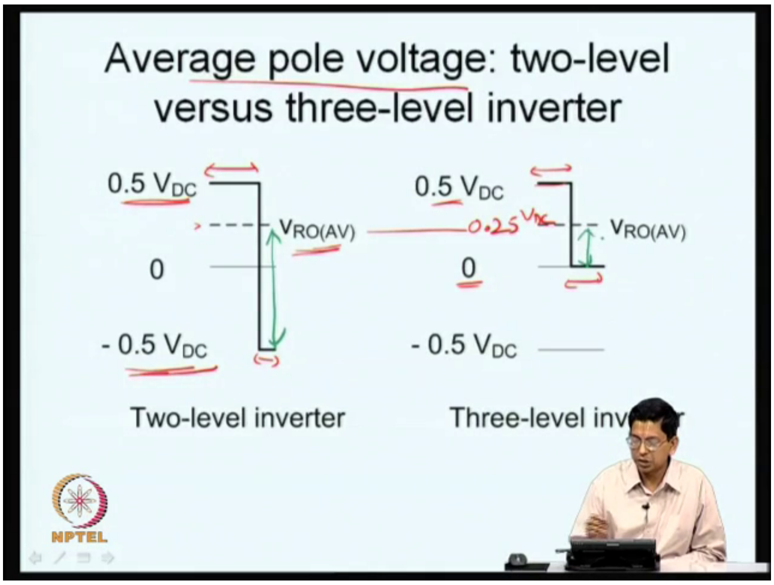

So, you can control this to any value which is less than V DC by 2. So, if both are sinusoidally modulated; in a 2-level inverter also you can modulate it sinusoidally, in a 3-level inverter also you can modulate the average pole voltage in a sinusoidal fashion. What is the really the difference between the 2? The way the average voltage is realized, the way the average pole voltage is realized is different between a 2-level inverter and a 3-level inverter. In a 2-level inverter there are only 2 voltage levels that can be applied at the pole; one is plus 0.5 V DC and the other one is minus 0.5 V DC. Now, if you need an average voltage as indicated here what you do is, this is the average voltage you have indicated here in these dashed lines, what you do is, you connect the pole to the top throw for a long period or for some time and connected to the bottom throw, so that, it is equal to minus 0.5 V DC for a short duration of time.

So, the result is, you get an average value and the average value is what is given by V RO average. Now, in this case this V RO average is something like 0.25 V DC. Now, let us say you want the same point 0.25 V DC as an average applied here in a 3-level inverter. What you can do is, you can connect the pole to the top throw, that is, plus 0.5 V DC for certain amount of time and to 0 for the remaining amount of time. So, this is for 50 percent of the time this is another 50 percent of the time. So, you are once again getting the same average value. This average value is same in the 2 cases, but what is different; the instantaneous applied voltages are different. How are they different? Here, it is plus point 0.5 V DC and minus 0.5 V DC, in a 2 level case whereas, in a 3 level case it is plus 0.5 V DC and 0.

So, the worst case error between the applied voltage, what is the worst case error here, this case the worst case error is here this is the worst case error between the applied voltage and the desired voltage, which is the average voltage whereas, in the case of a 2-level inverter it is much lower. This is the worst case variation and this is also same as that. So, you can see that the worst case error between the 2 is reduced, that is, the instantaneous error voltages are reduced. This is what leads to a better waveform quality. Your harmonic distortion is going to be substantially lower, because of this.

So, that is why you know 3-level inverter is said to give a better waveform quality than a 2-level inverter. This is something we saw in the previous class now.

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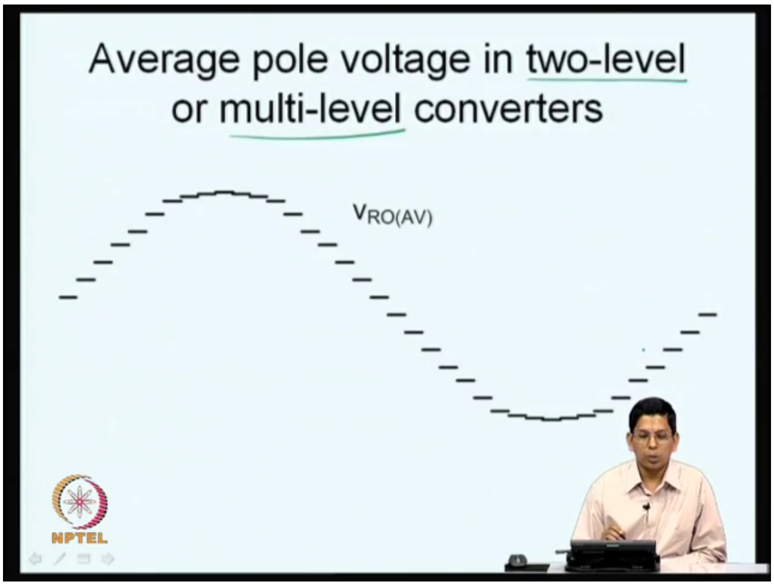

