Power Electronics
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Lecture 20
VSI PWM Techniques

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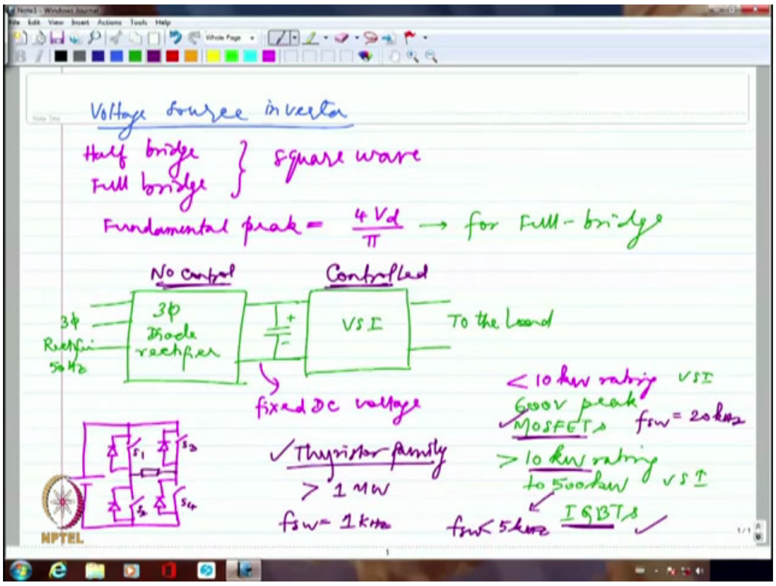

We had looked at voltage source inverter and we had looked at Half bridge and then Full bridge, both separately. And I said that normally what we do is Square wave inverter. These will be normally square wave. What we are looking at as the waveform is square wave. And we also derived what is the fundamental and we derived the fundamental peak to be $\frac{4V_d}{\pi}$. I think this is what we derived as the fundamental peak if I am talking about Full bridge inverter. So, this was the case for Full Bridge.

And invariably if am looking at voltage source inverter, so we are going to have V_d as a constant value. So normally what we look at as the source will be generally maybe a 3 phase or single phase rectifier which has 50 Hz as the supply and then you are going to have a three-phase diode rectifier preferably. And at the output we are going to have a capacitor. So, this capacitor will be normally an electrolytic capacitor which will be of very-very large value 3000 µF, 5000 µF that is the kind of values normally we are looking at.

So very-very high value capacitor because of which we will have a good filtering action. We normally see that the voltage is almost settling near the peak of whatever is the line to line voltage. So, line to line voltage is 415 V above 560 V the peak value it will be settling at.

And after that we will have the VSI here. And this VSI output is going to the load. So this is the way the entire circuit is going to function which means what we are having at the DC link this value is a fixed value. This is a fixed DC voltage. It is not going to be variable.

Because we put normally a diode rectifier, we want to have the control normally in VSI. If I can control the voltage by appropriately firing the devices in the VSI, then I should be able to control the output voltage. So, if you may recall we actually had drawn the full bridge somewhat like this. This is going to be the full bridge and I am going to have essentially the DC voltage connected somewhat like this.

And of course, I should have feedback diode. So, I am showing the feedback diodes as well. The switches normally are self-commentating devices like IGBT or MOSFET depending upon the rating. Again, little bit of more detail if I am talking about an inverter which is within 10 kW rating that will be essentially.

So less than 10 kW rating which will be normally about 600 V peak and maybe 10 or 15 A of current these are generally made up of MOSFETs. MOSFETs are available for ratings less than 10 kW very easily in the market and they are definitely less expensive as compared to IGBTs. So that is the reason normally we tend to use MOSFETs for less than 10 kW rating VSI.

If I am having greater than 10 kW rating maybe until about 500 kW or something like that, then I would like to go for IGBTs. So, if I am talking about 510 kW rating to 500 kW, then I would try to use IGBTs. And if I look at the switching frequency if it is less than 10 kW we may be able to go easily until 20 or 30 kHz in the case of MOSFET.

So, switching frequency if I try to look at this maybe 20 kHz or around the range of 20 kHz easily. MOSFETs can go until 1 MHz of switching frequency provided the power rating is really-really small. Please understand that whenever I turn off a device the charge carriers have to be swept off. They have to go through recombination, only after that the device will be put into off condition. It will turn itself into off.

So, you need certain amount of duration for the larger amount of charge carriers to be swept off if I am talking about the larger current rating. So larger the rating of the device generally the operating frequency will come down. I will not be able to operate it at as higher frequency as normally I would operate for a say 10 W or 15 W or 50 W circuit. Compared to that if I look at 10 kW circuit, obviously the frequency of operation will come down. I will not be able to operate it at a higher frequency.

So, although MOSFETs we say are capable of operating until 1 megahertz that is only meant for very-very small power rating, less than 50 W or 100 W. Whereas when I go for 10 kW rating and above I definitely need to bring down the switching frequency. If I look at more than 10 kW rating and especially close to 100 or 200 kW rating the switching frequency generally cannot go beyond 5 kHz, it will be generally less than 5 kHz.

