Power Electronics
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Lecture 19
Voltage Source Inverters

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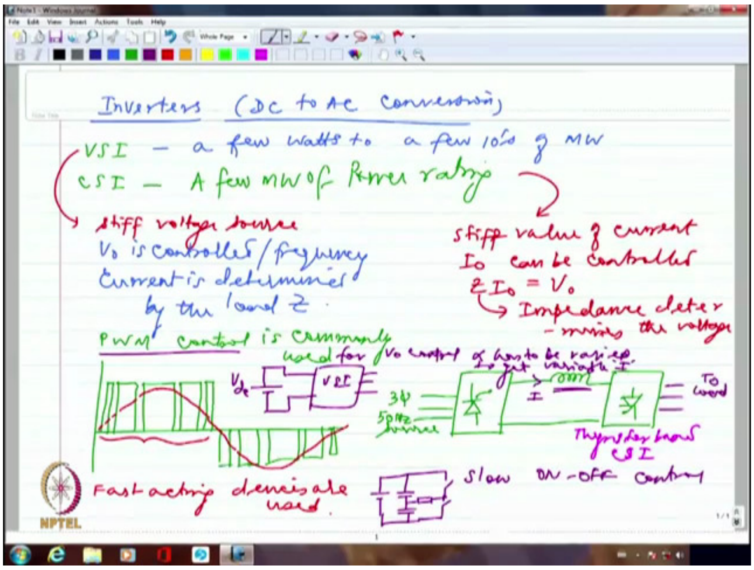

we were supposed to start on inverters the other day. Which are meant for DC to AC conversion. So, DC to AC version is normally done with the help of inverter, it can be DC to single phase AC or it can be DC to 3 phase AC. As I told you the other day there are two types of inverters VSI and CSI. Current source inverter and voltage source inverter.

And voltage source inverters are normally going to be appearing everywhere. Current source inverters are generally rare. We do not use them very commonly. They are used only in 10's of megawatt or at least a few megawatt power rate. Not really at lower levels. Whereas, VSI's are used right from a few watts to a few 10's of megawatt. Whereas, if we want to go for 100's of megawatt generally VSI's are not very good because VSI's generally are switched very fast.

Let me write the characteristics, basically these are going to be having a stiff voltage source which is connected to their DC link. So, what I control basically is the way I switched in and switch out the devices because of which the output voltage is controlled. The current is determined by the load that has connected so output voltage is controlled V_o is controlled by switching on and switching out the devices and frequency is controlled, both are controlled.

But the current is determined by the load impedance I should say, Whereas, if I try to look at the voltage source inverter, the current source inverter rather in the current source I am going to have fairly, I would not say exactly, but stiff value of current which means it is a steady value of current. So stiff value of current this is what we are going to have as the input which is a DC current.

So obviously I cannot vary the direction of current on the source side. I am going to have a large inductance which is going to almost maintain the current direction and magnitude both as constants. So, I will not be able to reverse the direction of current in this particular case. And if I try to look at the output I_0 can be controlled, but what is the voltage that will be $Z\ I_0 = V_o$. So, I am going to have impedance determining what is the voltage.

That is not going to be controllable as far as I am concerned. With the help of switching I cannot control it. And because we are normally going to operate the voltage source inverters at pulse width modulated control, PWM control, we just introduced in the last class. I just introduced the terminology. So, pulse width modulation is width of the pulse is modulated.

I can have complete 180 degree as positive pulse, 180 degree as negative pulse which is no control. If I try to introduce only about 90 degree is positive pulse, 90 degree is negative pulse rest of the times it is all dead. The circuit is dead then I am essentially modulating the pulse. So generally, pulse width modulation is very commonly used in this particular case which means I may have multiple pulses.

That is, I can think of, in the positive half cycle, I may have a wide pulse in the middle. I may a have little smaller pulse, then I may have very thin pulse and again I may have somewhat wider pulse and very thin pulse, like this. Similarly, I can make the negative half. I can have a thin pulse, little wider pulse, wide pulse, then something like this. So, this is essentially almost emulating I am not saying exactly, almost emulating a sinusoid. So, if I try to look at what is the kind of value I am going to get? I will probably get a value somewhat like this. This is how it will be.

So I can say the width of the pulse is modulated as per the amplitude of the sine wave that I want to get at any instant, this is generally known as sinusoidal pulse width modulation. Wherever, I want to modulate the pulses as per the sine wave amplitude. Wherever the amplitude is maximum I want to have maximum width of the pulse. Wherever the amplitude of the sine wave is minimum I want to have the minimum width of the pulse. So, this is generally known as sinusoidal pulse width modulation which is very commonly employed in inverters.

But this kind of control will really require multiple number of switching's to be done in 180 degree interval itself which means within 20 millisecond I may have 10 or 20 switching's or even more which means very fast acting devices have to be used. Here fast acting devices are used which means I will need basically IGBT or MOSFET or any other controllable device that can be used in this particular circuit.

Whereas, if I try to look at CSI, normally CSI will have the front end converter to be a controlled rectifier what we discussed all along initially. And this is connected to a say 3 phase 50 hertz source. Now the controlled rectifier output is connected through a large inductance to the CSI and CSI also may be made up of thyristors in all probability. So, I will have to essentially operate if it is thyristor based CSI. I am talking about here thyristor based CSI which means I have to operate it slowly because thyristors definitely take a little longer as compared to MOSFET or IGBT on IGBT I remove the pulse it will go off.

Whereas thyristor I remove the pulse it will not go off, I have to definitely have an external circuit, commutation circuit to make sure that it goes off. But the major advantage is thyristor will be able to handle single-handedly 30 megawatts and so on and so forth. Whereas, if I use IGBT or MOSFET they can handle very-very small power capacity as compared to what the thyristor can handle.

So generally, CSI's go hand-in-hand with thyristors and because it is thyristors it will not be fast acting, it will be slow on of control. I will not be able to really make it operate at a very very high frequency, so PWM is not very commonly employed in CSI, whereas VSI always employs PWM pulse width modulation because it can act fast that will act like a source for modifying the amount of voltage.

Here I cannot modify the voltage current that is coming out, if I want to control the current only way I can control is the controlled rectifier. So invariably I will modify the source itself. Whereas here, I will not modify the source because if you look at the normal VSI circuit it will have a battery or a steady DC voltage that is coming out of a rectifier with the capacitor filter. There will be a big capacitor filter. Thousands of microfarads.

So, what I have is a fixed value of DC and this will be going out to the VSI and VSI output is going to the load if am talking about 3 phase VSI. Similarly, here, this is the CSI and this will be going to the load. So hardly ever we use PWM control here, whereas we use all the time, 99. 9 percent of the times we will be using PWM control. The PWM control essentially allows me to modify, if I just reduce the width of this pulse, reduce this further, reduce this further obviously am going to get less and less amount of RMS value of voltage.