So, going back to this either you are talking about 2-level inverter or any multi-level inverter it is possible for you to modulate the pole voltage in a sinusoidal fashion and we are going to modulate the pole voltage in a sinusoidal fashion now.

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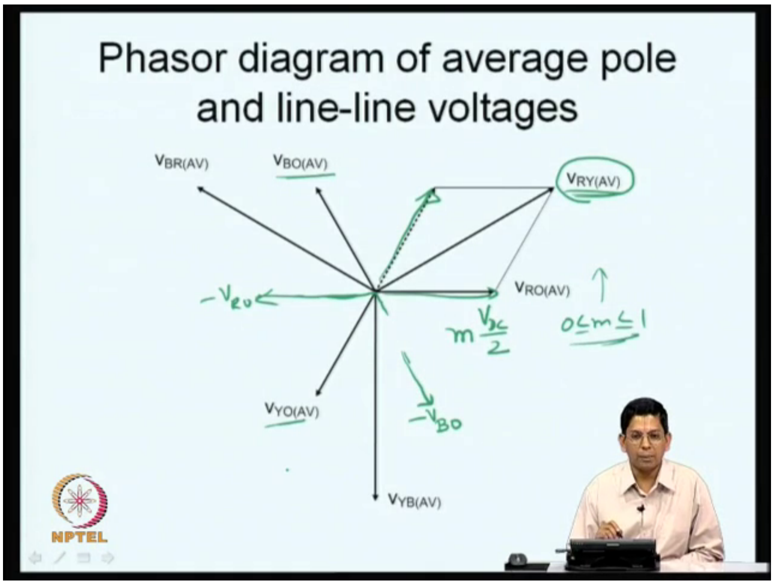

So, if this is V RO average, let us take a look at how are the other average pole voltages now. This is V RO average. As I mentioned here, this V RO average can have a maximum value equal to V DC by 2, that is, its peak value can be equal to V DC by 2 or you know it can be anything like m V DC by 2, where m, is anywhere between 0 and 1. This is what you can have now. So, if your V RO average is controlled here, then your V YO average is as indicated here is 120 degree phase shifted and they are revolving like this and V BO average is another phase shifted by yet another 120 degrees now.

So, this is how if R is modulated in a sinusoidal fashion Y and B are also modulated in sinusoidal fashion. So, they also have same amplitude there is only a phase difference now, all of these are at the same frequency. So, if this is V RO how about the line-line voltages. So, this is what we have at V RO average. V RO average is a sinusoidal quantity that is why; we are representing it as using phasor. So, V RO average, V YO average and V BO average are all phasors, I mean are represented as phasors, because they are sinusoidal quantities. How about V RY average? V RY average is nothing but V RO average minus V YO average.

So, this is V RO average and this is minus V YO average. So, V RO minus V YO average gives you this V RY average. You can see that this is going to be root 3 times of V RO average now. If V RO average is something like 200 volts that will be 200 into root 3. So, similarly V YB average is equal to V YO average minus V BO average, if V

BO is projected this way this is your V BO average now. So, V YO minus V BO average this is minus V BO, V YO minus V BO gives you V YB. The same way V BR is equal to V BO minus V RO average. This will give you this length. So, this is how you have your three-phase line-line voltages, three-phase average pole voltages and the three-phase line-line voltages now.

And the amplitudes are controllable. That m it can be anywhere between 0 and one. So, it is controllable up to V DC by 2. So, you can also control the frequency. So, you can control the amplitude and you can control the frequency, this is what helps us in controlling an induction motor as we will see shortly now.