So, if I talk about hundreds of kW I have to have $f_{sw} < 5kHz$ because again the amount of the current that is flowing will increase as the kilowatt rating increases. So, it takes more time for the device to be turned off. So, this essentially puts some kind of limitation on the on/off frequency that I can employ in my circuit. So, there is a reason why this is generally dominated by IGBTs.

But if am talking about megawatt level drives which are very commonly used in cement mills, they are also used in fraction applications, for example all your Rajdhani train if you look at they have generally 850 kW motor, four of them simultaneously driving the entire Rajdhani train. So, you have the rating of those Rajdhani train's motors to be very very high.

In those cases, generally IGBTs are not employable again and because we are looking at very high rating any device from thyristor family I should say. So, thyristor family you can say GTO gate turn off thyristor or the normal SCRs but we have three different kind of SCR as I told you, one is converter grade which is used in rectifiers, the next one is inverter grade which we can use in this case.

And light activated SCR that is another third type of SCR where the gate requirement is really small because it will be triggered by light those are using HVDC very commonly light activated SCR. So, thyristor family of devices are used for 1 MW and above normally, and obviously because the current rating is so high and they belong to thyristor family they are very slow.

So even if I operate it at the most the switching frequency could be 1 kHz even this is quite high. At the most, nothing more than that generally 1 kHz that is a kind of switching frequency we operate. Of course, a lot of research is going on in devices, so which is bringing down actually the constraints which means the switching frequencies are slowly increasing.

Slowly and steadily, but as of now it is still within 1 kHz. When we were students, we used to say not more than 250 Hz and eventually it became 500 Hz. Now it is about 1 kHz. I am sure within a few years it will again increase further. So, this is the way normally we decide on the devices. So very low rating MOSFET, medium rating IGBTs, very high rating thyristor family, so this is the way it works normally.

But in general, in all the VSIs we are not going to have any control over the DC output that we are getting. The DC output is going to be a fixed value which is feeding into the inverter, but inverter will have the control. So whatever kind of control we want to implement that will be done only in the VSI. So just to expand upon this if these are the four devices, we had named them as S_1, S_4, this is S_2, this is S_3. This is the way we had numbered the devices and we had connected the load somewhere here.

This is how we had connected the load, so the load voltage it has to be modified or changed then correspondingly the duration for which S_1 and S_4 are on and the duration for which S_2 and S_3 are on during the negative half cycle these two have to be adjusted. So, whatever I showed as the pulse width modulation.

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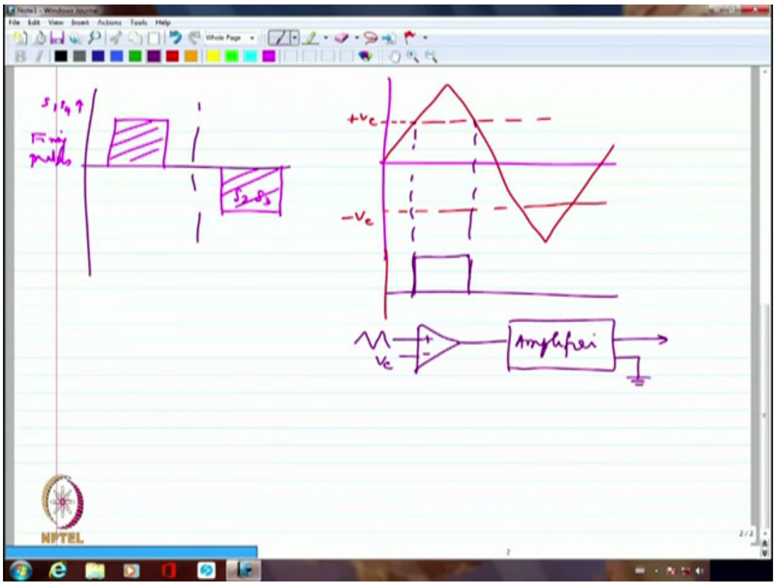

Last time I showed, in the last class I had shown the pulse width modulation somewhat like this. I can just have the pulse for so long a duration, and I can have the pulse for so longer duration as far as the negative half cycle is concerned. This pulse is essentially talking about the firing pulses. What I give as the firing pulses to, for example this is to S_1 and S_4, whereas this is to S_2 and S_3.

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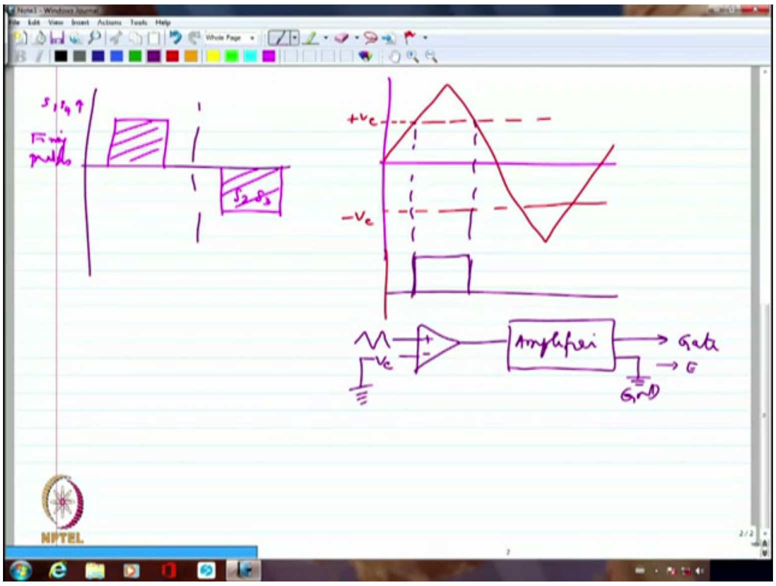