So I would be able to adjust the pulse width to get variable voltage. Whereas here, if I want variable current, generally I adjust the α, firing angle α of the input side converter. So, this α has to be varied to get variable I, whatever is the current I am talking about. Whereas here, PWM control is commonly used for output voltage (V_o) control.

The last but not the least, one more major difference is because I have VSI always connected along with the capacitor, if you may recall the circuit, we had something like this. This was the DC and I was showing as though there were 2 capacitors is in series and I told you that there will be 2 switches like this and then I am going to connect a load like this. This is what we showed as half bridge VSI.

By chance if I turn on both these together, I will have a dead short-circuit which is deadly. We call it as shoot through. Shoot through is deadly in the case of the VSI. Whereas in CSI because there is a large inductance sitting here, it will not allow rise of current in a big way, in a very short span of time. The impedance that is sitting in between the rectifier and the inverter that is going to make sure that the current does not rise right away.

So, you have enough time for the protection to act. If there is a protection circuit, it will be able to act quite well. So, CSI's need not be protected against shoot through or short-circuit. Whereas, VSI's have to be protected against shoot through because VSI's do not have any current limiting component, whereas CSI's have a current limiting component sitting right up front which is actually our inductance or impedance I would say because the inductance will definitely have some inherent resistance as well.

So, most of our discussion will be centering around VSI initially maybe 1 lecture I will devote to CSI finally, Most of our things will be centered around VSI because VSI has plenty of applications, whereas CSI has mainly couple of applications. One application typically is high-power drives, synchronous motor drive, induction motor drive whichever of 10's of megawatt rating they are normally controlled with the help of a CSI that is one of the applications.

The second application is only HVDC transmission system, High Voltage DC transmission system. These are the major two application of CSI if I drive. One is the drive itself. So, CSI basically is applied into things one is CSI if I drive itself large capacity motors, the second one is HVDC transmission system, High Voltage DC transmission system. These are the major two applications of CSI.

Whereas you name any other application it is all VSI. You talk about home inverter, you talk about microwave oven, you talk about CFL that is compact fluorescent lamps. You talk about induction furnace, induction heating anything all of them are generally VSI's not CSI's.

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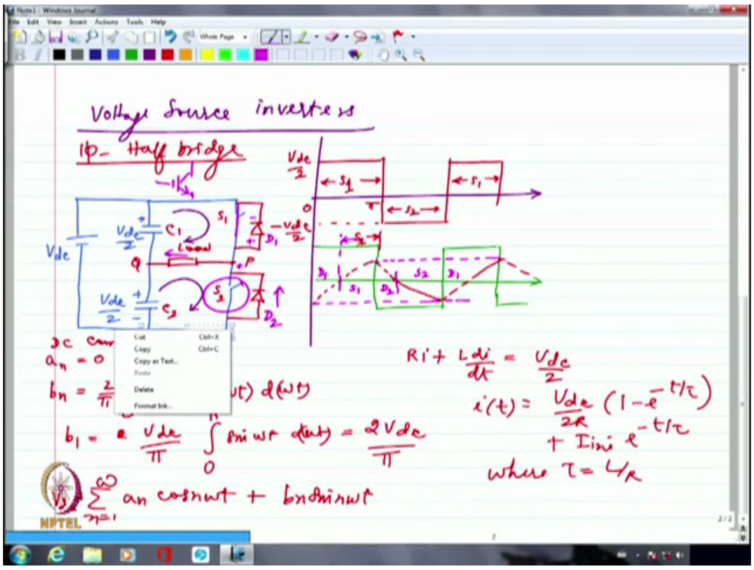

Now let us now go into VSI, voltage source inverters. So voltage source inverter let us start with first of all single phase half bridge. We had seen this already in the form of a half bridge DC DC converter, only thing is the rectifier portion has to be eliminated, that is all is the difference. So we will have one voltage source which is V_{dc}. We are going to have normally two capacitors dividing the voltage equally.

So this is plus minus, this is plus minus, say this is $\frac{V_{dc}}{2}$, this is also $\frac{V_{dc}}{2}$.Now this has one switch here and one more switch here and we are going to have a load here connected between these 2. So let me call this as C_1, this as C_2, let me call this as S_1, this as S_2 and the load is let us say connected between let us say P and Q. So, when we turn S_1 on I am going to have essentially the current going like this through the load, through S_1 .

Whereas, if I turned S_1 off and then I turn S_2 on I am going to have a current flowing like this. So obviously in the in the load the current is always alternating depending upon at what frequency I turn on and turn off S_1 and S_2 respectively and we will do it with respect to half phase symmetry. We do not want positive half to dominate over the negative half or vice versa. We do not want to have any DC component because what we anticipate is that the load should get a pure AC as much as possible, I am not talking about sinusoidal AC as such.

It is pure AC, so I do not want any DC component which means the positive half and negative half exactly have to be the same or equal to each other. So if I am looking at actually the waveform, when I am going to turn S_1 on maybe I am going to have a voltage like this which is actually $\frac{V_{dc}}{2}$. A positive voltage is going to be $+\frac{V_{dc}}{2}$ and similarly, when I am having, so this is S_1 on, S_1 is on during this particular interval and I am going to have S_2 on for the next 180 degrees, again S_1 on for the next 180 degrees and so on and so forth.

And if I look at the current if it is resistance load then the current would be exactly the same as voltage. So, I should be able to get what is the value of the fundamental voltage under this condition.

If I want the fundamental voltage, I can say that a_n=0 because this is all co-sinusoidal component half wave symmetry is there, if I try to do the Fourier expansion. The DC value will also be 0, I will not have any DC or average value. So, I should say DC component is 0 and a_n =0. So b_n, I should be able to calculate as $\frac{2}{\pi}$, 0 to π because even if I integrate from 0 to π it is the same this is -$\frac{V_{dc}}{2}$.

So,

$$b_n = \frac{2}{\pi}\int_0^{\pi} \frac{V_{dc}}{2} \sin(n\omega t)\, d(\omega t).$$

So, if I want to get the fundamental which is b_1 I should be able to write this as,

$$b_1 = \frac{V_{dc}}{\pi}\int_0^{\pi} \sin \omega t d(\omega t) = \frac{2V_{dc}}{\pi}$$

If I write the entire Fourier expansion as whatever is the DC component?

$$V_s = \sum_{n=1}^{\infty} a_n \cos n\omega t + b_n \sin n\omega t$$

So, this is actually the peak of the fundamental. What we get here is the peak of the fundamental. So, if I want RMS I have to divide this $\sqrt{2}$ because I am looking at the fundamental wave as a sinusoidal component. So, I should be able to divide this by $\sqrt{2}$ to get whatever is my fundamental RMS value.