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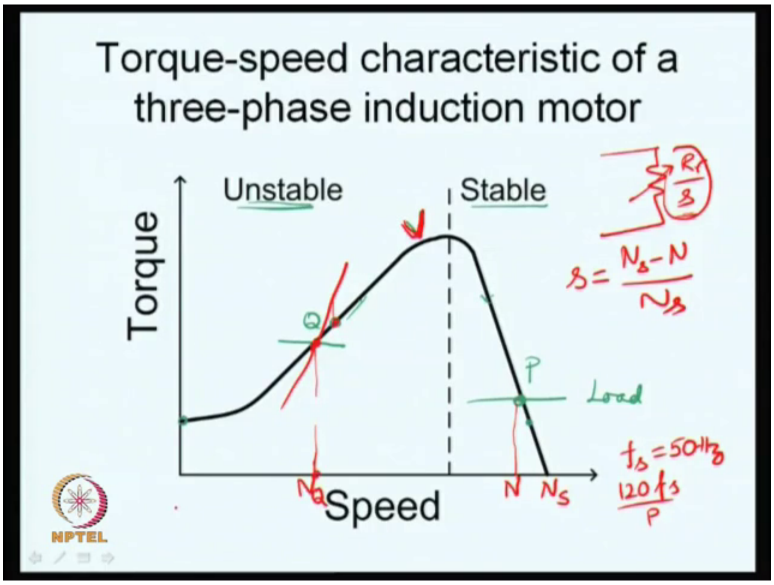

So, let us look at now an induction motor. So, this is the torque-speed characteristic of an induction motor, when some particular voltage V has been applied the stator voltage is some particular V let us call it. So, for this value of V this is how you get here. You can easily obtain this from the steady state per phase equivalent circuit of the induction motor also now.

So, the torque this is what is called as the starting torque and it goes on. You can as you know that the induction motor is self starting, it has certain amount of starting torque. There are courses on electric machines available on NPTEL, which describe in detail about the operation of an induction motor. So, you have a characteristic like this and this part of the characteristic is called unstable and this part of the characteristic is called stable, why is it? So, how does the operating point is how is the this is the torque-speed characteristic of an induction motor, now, where exactly will it operate. It can operate on any point on this curve. How is that point chosen? It can be here, it can be here, anywhere. How is that chosen? That is chosen by the intersection of the load.

If let us say we have a load whose characteristic is like this. This is the load let us say the load has such a flat torque-speed characteristic. So, this will be the point of operation and this point of operation is supposed to be stable, why is it stable? Let us say there is a small disturbance because of the small disturbance this point moves here. So, this point is moved here, what happens is the torque is now lowered. The torque is now lower than what it was. So, the machine will naturally decelerate and it will go back to the origin.

So, you can see from this operating point you can look at any kind of. Either in torque or in speed, you will see that the operating point will return to this point. So, let us call this point P. So, any for any disturbance you know it will tend to come back to this operating point and therefore you call this operating point as stable operating point and the set of all operating points on this region are supposed to be stable like this. So, you call that as the stable region of the torque-speed characteristic of induction motor now.

So, why is this side called unstable? The same way if you have a load torque characteristic like here and now let us consider a point Q; from Q let us say if the motor somehow shifts and goes to this operating point, what is happened now? The torque has increased now the speed is already little higher and the torque is higher. So, the torque produced by the motor is higher than the torque demanded by the load and therefore, it goes on accelerating. Therefore it will move away from this particular operating point.

So, if at P any disturbance you consider you will see that there is a tendency of the motor load system to come back to this operating point whereas, at the operating point Q in case of any disturbance it will run away from that operating point. It do not come back to that operating point and therefore, you call this as an unstable operating point and this entire region has an unstable operating region.

Now there could be a question, can I operate it in the unstable region is it possible at all to operate it in the unstable region yes you can operate it for example, let us say you have a load torque characteristic like this, you observe the relative slopes. What I mean the relative slope? At this point Q, the torque-speed characteristic of the motor has a particular slope and the green line indicates a particular slope of the load and the red line indicates that under slope, of the load torque-speed characteristic.

If the load, where, having a torque-speed characteristic as indicated by the red ink rather than as indicated by the green ink, the situation is different now. Let us say from this operating point Q, it once again goes back here. So, what happens, it is now producing a slightly higher amount of torque, but at that speed the torque demanded by the load is still higher and therefore, there is a decelerating effect and the motor load will set we will come back to this same point Q.