See if you control, actually if you put the thyristor rectifier you are going to be able to control the DC, alright but you may not be able to control the waveform at the output of the inverter. Here it serves two purposes when I employ PWM like what I mentioned in the last class it not only varies the magnitude, but it also varies the harmonic content that is available in the output waveform.

But thyristor family of converters basically are known for making the harmonic content more and more. So, it is not really helping us in both ways, it is probably helping us in one way that is to reduce basically the magnitude of voltage or increase the magnitude of voltage that I can do adjusting the magnitude of DC voltage I can do, but I cannot really eliminate the harmonic content at the output.

So PWM what we are going to talk about eventually will eliminate the harmonic content or at least push the harmonic towards the higher frequency, so that I can put a low pass filter which will send out all the lower frequency components only and high frequency components will be bypassed. So that is the way normally the sinusoidal PWM technique works.

These two pulses are essentially going to the devices that are actually being employed in my inverter. So, I can think of something like this. Let us say I have a triangular waveform like this. Active frequency at which I want to generate my AC output, okay. This is the control circuit voltage, not the power voltage. So, this may be 5 V, 2 V, 3 V whatever, so this is a control voltage which I can generate using an oscillator, using an op amp circuit very easily, that is not a problem.

Triangular waveform can be generated very easily using an op-amp circuit. Once I generate this if let us say I compare this with $+V_c$ on one side and $-V_c$ on the other side, In which case I would be able to get if I say that my comparator output is taken whenever this particular positive half cycle of the triangular wave voltage is the triangular wave voltage is greater than the control voltage. So that essentially tells me how long I will fire S_1 and S_4.

So, depending upon what kind of output pulse width I want I can adjust V_C. So, by adjusting V_C, so V_C is generally standing for control voltage I can say that as control voltage. So, by adjusting the control voltage I should be able to get whatever is my pulse width according to my requirement. So, this is typically the case of generating a firing pulse using a triangular wave generator along with a control voltage.

So, I can imagine as though it is a comparator. If I am looking at it from analog circuit implementation on one side, I am going to give a triangular wave, on the other side I am going to give a control voltage. Now whatever comes out of this will be essentially positive whenever that triangular wave is dominating over the control voltage, this can go as the firing signal of course after amplification.

Because what I get out of the operational amplifier may not be strong enough to drive my gate, MOSFETs gate or IGBTs gate. So, I might have to amplify this. So, in all probability I will use an amplifier after this, Triangular wave how I generate is a matter of detail. So, if you guys have studied oscillator you should be able to say that sinusoidal triangular wave, so many things can be generated using an oscillator, that is not a problem.

So now, this amplifier output will definitely have a common ground, of course. There will be a common ground and whatever is the output that will go to the gate. So, this has to be applied between gate and cathode, if am talking about a thyristor for example but if I am talking about let us say an IGBT between the emitter and the gate terminal of the IGBT I have to apply this, but please remember if I am going to have a common analog ground.

I am going a little bit into the matter of details in terms of hardware implementation, pulse width where are you giving this pulse? So, there was a little confusion because I mixed up analog, electronic side of the power electronics and the power side of the power electronics. So now, I am trying to exactly say which goes towards the analog electronic side or control electronic side and what is the power side?

So, what comes out now, if this is the common ground for all the four devices maybe I will have operational amplifiers that there are chips that are available with four operational amplifiers in one single chip, 741 has only one operational amplifier, but 747 or something has basically two or four operational amplifiers together, so the ground will be common. So, the ground is common and here also I am going to have a common ground maybe the control voltage will be applied with respect to a common ground.

Now, if I try to apply this signal to the gate and this to the emitter look at the circuit what we had.

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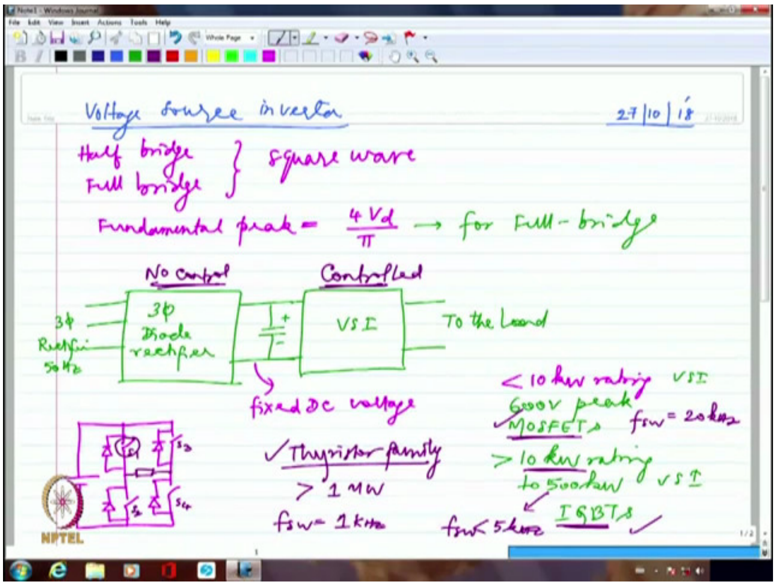