Now, if the current is analyzed it will be the same if I am talking about resistive load, but if am going to have inductive load, let us try to take a look at the current what is going to happen. So, I said that this is the voltage let me redraw the voltage, so that we just superimpose the current on this itself, so this is going to be the voltage. If I want the current, the current should actually increase as long as I am having a positive excitation and it should start decreasing as long as I have the negative excitation.

So, I will have essentially the current increasing say somewhat like this maybe from a negative value it will start increasing and then it will again start decreasing, again increasing, decreasing and so on. This is the way I am going to have my current. Because this will essentially follow

$$Ri + L\frac{di}{dt} = \frac{V_{dc}}{2}$$

Assuming that the capacitances are retaining the same $\frac{V_{dc}}{2}$ all the time. Assuming that the capacitance is really of a large value then I should be able to maintain the voltage somewhat constant. Although in actuality you will see a small amount of difference in the voltages. It will be coming on and off although we are actually taking out the energy from this capacitor whatever is the energy taken out of this capacitor equal to the energy that is fed by this capacitor as well because we are keeping them on for 50 percent each duration for a complete cycle.

So, this will be my expression,

$$i(t) = \frac{V_{dc}}{2R}\left(1 - e^{-t/\tau}\right) + I_{ini}e^{-t/\tau}$$

That will be the expression for the current normally like a first order differential equation solution, where $\tau = \frac{L}{R}$.Now please note I am not going to keep the switch S_1 on beyond this point. So S_1 turns off at this point. S_1 is off, Where the arrow ends, I am going to have essentially S_1 turning off at that point which means I have to provide an alternate path for this positive current to flow. Otherwise you are going to have a huge $L\frac{di}{dt}$ that is coming into picture. So normally what we do is, to have a diode which is known as the feedback diode.

We will always have a diode connected in parallel with a transistor or IGBT or FET. So, if the current is flowing in this direction I want the current to flow in the same direction. Only thing that can carry the current in the same direction is this diode, not that other diode. So until now C_1 was discharging, now C_2 will get charged, so there is a good possibility for C_2 voltage to rise. Already it was not discharging, now it is also taking up the energy from the inductive load because of which you can have a slight rise in the capacitor voltage, and this is what is the major root cause.

Initially C_1 was discharging, now C_2 is getting charged, so that can be little difference in the voltage between C_1 and C_2, ideally we do not want this difference, but it is kind of not very easy to eliminate the difference completely. There are several control techniques we adopt to make sure that the two voltages are balanced as much as possible. So normally what you are going to do is, to allow another alternate path for the current where D_2 is going to take over.

So, if you actually look at it during this interval D_2 will take over. And from here to here although you had tried to turn on S_1 right from the beginning, but S_1 will turn on only from here where the current is in the positive direction. You may give the pulses even before that, but S1 will not be able to turn on until D_1 is conducting. D_1 will be conducting during this portion.

So, when D_1 is conducting there is no way S_1 can turn on. Please note that S_1 will be reversed biased when D_1 is conducting. Because when D_1 is conducting I am going to have positive here and negative here and a switch that you connect here will be in this direction, this is how it will be. So, you want basically V_{ce} to be positive that will not happen when the diode is conducting.

So D_1 will be conducting for this duration and S_1 will be conducting for this duration. D_2 will be conducting here, S_2 will be conducting here, again D_1 will be conducting here and so on and so forth. So, the steady state here corresponds to the minimum currents remaining at the same value cycle after cycle. Similarly, maximum currents remaining at the same value cycle after cycle, rather half cycle after half cycle.

So, you are going to have this value to remain the same and this value will be remaining the same. I minimum and I maximum will remain the same cycle after cycle, that is what you would see, that is what is known as steady state. There is nothing like a normal DC current which is going to assume a fixed value that is not going to happen. So this particular circuit consist of only two switches and two diodes and although your input supply is V_{dc} what you get as the output is only $\frac{V_{dc}}{2}$ and when you are having $\frac{V_{dc}}{2}$ actually being delivered.

If this switch is a short for example, please note that this positive is connected here. When this switch is not conducting you are going to have this positive connected here directly and this is negative here which means V_{dc} will come across the non-conducting switch that is twice the voltage of what it can deliver. So, half bridge normally each of the devices will face the stress corresponding to the twice the voltage of whatever it could deliver as output.

So you are going to see that if it is delivering $\frac{V_{dc}}{2}$, V_{dc} will be the voltage stress or voltage that it has to block whenever it is in off condition. This is one of the problems of half bridge because if I am talking about kilo volts level of an inverter, I do not want really to increase the cost of those devices by simply having the rating to be increased twice as compared to what it can deliver.

So, half bridge is generally used only when I actually I am going to use it for smaller rating not for very large rating. Normally larger rating we hardly ever use half bridge. We will only use full bridge in that case.

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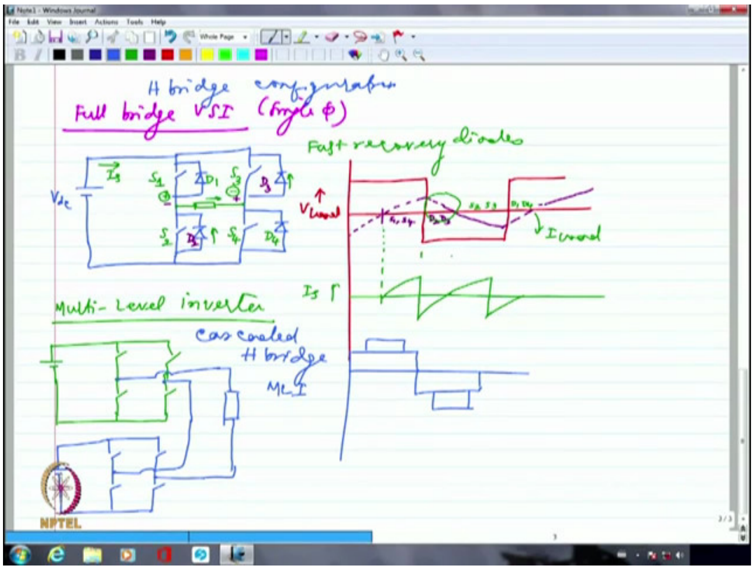

So, let us try to take a look at Full Bridge VSI. Again, we are talking about single phase. So, we are looking at a DC voltage source and then I am going to have 4 switches which is similar to that of whatever we studied in full bridge DC to DC converter, it is exactly similar and there will be feedback diodes in this cases also. These diodes are known as feedback diodes because they feedback the energy stored in the load inductance, so these are feedback diodes.