So, it is possible to operate it in the so called unstable region, by having a different kind of torque-speed characteristic as I have shown here now. But, we generally do not do that because at this point if you look at there is the slip of the machine. So, if you look at this is the slip here and in this case this is the slip here at the point Q now. So, what is the slip now, there is this point, is the synchronous speed this point N S is what is called as the synchronous speed of the machine. That is, it is the speed of the synchronously revolving magnetic field that is rotating inside the machine because of the three-phase voltage is applied on the three-phase stator winding. Now, let if you consider this operating point P, let us call this speed as N. So, slip s is basically N S minus N r by or let us just N. N S minus N r by N, let me remove that using it is N S minus N divided by N S.

So, this is the slip now. So, the rotor side resistance in a motor is basically you would have seen that in a equivalent circuit it is R r by s. Now, in this case the slip is very small and therefore, R r by s is substantially high. If you take the next case this operating point Q the slip corresponding to the operating point Q, let me call this as the N subscript Q just to distinguish it from this N. So, N Q minus N S is now very high and therefore, the slip is very high if the slip is very high R r by s is actually very low.

So, normally in induction motors will operate with the slip of just a few percent points. So, R r by s will be much higher than R r. If s goes becomes higher and higher R r by s comes lower and therefore, your slip in the rotor resistance is what I am trying to say is, it is going to draw very high current prohibitively high amount of current. So, it may not be possible for you to operate and this operating point Q, in a sustained fashion whereas, this operating point P, it is possible for you to operate for a reasonably long period of time.

So, this is our understanding about the torque-speed characteristic. Here, what we are trying to do is, what we have done is, we have considered a particular voltage which is this V as I have indicated here. This is the stator voltage now. We have also considered a particular value of frequency say something like fs is equal to 50 hertz. This is the stator frequency now. So, you know that 120 times fs by P, is what is your synchronous speed now.

So, this is for a particular stator voltage and a particular state of frequency.

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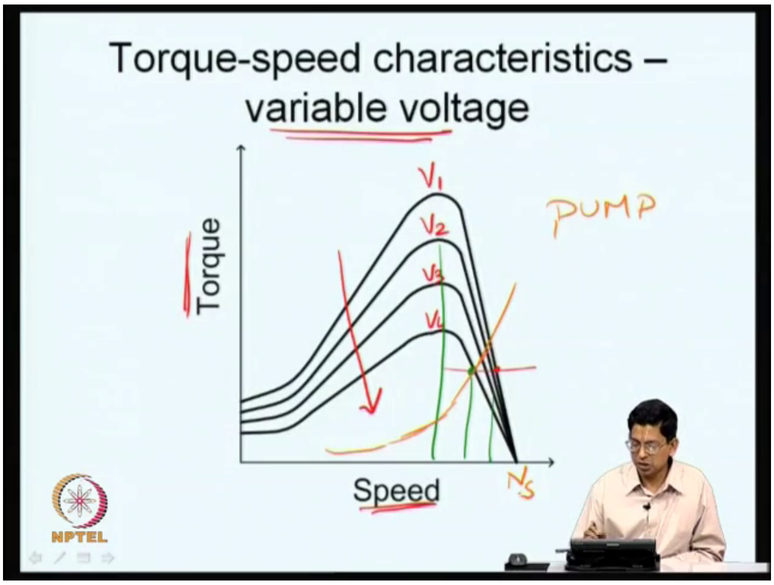

So, we should move on to, what happens if you vary one of them let us first vary the stator applied voltage.

So, now this is the torque-speed characteristic with variable voltage. You are still looking at the same torque versus speed, but the voltage is now varied. This can be some voltage V 1, this is some voltage V 2, V 3, some voltage V 2 and the voltage is decreasing in this direction. As if you reduce the voltage the peak value of the torque-speed characteristic really comes down. You might already know this very well, if you do not know you can verify this very easily. You can also you verify it from the equivalent circuit of the induction motor.

So, it comes down and V 3 comes down. It goes lower and lower. This is also possible this is the way the characteristic changes now. So, if you consider a particular torque-speed characteristic, let us say you have a load torque like, this is your load torque characteristic. When you have applied a voltage V 1, you have you have the motor operating at this point like this, when you reduce the voltage it will come down to another point like this. So, it is possible for you to vary the speed of the motor over a small range by going in for such kind of voltage control, but you know it is restricted over a small range it is restricted only within this so called stable operating region here and this is ideally suited as you might know for the characteristics.