So, I am going to have each of these as emitter base collector or emitter gate and collector in the IGBT. So, if I am connecting the ground here, the same ground becomes the collector for the other IGBT, so I cannot afford to do that, I hope you understand. I have a collector here for the IGBT this will also be the IGBTs collector, so here will be the emitter, so this emitter and this collector are connected together, so I cannot have the common ground connected everywhere to the emitter of all the devices in which case this will be like a dead short.

Because this is the emitter of the previous IGBT, this is the emitter of the other IGBT, both emitters will be connected to the ground. So, you are just short-circuiting this device that is what it means. So, in the inverter it is absolutely essential to have isolation between the electronic ground and the ground of the power, especially when I am connecting the gate signals to each of the gates and the emitter, so it is a pair.

I will get two wires. One wire will go to the emitter of the corresponding IGBT, the other wire will go to the gate of the corresponding IGBT. So, which means I necessarily need to isolate between whatever is available here at the amplifier stage.

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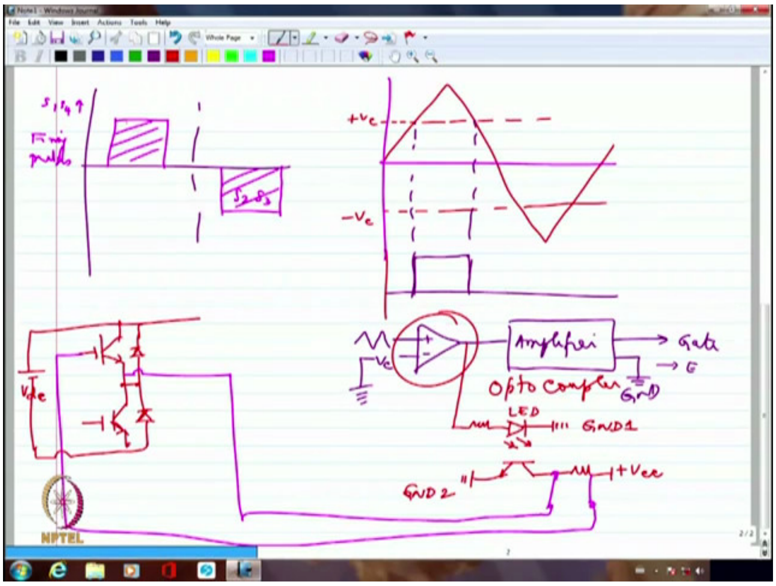

I should try to have some kind of isolation. I think I mentioned opto-coupler earlier also once. So normally what we use is an opto-coupler. What we use here will be an opto-coupler cum amplifier. So, what will happen in this case is, whatever comes out of this I will connect it through a resistance to an LED. So, this is an LED and LED emits light whenever it is going to get a positive signal.

So this will be connected to a photo transistor. So, this is the ground, and this is the collector and this is some $+V_{cc}$. So, if I may call this as GND_1 which is electronic ground, this will be GND_2 which is actually the power side ground, but all the GND_2 will also not be connected together, I hope you understand that. If I look at two devices, one device is here, another device is here, this is how they are connected.

And this is the feedback diode and I am going to have the gate here, gate here, these are the IGBTs. So, I will have to connect this GND_2, for example to this. So, I have to connect it like this, this is connected to GND_2 or I may connect it to this point that is also fine because I have to essentially take the pulses across this. Pulse is taken across this, so I can connect one of them to the emitter terminal, the other positive point has to be connected to the gate, so this is how it is going to be connected.

So, I can show it as though this is connected essentially to this and this gate is connected essentially to this. So, you have four circuits like this, independently four circuits like this, all the four circuits will be connected to the four devices what you have in the inverter, you get my point. So, it is not a very simple thing, it is a pretty complex thing when you connect all of them together, you understand my point.

So, this is going to be my V_d. V_{dc} power, so this is the power portion whereas this is all the electronics portion. So, whenever I use an IGBT, generally it will be a must to use and opto-coupler. IGBT or MOSFET, it will be a must to use an opto-couplers to make sure that the grounds of the power and electronics are segregated and there is no dead short-circuit between the devices which are being employed in the VSI. So, we will have a large amount of accessories for the VSI.

The power circuit maybe this small, but we will have a lot of accessories in terms of firing circuit, protection circuit and so on and so forth. Control circuits, all those things. So, this pulse that I am talking about is generated using this operational amplifier which will have two inputs, one is the triangular wave, the other one is the control voltage and the control voltage can be increased or decreased to adjust the pulse width. So, this is essentially a single pulse modulation.