So each of them is going to be connected to a feedback diode in anti-parallel. And please note that these diodes have to be fast acting. They cannot be power frequency diodes. We talked about 2 or 3 different types of diodes, you remember. We talked about power frequency diode, we talked about fast recovery diode and Schottky diode. So fast recovery diodes have to be used in this case because they have to essentially work very quickly.

So, unless they act very quickly it is going to be difficult especially if I am using in PWM. So that is the reason why what we use will be normally fast recovery diodes. So, the load is going to be connected here. So I can name this as S_1, S_3, S_2 and S_4. Now if I am looking at positive half cycle which is actually going to make the current flow in this direction S_1 and S_4 have to be turned on.

And after S_1 and S_4 are turned off if I want the current to flow in the same direction. I want the current to flow in the same direction means I am going to have this these two diodes. This diode and this diode conducting with the current direction being the same, but please note it is feeding back the energy to the battery. So, the battery will get charge it is like regeneration.

So, we are going to have the current flowing in the same direction with the diodes feeding back the stored energy of the inductance, load inductance back to the battery. So, let us again try to draw the waveform for. So, let us say this is the positive half cycle and this is going to be the negative half cycle and again positive half cycle and so on. So, let us say this is V_{load}

Now if I am looking at the current maybe it is starting from some negative value and then it is reaching the maximum value like this and again it is going to be something like this and so on and so forth, this is how the current is going to be. So, during this particular duration I am going to have actually, during this duration I am going to have S_1 and S_4 both conducting. That is why the current is also positive and voltage is also positive which means the power is flowing from the DC side into the AC side, the power is positive.

It is being consumed by the load when voltage as well as current are positive, it is going to be consumed by the load. That is why the current is increasing. Now during this portion, I am going to have the current flowing, let me try to name these things, this is D_3 and this is D_2. So, I am going to have D_2 and D_3 conducting during this portion. So, the voltage is going to become negative because I am having essentially the positive being connected through the diode here and negative being connected through the diodes here.

So, voltage has reversed its direction. Originally when I looked at the voltage S_1 was connecting positive here and S_4 was connecting the negative here. Whatever I have mentioned in Green is when I had S_1 and S_4 conducting. Once they have gone off, I am going to have D_2 and D_3 taking over which is going to have a negative voltage. And similarly am going to have S_2 and S3 conducting here and I am going to have D_1 and D_4 conducting here, if I may call this as D_1 and this as D_4 So D_1 and D_4 are going to conduct here.

If I try to look at what is the kind of current, I am going to see from the source side, so this is load current and this is load voltage. So, what is the kind of supply-side current that is going to come up? So, when I am looking at S_1 and S_4 conducting. I am going to have essentially the current going like this, this is how it is going to be. Whatever is S_1 and S_4 current it is going from the supply towards the load.

Whereas, when I am looking at this current, this portion of the current that is essentially flowing from the load into the supply. So, it is in the opposite sense. So, I have to show it as though this is essentially coming until here maybe somewhat like this. And again when S_2 and S_3 are conducting I am going to have the current essentially going like this. And again I am going to have the current being fed back to the supply whenever I have the diodes conducting. So, this will be the supply current.

So, this is essentially, if I call this as I_s. I_s waveform is going to be somewhat like this, I hope you get this. Whenever I am going to have the devices conducting, I am having the power flowing from V_{dc} to the load. So, it is in positive direction, the current is in the positive direction and whenever the diodes are conducting it is actually flowing back from the load to the supply itself. It is trying to replenish the battery.

So, this is going to be the kind of supply current that we are going to have. So, battery is getting charged and discharged alternately in this particular case when am going to have RL load. And if I try to look at any of the devices what it has to block, it will be blocking V_{dc} itself, you can analyze and you can definitely find out that in full bridge converter they are not going to be rated for more than V_{dc} that is away normally our full-fledged VSI works.

So full bridge VSI is normally employed in a larger power rated circuits. They are very commonly used in many of the larger power rated circuits. But sometimes if I am going to have 20 kilovolt or 30 kilovolts as the overall voltage rating of my circuit, it might be sometimes difficult to just employ a pair of devices. So, you might have to employ many of them in series.

Rather than that we sometimes employ something called multi-level inverter. I am just introducing the terminology I am not going to go in-depth into this because this is being researched extensively now. So, I thought at least I should introduce you to what is a multi-level inverter. So, in multi-level inverter, let us say I have one inverter here. So, this is one inverter, I can have one more inverter like this.

So, if each of them is producing let us say 250 volts approximately by connecting them in series I would be able to produce 500 volts. I would be able to definitely produce larger amount of voltage and I can also control each of them such that maybe rather than getting a complete square voltage if one of them is conducting for a longer duration and the other one I make it conduct only for a shorter duration.

I can make it closer to a sinusoid, I can have multiple number of steps like this, I can make basically a stepped voltage waveform which will be emulating somewhat a sinusoid. I am not saying this is exactly a sinusoid, but I would be able to get closer and closer to the sinusoid provided I have multiple levels of voltage source inverters like this. So now what I can do is, this is one end of the load terminal, so let me take that out and from here I can connect it to this and from here I can connect to the load.

So here I can connect my load. I am essentially connecting the two outputs in series, you imagine whatever we did in auto transformer, something similar. What we are doing is essentially connecting one end of the load here, the other end of the load here and in between we are connecting them in series, that is it.

So, this will allow me to get twice the voltage of whatever is the voltage that I am applying here and here. But please note I have drawn two independent voltage sources I can connect them also together. Either I need to provide isolation on this side between the 2 voltage outputs or I need to provide isolation on the input side either on the input or on the output I need to provide isolation otherwise it will be a dead shot.

So, this is typically used whenever, for example solar water pumping system where I may have each of the solar cells having very small value of output, I can connect two solar cells independently to the 2 inverters connect them in series and together I can give it to a motor that is a possibility. So, if I have multiple number of this, then I call them as cascaded H bridge.

Each of these full bridge inverters is generally called also as H bridge configuration, so we call this as cascaded H bridge multilevel inverter. So, each of them can function independently as a single phase inverter, no doubt. So, the major advantage I can visualize in this case is, if I have 5 such inverters connected in series, one of them conk out I need to essentially have in the inventory multiple number of the single phase inverter, remove the faulty inverter, put the good inverter, you can do that.

So, it is like parallel operation of transformer what we talked about earlier in electro mechanics course, we said that rather than using 20 KVA transformer directly you can use 210 KVA transformer in parallel. So, what backup restore is only 10 KVA not 20 KVA. So that way it also reduces the rating of the backup that is one of the major advantages we have in this cascaded H bridge multilevel inverter topology.

One more thing is that each of the switches need to be waited only for V_{dc}, not to V_{dc}, each of these switches need to be rated only for V_{dc} there is nothing like you have to rate them for higher voltage. So that way it becomes much more comfortable to construct smaller units and then put them together. So, this is a very upcoming area which is being researched extensively, multilevel inverters.