Like, here you may have certain characteristics like in pump or such kind of loads which will have a characteristic going up like this. So, which is typically used in such drives, pumps etcetera, they may have a kind of a parabolic relationship between torque and speed and. So, sometimes it is used there in this situation here. But, what we want to now see is, this is the effect of varying the stator voltage on the torque-speed characteristic now. So, if you instead of applying the rated voltage, let us say about 400 volts if you apply 200 volts or 300 volts what happens is, you find that the torque-speed characteristic changes in this kind of a fashion, that the peak torque essentially comes down.

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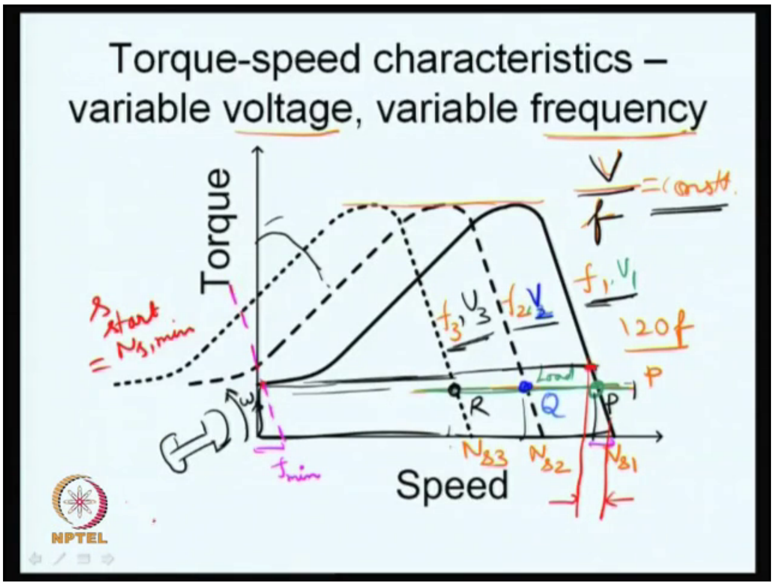

So, now let us look at the next scenario where both the torques, both the voltage is varied and the frequency is also varying. The previous case, we kept the frequency unchanged. The frequency unchanged meaning the synchronous speed was unchanged.

So, now, you are changing the frequency. This is some frequency f 1, this is some other frequency f 2, this is some frequency f 3. If your state of frequency is equal to some f 1, then you will have a corresponding synchronous speed N s1. This will be like the same 120 f by P and f is now changed from 1, 2, 3 etcetera and we are typically considering a 4 pole machine let us say.

So, for a 4 pole machine 50 hertz would mean 1500 rpm and if it is 50 hertz, is changed to 40 hertz then this 1500 rpm will get reduced to N s2. N s2 will be something like 1200 rpm now and f 3 if it is 30 hertz, there will be a corresponding synchronous speed N s3 and this will be something like 900 rpm now. So, what happens is, if the synchronous speed changes if you do that now and if you do it in such a fashion that the voltage to the frequency ratio is kept constant. This means effectively, that the torque I mean the flux is maintained at the constant value. So, therefore, the peak torque is never getting affected.

Earlier, if you see that the peak torque was getting affected. Why, because the frequency was held the same, but the voltage was reduced you have V 1 by f. Now, V 1 by f is actually greater than V 2 by f, therefore, when we apply V 2 which is lower than V 1, the peak torque comes lower. This is again greater than V 3 by f and therefore, you see that you know that the peak torque goes on changing with the V alone. Now, what we are trying to do is, we are varying both V by and f and that ensures the peak torque is fairly constant and the effect is basically, that you see that the characteristic itself is getting shifted. What you see is, that the torque-speed characteristic is kind of getting shifted everywhere.

So, what, now let us say, I have a load whose torque-speed characteristic is like this. Let me use a different colour ok. So, let me use this green colour, let us say this is the torque-speed characteristic of the load. So, if I am applying a frequency f 1 and a corresponding voltage V 1 let us say, let me call this corresponding voltage as V 1, then I operate at this point. If I apply a frequency f 2 on the corresponding voltage V 2, such that V by f is constant and it is equal to its rated value, now I can operate here at this point, let me just change the colour. Let me say I can operate here now. So, this is when I have V 2. Now, let us say I have yet another operating point this is f 3 and V 3. So, here the same load it can operate at this point.