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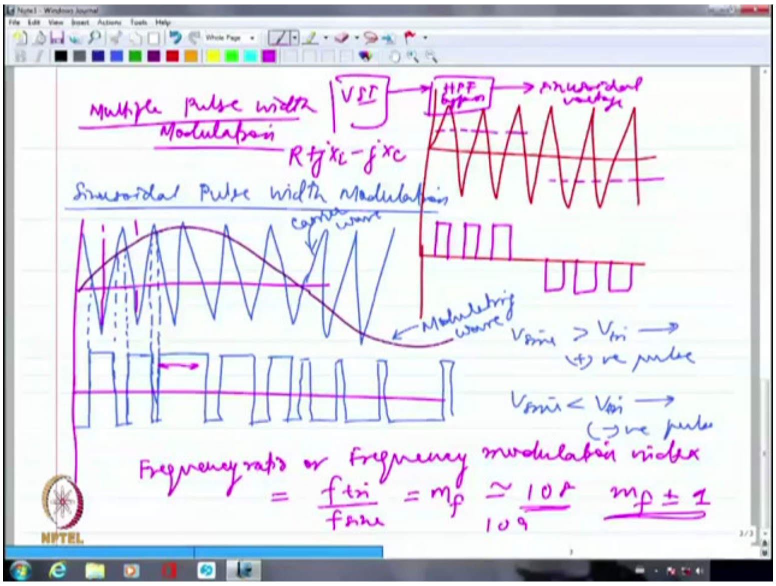

Whereas, if I look at maybe I am going to have a triangular wave at a very high frequency, maybe compared to whatever I want it to be as my output frequency. And probably for the initial three cycles I will compare it with $+V_c$, for the next three cycles I will compare it with $-V_c$. So, whenever I compare with $+V_c$ I will get three pulses which are positive side.

I am going to get some pulse somewhat like this. If I try to draw the pulses, I may have the pulses somewhat like this, one pulse here, second pulse here and third pulse here, all of them will be of equal width. Whereas, on the other side I will have similar one with, three pulses somewhat like this. So, I am essentially looking at multiple pulse being generated with a high-frequency triangular wave and a control voltage this can again go through an operational amplifier comparator to give me the output waveform which I can amplify and so on and isolate, then I can give it back to my gate, the devices.

So, this is generally known as multiple pulse width modulation, but in both these cases I am really not going to get the waveform which is closer to sinusoid.

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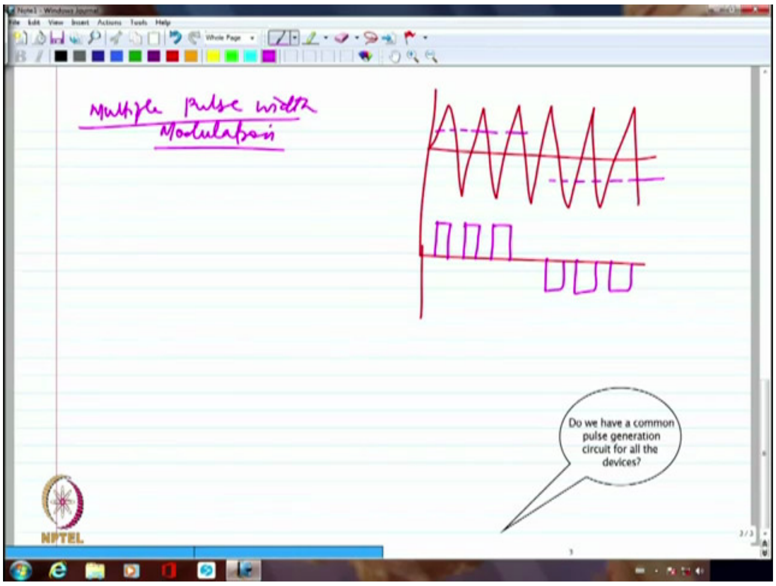

Do we have a common pulse generation circuit for all the devices?

You have to have one more comparator. You need not add both of them because you are specifically firing one particular S_1, S_4 for the positive half and the other S_2 and S_3 for the negative half, so you can segregate them. Segregate them that is not a major issue.

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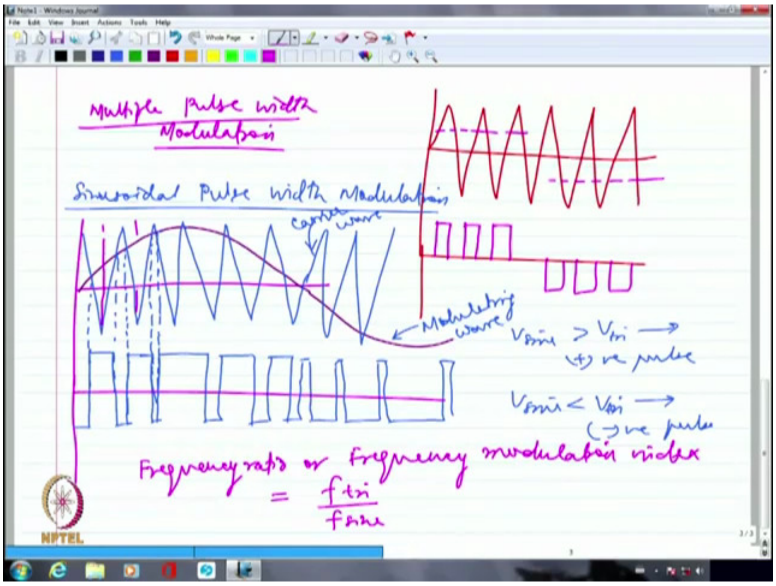