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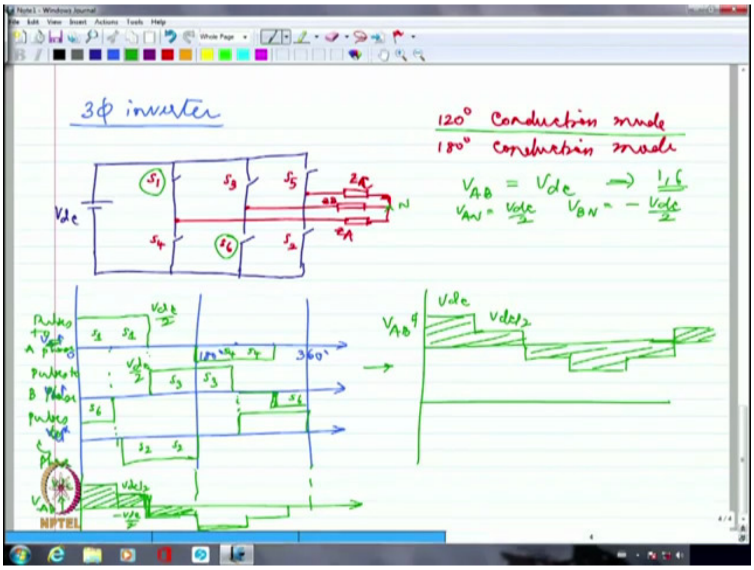

Now, let me just go over to the 3 phase inverter. After discussing all of them in square wave, then we will go for directly discussing them with different PWM techniques. So, three-phase inverters normally are actually constructed in half bridge fashion. That is, I will not have four devices instead I will have only two devices for every phase. So typically, I am going to have something like this.

This is my V_{dc}, so I am going to have one switch, another switch this is belonging to A phase. I am going to have one more switch and one more switch this belongs to B phase, then the third leg which belongs to C phase and numbering we will do very similar to what we had done for the rectifier. So I will call this as S_1, this as S_4, this as S_3, this is S_5, S_6 and S_2 of course each of them will have diodes as well in parallel. They will have diodes as well in parallel, no doubt.

And we are going to connect from here the 3 loads, and I am going to take star connected load for now. I am going to leave the delta connected load to be analyzed by you guys. You guys would do it, okay. So, I am going to do it for star connected load. So, this is one load, this is the second load and this is the third load. So let me call this as Z_C, Z_B and Z_A because S_1 and S_4 I want to take it for A phase.

There are two modes of conduction normally we analyze in a square wave inverter for three-phase case. Each of the devices can conduct for 120 degree or each of the devices can conduct for 180 degree, either way is fine. So, we call one of them as 120 degree conduction mode, the other one as 180 degree conduction mode. These are the two types of conduction which we would be analyzing.

So, let us say we are talking about 120 degree conduction mode to start with. So, first of all let me draw the A phase, B phase and C phase voltages. Then we have to draw the line to line voltages as well because we would like to definitely know how the line voltages are always the load may not be star connected, but never the less we should analyze for both star as well as Delta configuration because the loads could be connected in either way but in either case we should know what is the phase voltage as well as line voltages,

So, if this is the way it is and let us say I am going to have probably, let me call this as the 180 degree point this is 360, so this is 0, this is 180 degree, this is 360 degrees. And then I am also drawing 60 degree intervals like this. So, I am going to have in all probability let us say 1 is going to conduct for some time, like this. So, if 1 is conducting like this and we are talking about 120 degree conduction.

So obviously 3 has to start conducting from here from here until this point, this is how it will be and I am going to have 5 conducting from this point until here. They are all 120 degrees shifted from each other. This is how it is going to be. So, when I am having 120 degree conduction mode I will have in all probability 1 and 6 overlapping with each other. I definitely need an overlap otherwise I am not going to have the return path for the current.

So I will have essentially the current going from S_1 through Z_A and returning through Z_B through S_6 back to the negative side. So what I get as the voltage overall, what I get will be essentially V_{dc} across whatever is my 1 and 6, so that is V_{AB}, that is going to be V_{dc} value itself. So I am essentially going to have this, let us say along with this, so this is S_1, so along with this I have to have S_6 conducting.

Clearly I have to have S_6 conducting and under this condition, so if S_6 is conducting here, S_6 must have conducted here also for 60 degrees clearly and I should have a 60 degree dead band here like what we had in the case of rectifier without commutation overlap. I am essentially drawing the pulses rather than drawing V_a, V_b, V_c I should say first of all I am drawing the pulses.

So when I draw the pulses I am essentially going to have the pulses that are delivered to any of the devices somewhat like this. So when S_1 is conducting, it is this way, this is S_3 and along with S_3 initially S_2 will be conducting, so I should show from here I will have S_2 conducting for two 60 degrees duration. And then I am going to have for these two also this is S_6, S_4 I am here to draw S_4.

So, from here it will start, and it will go through this. This is going to be S_4. So, when I am having the pulses, so this is pulses to A, pulses to A phase devices and this is pulses to B phase devices and this is pulses to C phase. So, if I try to look at actually what is the value of the voltage during this particular time? With respect to neutral I have to see what the voltage across each of the loads is. That is what will give me exactly whatever is the phase voltage of the load.

We are looking at the phase voltage of the load. So, if I am looking at the phase voltage of the load when S_1 is conducting I am going to have S_1 and S_6 are conducting, I am going to have $V_{AB} = V_{dc}$ when 1 and 6 are conducting. So I am going to have $V_{AN} = \frac{V_{dc}}{2}, V_{BN} = -\frac{V_{dc}}{2}$ because I am assuming that it is all balanced load, completely balanced load that is how it is going to be.

So I should be able to say that whatever are the pulses I have got exactly they are the magnitude of voltage is also across the load phase, but only thing is, each of it is $\frac{V_{dc}}{2}$ not V_{dc} itself. It is going to be $\frac{V_{dc}}{2}$. So, I am going to have $\frac{V_{dc}}{2}$. This is also going to be equal to V_{dc} by 2 each of them.

So, whatever I have got I should be able to directly draw them as the phase voltages. How will you get now line to line voltages that is what you have to check. So, we have said V_{AB} = V_{dc}, agreed. But we can also get, what is the line to line voltages by subtracting V_{AN} minus whatever is my V_{BN} directly. So if I have actually, if I want in this particular case this is $\frac{V_{dc}}{2}$ - $\frac{V_{dc}}{2}$, so it is - $\frac{V_{dc}}{2}$. So, this is V_{dc}, so let me write V_{AB} or shall we draw it here itself, so that the timescale is exactly the same.