So, what you can do, you are able to control the speed. The speed was earlier here and that speed got reduced to so much and then this speed is getting reduced to so much. Now, what are you doing essentially here? Earlier, in this case like a variable voltage, what happens is it is an induction motor. In an induction motor you are applying you know, it has a three-phase stator winding and you are applying a three-phase voltage now and this three-phase voltage produces a revolving magnetic field. It produces a revolving magnetic field inside, like this. There is something it is a magnetic field that revolves now. At what speed does it revolve? It revolves at a speed which is directly proportional to the frequency.

So, here what you are trying to do is, you are not changing this frequency, but you are trying to change the slip. By changing the slip you are trying to vary. Here, what you are trying to do is, you similarly have a revolving magnetic field inside, what you have is a revolving magnetic field. You want to control the speed of the induction motor, what you can do? One of the easiest things for you to do is, to reduce the speed of this revolving magnetic field. Let me call this as omega s or fs, I can just reduce the speed. It is an induction motor which will typically run at 1500 rpm something close to 1500 rpm. Now I want it to run at a speed closed to 750 rpm, what should I do? I must reduce this speed of this revolving magnetic field by roughly by 50 percent. How can I do that? I can very easily do that by reducing the frequency to 50 percent of its rated value. Instead of applying 50 hertz I can apply 25 hertz.

So, speed control is achieved here by essentially by controlling the speed of this revolving magnetic field, that is, by controlling the stator frequency, but for this you have to make sure that the strength of the magnetic field is constant and that is given by this ratio V by f and you maintain this V by f at a constant value equal to its rated value. Therefore, you can maintain the flux at more or less equal to the peak flux. Of course, here we are making an assumption that the resistance drop is negligible. Basically, V equals i r plus d psi by d t n we are neglecting the i r term here.

So, the resistive drops are negligible you do that. When you go to lower and lower speeds the resistive drops might not be negligible and therefore, if you reduce frequency much lower you may find that your peak torque is really little lower than that. At here you may find the peak torque to be kind of lower than what you get here. So, what you do typically at lower frequencies is you boost up V, you do not maintain V by f at the rated value. You keep V at I mean, make it a little higher than what it should be. So, this is what you do to take care of that effect now.

So, what is it that you are able to do now? You are able to control let us say this is the rated torque, let us say this is somewhere the rated torque, now you are able to operate your machine over the entire range now. The load torque is whatever it is, but you are able to change the torque-speed characteristic of an induction motor. You are just able to pull and push it, it is like drag and drop that you might do with your mouse. Something similar to that you are able to do here by changing its voltage and frequency and now the point of intersection is different. If its point was P, this point is Q and this point is R, the same torque-speed characteristic. It can either operate at the so called point P, Q or R. How do you do that? By changing the characteristic V 1 f 1 makes it operate at point P, V 2 f 2 makes it operated at Q 3 and if the applied voltage is V 3 and the frequency is f 3 you get it to operate at R.

So, this also gives you a fairly simple way of getting the induction motor started. How do you get an induction motor started? As you always know that the starting currents are very high, if a direct online start you may get currents roughly some 5-6 times the rated current as your starting current, but that is only for a short duration of time and the motor is designed to stand that. But, many a times you want a smooth starting, why, because your inverter, your motors if it is going to be fed from an inverter the motor can take high starting current, but the inverter might not be able to take a high starting current. That is one reason why you have limit your starting current to as low as possible now. So, how do you do that?

So, let us say, you want to give it very low. So, what you can do is, you shift it to a point let me use a different colour that I probably not used still, what I can try to doing is I can shift this like this. I can shift the characteristic like this, such that, this is my rated slip frequency and I bring it to here. So, in this case what I am trying to do is, I am trying to apply something as f minimum I call, this is the f minimum and this produces a very small synchronous speed and this synchronous speed and here the rotor speed is 0.

So, here the slip is small and the slip is still comparable to that of the rated slip. As long as this slip is not very high let us call this as starting slip. I will call this as slip at starting this should be equal to whatever is my N s minimum. Let me do my slip at start is going to be this f minimum corresponds to certain N s minimum. This N s minimum and what is N is now 0 and I can give come up with whatever is my N s minimum. So, here I am the slip as such as high if you look at the slip frequency here the difference is. So, you look at this let us say this is the rated operating condition and this is your synchronous speed now. So, this is the difference between what you would call as the rotor speed and the synchronous speed.