So, you definitely need to have multiple number of components, so many sequence of components that is what I said. Compared to the inverter itself this will become much bigger normally that is what it is, okay. Now, if I want actually approximately sinusoidal waveform, we call that as sinusoidal pulse width modulation. So sinusoidal pulse width modulation technique is very-very commonly used for inverters whenever I want the output to be close to a sinusoid.

For example, all your UPSS they all use sinusoidal pulse width modulation technique. Home inverters many of them do not use, but if they use sinusoidal pulse width modulation technique, it is advertised in a big way. Your home inverters gives you approximately sinusoidal waveforms or your motors will not make noise and so on and so forth. A lot of advertisement is given for that.

All the large capacity motor drives which are run by inverters they all have to have definitely sinusoidal pulse width modulation technique employed, otherwise the motors will groan. It will not be possible for you to run the motor effectively or efficiently. So, in sinusoidal pulse width modulation technique what we do is somewhat like this. I am showing first of all one half cycle, so this is my sinusoidal voltage for one half cycle, of course it will continue on the other side this is how it should be.

This is the voltage I want to have as the output approximately and I actually would compare this with a high-frequency triangular wave. If I am not drawing uniformly it is not my problem, but it should be uniformly oscillating triangular wave throughout. So, I am going to have a high-frequency triangular wave being compact with the sine wave, please note this sine wave is a sine wave we want to have at the output but high-power level, at high-powered level.

And what I will generate as the control sine wave maybe of 1 V amplitude. I can use an oscillator very easily to generate with an electronic circuit, a 1 V amplitude sine wave, it is not a big deal and I will be able to essentially adjust the frequency as per my requirement. I may require 50 Hz, I may require 100 Hz, I may require 120 Hz. Correspondingly I may have an oscillator something similar to voltage controlled oscillator.

So, in voltage controlled oscillator according to the voltage you give the oscillation frequency will essentially adjust itself. So, you can have the oscillator generate the sine wave at variable frequency as per your requirement. Now, whenever I am going to have the sine wave greater than say the triangular wave, so I am going to have essentially at this point, I am going to have the sine wave greater than the triangular wave.

So, I will have positive pulse, let us say. So, I am saying that when sine wave is greater than triangular wave I am going to have positive pulse and when sine wave is less than triangular wave I am going to have negative pulse let us say. So, I am going to have essentially during this portion I will have a negative pulse and let me look at this again here the triangular wave is greater than the sine wave, so you get my point basically.

I am going to have wider and wider pulses of positive nature and narrower and narrower pulses of negative nature. This is how it is going to be. So, near the peak where I am going to have wider pulses, so essentially, I will have wider pulses than maybe a narrower pulse and a little narrower pulse and so on this is how it will be. So, I am essentially looking at during positive half, the positive side of the pulses will be wider and the negative pulses will be narrower and it will be just the other way round.

When I am looking at because again this, I have to show it as though it is being compared with the negative side as well. So, I am going to have essentially just the opposite, for example maybe I will have something like this, something wider then something further wider and so on, you get my point. So, this is the way I am going to have the sinusoidal pulse width modulation output waveform. So, all I need is basically a triangular wave generator and I am going to have a sine wave generator.

And sine wave frequency as well as the magnitude could be completely in my hands. What I generate as the sine wave, reference wave, modulating wave I may call this as modulating wave because I am talking about the whole thing as pulse width modulation. So, this one is modulating wave and this one is triangular carrier wave. So, it is very similar to what you do in terms of modulation techniques that you use in radio waves and other wave transmissions.

So, we are going to have mainly two quantities here. One is frequency ratio or frequency modulation index which will be actually frequency of the triangular wave divided by frequency of the sine wave. And frequency of the triangular wave will be very large normally compared to the frequency of the sine wave. So, if sine wave frequency is 50 Hz the triangular wave frequency can be as high as 5 kHz.

So, in which case I will have hundreds of switching’s within one cycle very clearly. So, what will happen is if I have multiple number of triangular waves within one half cycle itself, if I just look at one cycle of this particular triangular wave the sine wave will look as though it is a constant during that particular sampling interval, you get my point.