So V_{AB} is going to be V_{dc} during this portion. What is going to be the next value of voltage? Here I am having 0 volts as V_b, whereas here it is going to be $\frac{V_{dc}}{2}$. So, I will have during this portion I will have $\frac{V_{dc}}{2}$ as the voltage. So, this is V_{dc}, whereas this is $\frac{V_{dc}}{2}$. Please note that this is going to be my line to line voltage. After that I am going to have S_3 which is actually $\frac{V_{dc}}{2}$.

So, this is $\frac{V_{dc}}{2}$, so I am going to have - $\frac{V_{dc}}{2}$ here for another 60 degree duration. So, this is going to be -$\frac{V_{dc}}{2}$. After that I am going to have this and 4 both of them conducting. So, I am going to have -$\frac{V_{dc}}{2}$- $\frac{V_{dc}}{2}$. So that will be - V_{dc}. So, I am going to have voltage like this which is actually V_{dc} then this is going to be just -$\frac{V_{dc}}{2}$ itself.

So, essentially my waveform will be somewhat like this. I am having first V_{dc} , then $\frac{V_{dc}}{2}$, then -$\frac{V_{dc}}{2}$, then V_{dc}, then again this and so on. This is going to repeat itself, so each of them is V_{dc} and $\frac{V_{dc}}{2}$. Please note what we applied was just V_{dc}, but we are essentially getting 2 levels of voltage on the positive side and 2 levels of voltage in the negative side as well as far as the line to line voltage is concerned.

If I look at the line to line voltage it is going to oscillate between $\frac{V_{dc}}{2}$ and V_{dc} every time in the positive side as well as negative side. So similarly, you should be able to draw what is V_{dc} and V_{CA} and so on, all of them will be displaced on each other by 120 degrees at the fundamental frequency. Whatever is my frequency that I have chosen to turn on and turn off.

Now this is for 120 degree conduction mode. What we analyze now was 120 degree conduction mode. So in 120 degree conduction mode what I look at is the load phase voltage that will be having either V_{dc} level, $\frac{V_{dc}}{2}$ level on 0 level we do not have anything in between. Whereas the line to line voltages are going to have 3 levels basically and there is no 0 voltage interval at all in any of the load voltages in the line to line.

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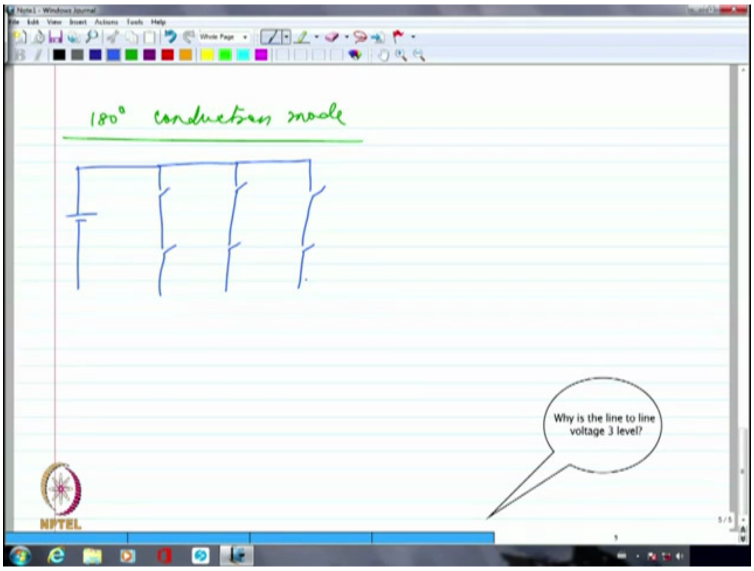

So, if I look at the 180 degree conduction mode. So, let us again take the same inverter.

(Student Professor Discussion starts)

Student: Why is the line to line voltage 3 level?

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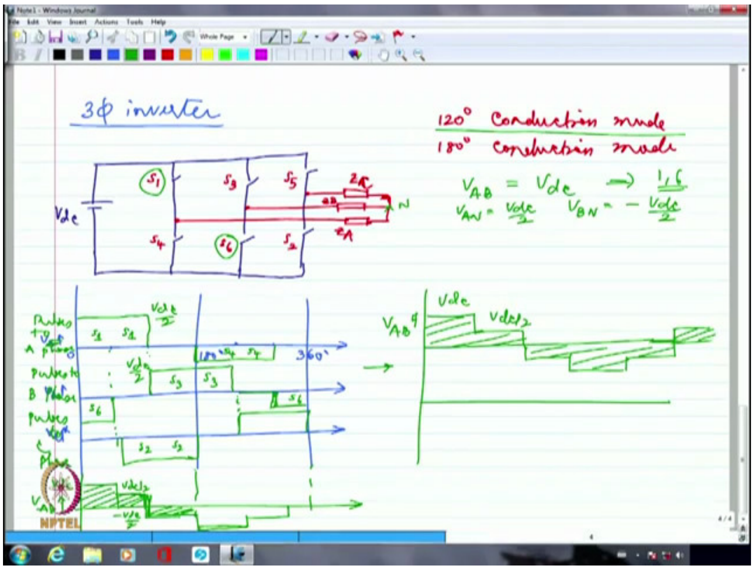

Professor:3 stages are because if I am not having any voltage at all in B. So, whatever is my A phase voltage that is returning through the third phase not through B. It is returning through C phase. So, B phase is not at all involved there is no current through B phase, so B phase is dead. So if I want to look at what is V_{AB} I have to essentially subtract V_{BN} from V_A. V_{BN} is 0. So V_{AN} whatever is the value which is $\frac{V_{dc}}{2}$ that is coming out.

There is no 0, that is what I said there is nothing like a dead band, the complete 0 that is not existing in the line to line voltage in 120 degree conduction mode.

And we are analyzing it with respect to R load because if we involve RL load the complications would multiply because the diodes will get into conduction and it is very difficult to say how long the diode is going to conduct, so you may have the 3 phases involvement all those things will get into picture. So, it is not easy to analyze an inverter with RL load especially in 3 phase, especially in 120 degree conduction mode because we are assuming that the phase should stop right there and it is not going to stop, we know, that is the reason.