At start if you keep your speed such that the synchronous speed at start and the 0, I mean the rotor speed is 0, if you keep the difference between the 2 are just the synchronous speed at start to be lower than are comparable to that of this difference, that is the rated synchronous speed and the rated speed then you are okay. You are going to have a slip frequency which is much small and your machine is not going to see a large amount of current. So, what we are basically trying to do this, we are trying to if you want a smooth start we come to this waveform as I have indicated here we come to this kind of a torque-speed characteristic.

So, the starting torque is now fairly high and that could be closed to the rated torque and once the machine picks up speed you can gradually go on increasing the frequency, so that the torque-speed characteristic also keep shifting to the right and you can eventually move to wherever you want to move towards the end. So, thus you are able to control now. So, what are you doing now? You are controlling the speed. It is not an induction motor. An induction motor is now an induction motor drive why, because it is a controlled induction motor. What is being controlled? Its amplitude and frequency of the applied voltage are being controlled using a voltage source inverter.

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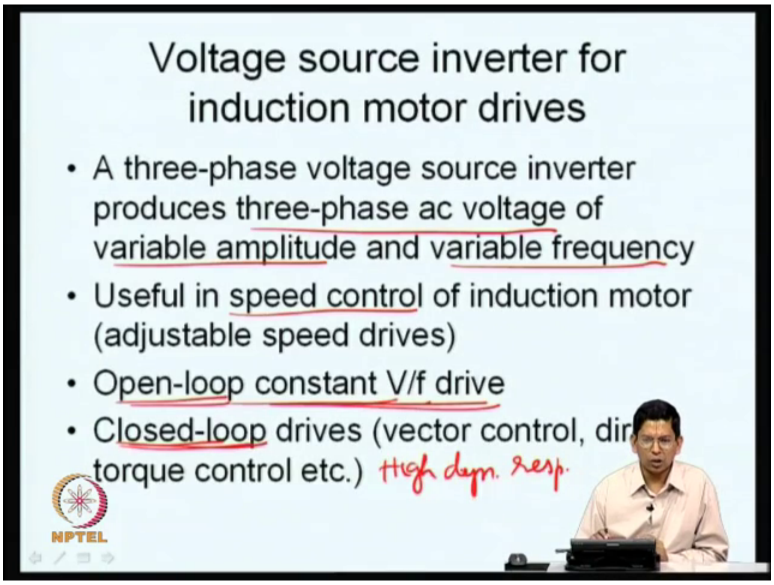

So, if you when we want a voltage source inverter for induction motor drives. Why do you want? Because, an inverter can produce three-phase AC voltage of variable amplitude and variable frequency; of course, there is an upper limit on the amplitude up to which you can do that and again there is a variable frequency and this frequency has to be also substantially lower than the switching frequency of the inverter now.

So, since you are capable of doing this, an inverter can be used for speed of induction motor and such things are called as adjustable speed drives or variable speed drives. The most commonly used one is a open-loop constant V by f drive. That is what we discussed tell some time back. So, we discussed V by f drive. So, we change the voltage, we change the frequency, we change the frequency to depending on the speed at which we want to operate and the voltage is always maintained proportional to the frequency so that, the flux is more or less maintained constant.

Here, you can also operate it at slightly higher speeds if you want, but beyond the rated voltage you cannot apply a voltage beyond the rated voltage because of insulation. There is a limit there. So, what you need to do is, if you go to frequencies higher than this, you have to apply it at a lower voltage. V by f ratio reduces. So, that is actually called flux weakening now. This course is not so much on the extensive control of induction motor. There are courses on motor drives again on NPTEL which will give you a thorough understanding of this various aspects of controlling this. So, it is also possible that you can do it in the there is something called a super synchronous operation and there is breaking and such things can all you can get a detailed idea about other I mean of this induction motor drive operation in other courses in this NPTEL forum now.

So, what we have also dealt with this basically is open-loop constant V by f drive. This is what we will be dealing with primarily in this course now, but there are also closed-loop drives this open loop V by f drive is ok, when you do not need a very good dynamic performance, in steady state performance is alright. When you want to change from one operating point to another operating point it is going to take considerable length of time. So, for high dynamic performance you will go for closed-loop drives this is for when you require a high dynamic response, very fast dynamic response you go for closed-loop dive.