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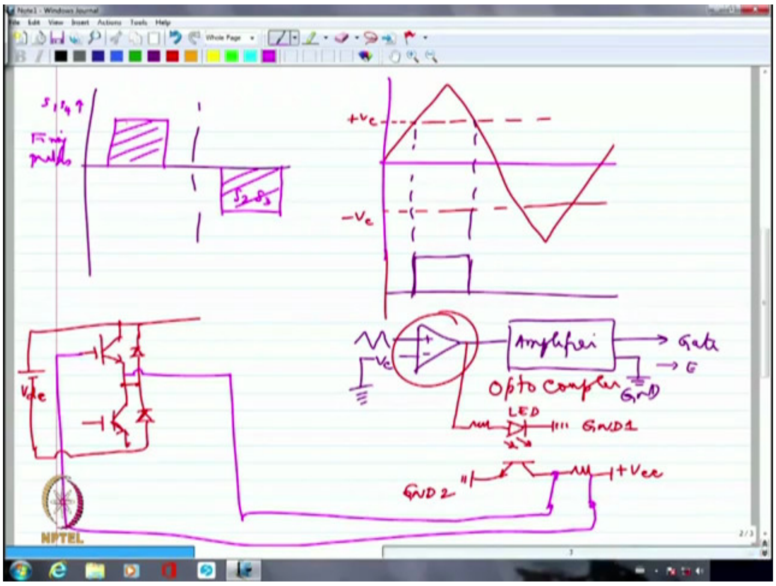

So, it becomes as good as what we looked upon here as control voltage being compared with the triangular base. So, if I look at every sampling interval because of the duration being so small because the frequency ratios are normally higher, I am going to look upon the sine wave almost as a constant.

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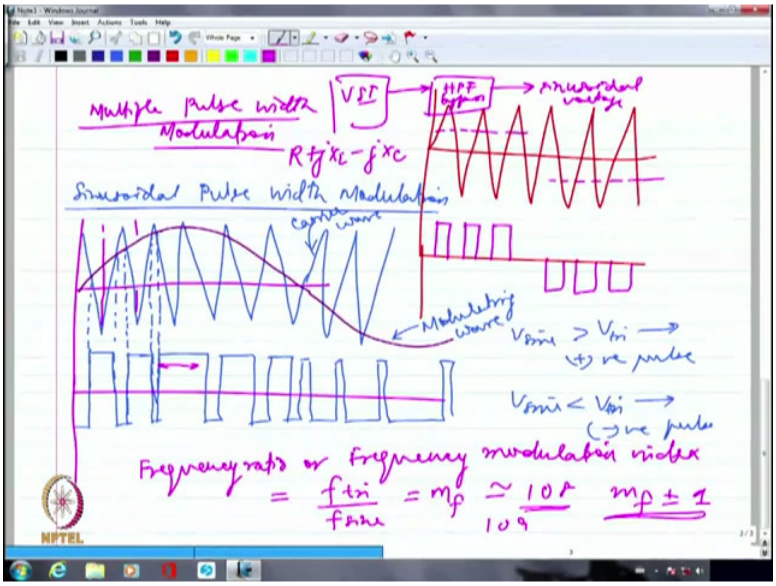

So, we said already that the control voltage what we had in the other case single pulse modulation decides what is the kind of output voltage I get. So, the output voltage becomes almost proportional to whatever is the control voltage that I am impressing upon my operational amplifier's control terminal.

So, in this case that is the reason why each of these pulse widths will be roughly proportional to whatever is the sign amplitude, sine wave's amplitude during that particular sampling interval or carrier interval. So, during the carrier interval whatever is my sine wave amplitude that will decide the width of this particular the pulse that am looking at which I am going to actually put as the firing pulse for my devices.

So, I am essentially looking at all these pulses emulating the sine wave amplitude corresponding to that particular carrier instant as simple as that. So, what I get ultimately it does not look like a sine wave definitely, but if I look at the area under the curve it will look as though it is emulating a sine wave. But of course, I have too many switching is, so switching losses will increase, no doubt this is one of the major disadvantages of PWM technology.

Pulse width modulation when I use sinusoidal pulse width modulation, I am essentially emulating the output which looks like a sine wave. In terms of the area under the curve. However, I am going to increase the switching losses tremendously because if I am having a carrier frequency of 5 kHz the switching on and off of the devices will be done at the rate of 5 kHz. So, switching losses are going to increase tremendously.

One more thing is that because I am switching the devices at a very-very high rate. So, if I call this frequency ratio as m_f. I will have all the harmonics beyond m_f because I will have superposition of a high-frequency switching on the 50 Hz wave whether I like it or not I will definitely have repercussions for having high frequency switching. So, if I do the harmonic analysis, let us say if I take my switching frequency for example to be 108.

I will have all the harmonic, actually $m_f \pm 1$ for example all those things will start appearing as the output side harmonic. So, I will have 50 Hz component, agreed. But after that the lowest order harmonic which will be perceivable that will be 107 multiplied by 50 or 109 multiplied by 50. If I am taking the switching frequency to be 108 times 50 Hz, so I will have all the harmonics beyond this m_f.

And if am going to look at those harmonics, they will be of good amount of magnitude they are not going to be small magnitude. They will be almost having, if I say fundamental voltage is hundred volts even this 107th harmonic, 109th harmonic and so on will be close to 90 or 100 volts easily. So, I need to put some kind of filter to bypass this output. So, I might have to so if I say this is VSI and I have to essentially put a bypassing, so HPF, this will be a bypass filter.