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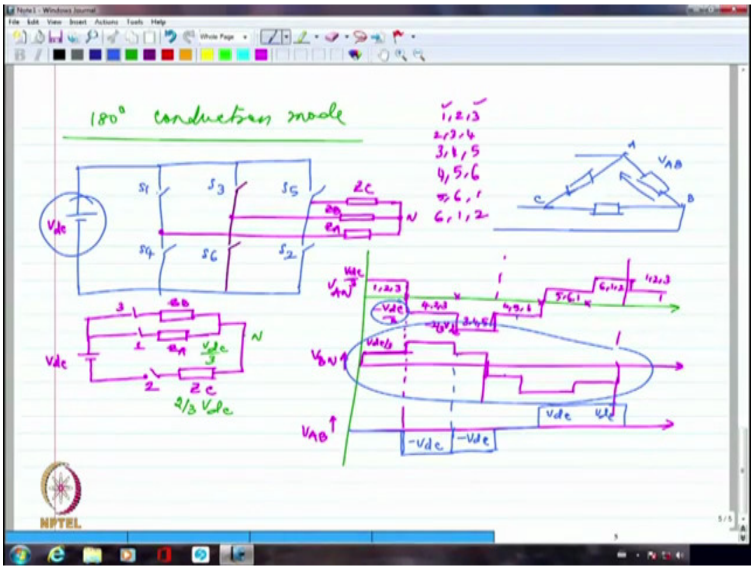

So in 180 degree conduction mode this is S_1, this is S_4, S_3, S_6, S_5 and S_2 and we are going to have A phase, B phase and C phase star connected. Again, I am taking star connected loads. Delta and star normally would be a dual of each other, so please draw the waveform corresponding to Delta, a little later for 120 as well as 180. You would see that the phase voltages and line voltages reverse their rules. Actually, in terms of the shape what you get.

So let us try to take a look at 180 degree conduction mode, so this is Z_C, this is Z_B and this is Z_A and this is the neutral and this is V_{dc}. If each device has to conduct for 180 degrees clearly, I have to have 1, 2, 3 conducting for 60 degrees. 2, 3, 4 conducting for the next 60 degrees. 3, 4, 5 and so on and so forth, so every device will conduct for 60 plus 60 plus 60, 180 degrees.

So, you will have 3 devices overlapping together. So, I am going to have 1, 2, 3. 2, 3, 4. 3, 4, 5. 4, 5, 6. 5, 6, 1. 6, 1, 2 these are going to be the combinations that I will have. So, whenever I am going to have let us say for example 1, 2 and 3. You have to imagine something similar to what we did in commutation overlap. So, 1 and 3 both are on the positive side whereas 2 is on the negative side.

So, I will have it as though this is my V_{dc} what I am applying, and this is 1 and this is 3. So, let us say this is 1 and this is 3 and through 1 I am going to connect Z_A and through 3 I am going to connect Z_B. Now these two are together and from here I am going to have Z_C which is connected to the negative through 2. This is the equivalent circuit that I am going to have for the inverter during 1, 2 and 3 conducting this is how it is going to be.

Please note that these two are in parallel, so obviously whatever is the current that I am going to get that has to be divided into 2 halves. So, the voltage drop that happens here will be half of the voltage drop of this. Together they have to make up for V_{dc}, so obviously this will be 2 /3 V_{dc} that will be 1/3 V_{dc}.So I am going to have the voltage drop here to be 2/3 V_{dc} whereas the voltage drop here to be V_{dc}/3and this is my neutral. That is all you are going to have the voltage drop.

So, if I try to draw what is the voltage waveform corresponding to this particular interval. So, let me probably again divide this into two 180 degrees interval and 60 and 60 and so on. So I am going to have actually V_{dc} let me try to draw what is V_{AN} ?So V_{AN} during this particular duration is going to be + V_{dc}/ 3.

So, it is going to be +V_{dc}/3. After this I am going to have 2, 3, 4 and please note 4 is also corresponding to A phase and 2 and 4 both of them are conducting parallelly. So, they will have - V_{dc}/3 across each of them. So, 2 corresponds to C phase, 4 corresponds to A phase and it will be - V_{dc}/3. So, I should have from here it will jump to -V_{dc}/3.

This is 4 conducting and here it is going to be 1, 2, 3 conducting, so along with 4 it is 2 and 3 they are conducting. Now when 2, 3, 4 the next one is 3, 4, 5 and 4 is the only negative side device conducting. So that will be- 2 /3 V_{dc}. So, I will have - 2 / 3 V_{dc} coming up. So, this is -2 /3 V_{dc} this will be 3, 4, 5. So like this we should be able to definitely infer 4, 5, 6 and so on and so forth.

So, this is going to be 4, 5, 6 then I am going to have 5, 6, 1 then 6, 1, 2 and then 1, 2, 3 again. So you can see again that phase voltage in this particular case has basically + 2 /3 V_{dc} then – 2/3 V_{dc},+V_{dc}/ 3 and -V_{dc}/ 3. So, you have basically for different levels that are coming up in this phase voltage as compared to what we got in the other 120 degree conduction.

So, we should be able to draw similarly, so if this is the way it is as far as (A phase is) V_A is concerned, V_B should be essentially 120 degree shifted. So, this is 120, so I should have something like this I suppose. Something like this I suppose. And then this should be somewhat like this. So, this is V_{BN} . This is V_{BN} . 120 degree shifted beyond whatever is V_{AN} . So, I have just taken this point and have shifted it by 120 degrees, that is all. That is what I have done.

I am sure when you will analyze you will get it this way. It should come this way otherwise we have done something wrong with the analysis. So how will you get now line to line voltage? Let us say this is V_{BN} . So, if I want V_{AB} , let us try to get V_{AB} . So, this is A and this is B. This is also V_{dc}/ 3 and this is also+V_{dc} / 3. So, during this duration I am going to have essentially 0 voltage.

We have 0 voltage. After that I have -2 / 3 V_{dc} and this is +2 / 3 V_{dc}. So – 2/ 3 - 2 / 3, – 4/3 V_{dc} we will get, is it not? I hope this will be -V_{dc}because this is - V_{dc} /3 ,-2 / 3 V_{dc}, this is V_{dc}itself. After this, this is 2 / 3 V_{dc} this is - 2 / 3 $V_{dc}$and this is V_{dc} / 3. So, this is again - V_{dc}. So I will have one more - V_{dc} this interval will also be - V_{dc}.

Then I will have here this value and this value are coinciding with each other, so I will have 0 voltage. I hope so that this will be something like this $+V_{dc}$and $+V_{dc}$. Just by half wave symmetry I am drawing it, that is it. Please note that compared to the previous case this has exactly been opposite, like there the line to line voltage what we got was this three-stepped or 6 stepped waveform.

Whereas this was a square wave, the phase voltage was a square wave, here it is exactly vice versa that is all is the difference. When you analyze delta you have to be little careful there is no neutral, so what you are getting as the voltage across each of the phase loads will also be line voltage, so that will be in all probability equal to V_{dc} itself. So, you have to be a little careful, you get my point I am trying to say that if this load whatever is connected is in delta.