This closed-loop drives are various things like vector control and torque control I mean director control etcetera and all. Vector control is also called as field oriented control etcetera. What we try doing essentially is, you see that the same you know it is just a single three-phase voltage is being applied and three-phase currents are being drawn. In the case of a DC machine, you have a separate field winding and an armature winding. So, field winding is current is controlled separately an armature current is controlled separately whereas, in the case of an induction motor both the torque component and the flux producing component of the currents are drawn from the same source. What we tried doing is appropriately by modelling it is possible for us to determine what is the torque producing component and what is the flux producing component.

We can control these 2 in a fairly independent fashion. It is possible for us to change only the torque producing component of the current without changing the flux producing component of the current. That is what in essence is vector control. In a DC motor drive you can leave the field current unchanged and you can only change the armature voltage and change the armature current. So, you can just change the torque without changing flux. So, similarly in an induction motor also it is possible that you do not change the flux producing component of the current and change only the torque producing component of the current. That is what you do in field oriented control or vector control.

As I said before there are other courses available on NPTEL which can give you a very good exposition on vector control of induction motors and I would ask you to go through such kind of courses to get a good understanding of closed-loop things and direct r control is yet another variety of closed-loop operation of this thing and various closed loop control for not only for induction motor, but other variants. This is what we have been looking at is a squirrel cage motor, for slippering induction motor and a synchronous machine and permanent magnet motors and varied kinds of motors you have a drive I mean operation is possible and all these control of such various drives are dealt with in various other courses now.

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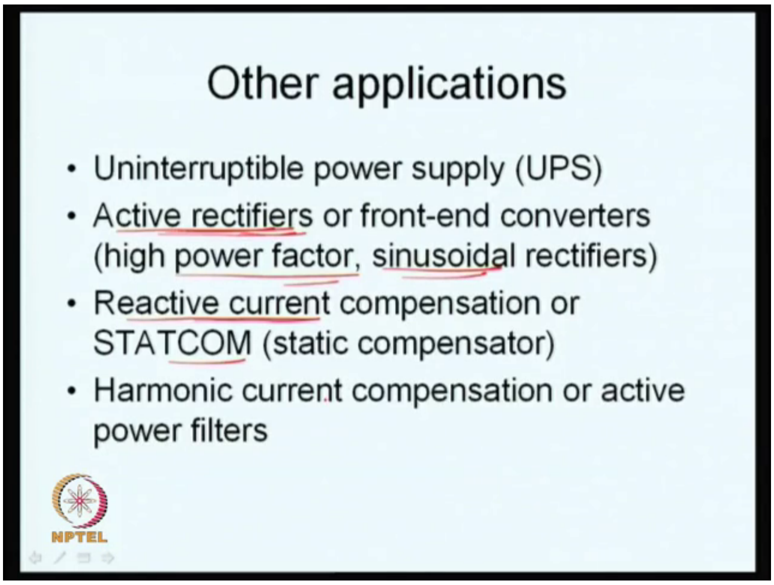

So, here today we have primarily looked at the voltage source inverter feeding and induction motor that is what we have looked at. The other applications as I mentioned before is an uninterruptible power supply and again as you are already aware that it is basically it has a battery, you need an inverter which will invert and provide power to AC loads whenever the mains are off. So, it basically has that an uninterruptible power supply.

About this active rectifier we just add a brief discussion at the beginning and in the next lecture we will have a fairly detailed discussion on this active rectifier. So, where rectification is done, DC to AC conversion is done. But unlike a diode bridge rectifier an active rectifier draws near sinusoidal currents and draws these currents at a fairly high power factor, something close to unity. Again, as I mentioned before a voltage source converter can be used to compensate reactive current.

If other loads are drawing a lot of reactive current you can have a voltage source converter that supplies the part of this reactive current or most of this reactive current and that is what is called as a STATCOM or a static compensator and once again if you have non-linear loads which may be drawing harmonic currents it is possible for you to supply these harmonic currents using a voltage source convertor. So, that is what is called as harmonic current compensation or active power filtering.

So, these are some applications namely like active rectifiers and reactive current compensation and harmonic current compensation. These are some issues and applications of voltage source converters which we will discuss in our next lecture. So, I thank you very much for your patience and your interest. And I hope you found this lecture useful and I look forward to see you again in the next lecture.

Thank you very much.