This is 1, this is 2 and this is 3 each of them is going to be connected to the terminals that is the mesh point. So we are going to have let us say this is A, this is B and this is C, so this will be V_{AB} with the voltage rising in this direction. And so on and so forth that is how it is going to be. So this point as well as this point for example will be connected to the DC link. If I am having say one of these switches and one of these switches conduct.

So, I will have essentially V_{dc} directly coming across any of the phase loads. So the phase voltages will come out to be V_{dc}. Every time when the appropriate switches are on, so please make sure that you take the switches correctly and ABC you number in this way like name in this way and then make sure that you draw V_{AB}, V_{BC} and V_{CA} what you are drawing is line to line.

The line to line voltages which are happening to be the phase voltages as well because it is delta. So please draw that and check it out whether you are able to. And for 120 degree as well as 180 degree conduction mode. Please try to draw those and then see what can be the output voltage. Now so far whatever we have seen whether it is three-phase or single phase all of them essentially are having the output as a function of V_{dc}.

Either V_{dc} / 3 or 2 V_{dc}/ 3 or whatever and we do not have any control over the magnitude of any of these voltages because they are keeping the switch on for entire 120 degree or entire 180 degree whatever be the case. So, if I am having a fixed value of DC voltage I will also have a fixed value of output voltage.

Only the frequency I will have control, I will not have any control over the magnitude of output voltage that is one problem. Second problem is, all the waveforms that we have got, all these things are far from being sinusoidal. They are not sinusoidal and if I have to adjust a motor drive to a particular frequency and then I want it to run very exactly at that speed without any torque pulsation and so on and so forth.

I definitely need to make sure that the voltages are somewhat close to sinusoid. I mean not be able to get exact sinusoid, but I may be able to get it close to a sinusoid by eliminating at least some harmonics.

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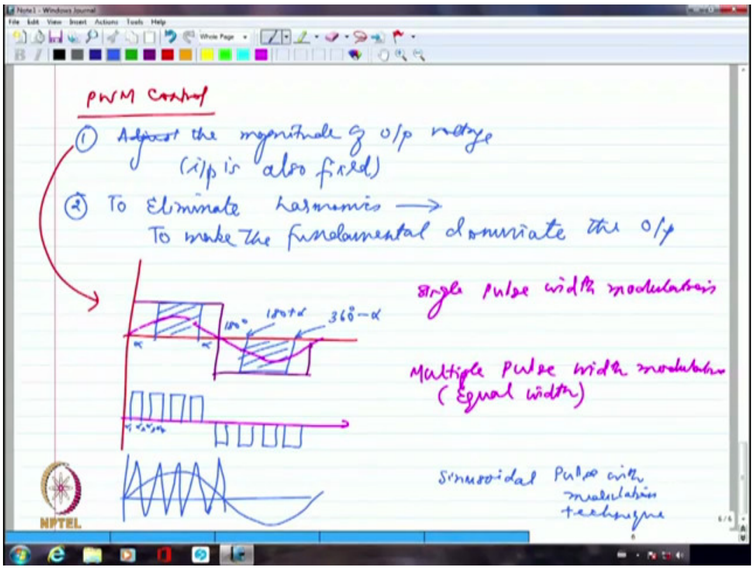

So, for these two purposes that is one is to adjust the magnitude of output voltage because input is also fixed. I am having a stiff voltage source which means my input is fixed. With fixed value of input voltage, I want to have a variable value of output voltage. So, we are essentially looking at first of all magnitude being controlled. The second one is to eliminate harmonics rather to make the fundamental dominate the output.

These are the major purposes of PWM control. So, pulse width modulation control is generally employed in voltage source inverters to fulfill these 2 requirements basically which are mainly meant for motor drives. Because motor drives are the ones which are probably going to require variable value of voltage and variable value of frequency as well as elimination of harmonics.

So in this case first of all the simplest thing to modify the magnitude will be rather than having the complete 180 degree what we had as the voltage. Let me try to have it only for let us say part of the duration and I would like to symmetrically place it. What I mean is, if I call this angle as α I would like this angle also to be α and here is my 180 degree. So, this will be 180 + α and this will be 360 - α.

So, I should try to place the pulse in such a way that the symmetrically placed whenever I look at any half cycle as such and other half cycle is exactly symmetrical as compared to previous one. This will ensure that I am not going to have, first of all DC component and also my fundamental will not be shifted with respect to the original square wave I have taken.

So, if I try to draw the fundamental corresponding to this maybe I will have it somewhat like this much less in terms of magnitude, agreed. But it will not be displaced from the original 0 crossing of my square wave. So, this is known as single pulse width modulation. We have only one single pulse corresponding to positive half cycle. One single pulse corresponding to negative half cycle and they are essentially adjusted. Both these pulses are adjusted, so this is essentially single pulse width modulation.

This will not have much of impact on the harmonic content. I may not be able to eliminate the harmonics because I am not really making the pulse width vary as per the sinusoidal magnitude, I am having only one pulse and that maximum pulse is near the 90 degree point and it is spread out completely. So, this will not allow me to eliminate the harmonics much. I may be able to get multiple pulse width modulation, but I am going to have in this case the first one I am discussing is equal width.

I am not really modulating the width of this pulse as per the magnitude or amplitude of the sine wave at that point in time. So, I may be able to get say 1 pulse, then second pulse, then third pulse, fourth pulse. Similarly, I may have one pulse, second pulse, third pulse and fourth pulse, all of them are of equal width. It does not have any other purpose again other than adjusting the magnitude.

I may turn it on and turn it off several times, so I have maybe multiple number of angles that I can adjust so that I will be able to adjust the magnitude of the output. So I may call this as α_1, α_2, α_3, α_4 then I can say this is 180 - α_4 4, 180 - α_3, 180 - α_2, 180 - α_1. On the other side it will be 180 + α_1, 180 + α_2 and so on. So, I can make them essentially symmetrical that is possible.

So, this will give me probably multiple variables to be adjusted so that I arrive at a particular magnitude, that is it nothing more than that. So, this is also not good for eliminating the harmonics. But rather than that the final one what we will be concentrating upon is sinusoidal pulse width modulation technique. So, this is essentially derived from, by having a sinusoidal wave which I want to arrive at and I am going to compare that with a very high frequency triangular wave.

I have shown it here as though it is only having a frequency of 1, 2, 3, 4 about 5. 5 times, not even 5 times less than that four and a half times and something. So, if I have a larger frequency triangular wave compared with that of a sine wave. I compare the 2 wherever the sine wave is having a higher magnitude I will have positive pulse. Wherever the sine wave is having a lower magnitude than the triangular wave I will have a negative pulse.

So I am going to essentially fire the positive devices $S_1 \text{and} S_4$ during the positive pulse and $S_2 \text{and} S_3$ during the negative pulse, so this is essentially the basic operation of a sinusoidal PWM. So, we will look at sinusoidal PWM in the next class.