It will bypass all the high-frequency and whatever is the output primarily will contain, the sinusoidal voltage. Now this high pass filter will be like a tuned filter, I hope you understand because it is a tuned filter L and C in series it is going to offer very minimum impedance you guys have studied about resonance, way back. Recall it, okay. In resonance, what do we say normally?

We will have $R + jX_L - jX_c$, so jX_L and jX_C if they cancel out with each other R is the only impedance that is coming up in the way of any harmonic that I am talking about where X_L will be ωL and xc will be $\frac{1}{\omega C}$. So I am essentially looking at something like this.

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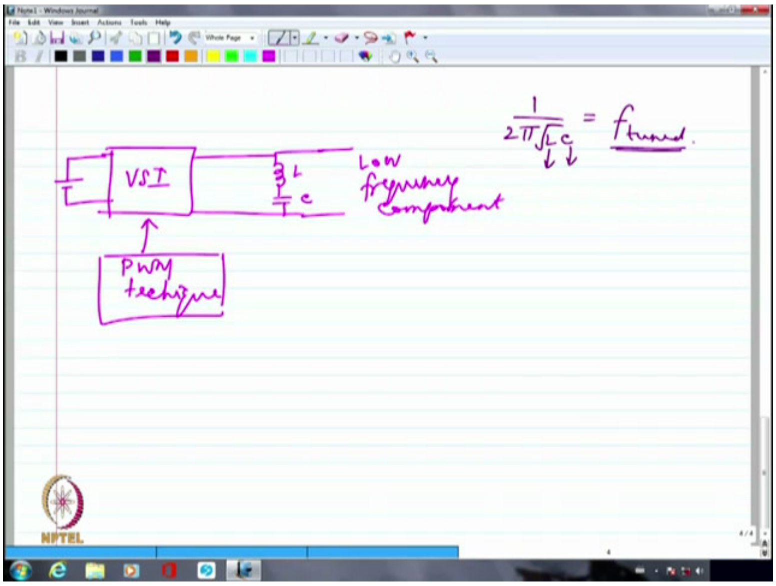

This is my VSI, I am firing it with PWM technique. And I am going to have a DC supply here. DC supply how it comes is a matter of detail. And at this output I am going to put a high pass filter which I can put it with L and C where this L and C will be tuned for any frequency higher than 100 times 50 Hz, 5 kHz. So, if it is tuned for high frequency obviously all the high-frequency component will only circulate with the L and C throughout.

And what comes out here will be mainly the fundamental component. So, this will be low frequency component and the low frequency component here primarily consist of 50 Hz. Now this L and C when I design I will normally use the same equation what I use in resonance $\frac{1}{2\pi\sqrt{LC}}$ equal to whatever is the tuned frequency and I want to tune it to 100 times 50 Hz, 5 kHz maybe 107 times whatever.

Now as this frequency increases L and C will be smaller and smaller, I hope you understand this. As I go to higher and higher frequency filtering L and C will become smaller and smaller because L and C become smaller and smaller the component size will also decrease, they will all decrease. So, I can say that if I have a very high switching frequency, I would be able to push all the harmonics to beyond mf which means the high pass filter need to be designed only for very high frequency.

If I do that then L and C sizes can decrease. So, I am trying to look at the pros and cons of having a high frequency ratio. If I have a high-frequency ratio m_f I will have only high-frequency components in the output because of which my high pass filter size becomes smaller to eliminate all the high-frequency components. But the negative side of it is I will have multiple switching's.

Switching losses increased tremendously and my device should be in a position to handle this kind of switching frequency, whether it will be able to handle this kind of switching frequency I have to question that for that particular power level.

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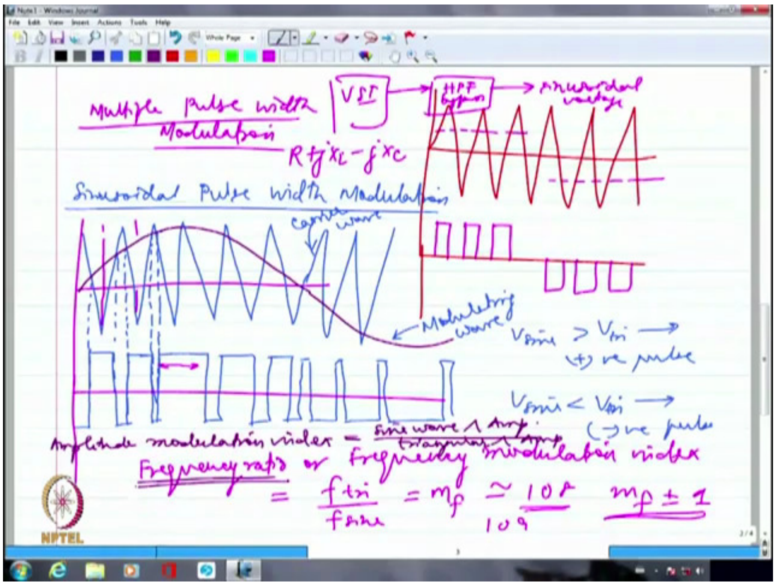

So, in sinusoidal pulse width modulation where I was talking about one of the important parameters as frequency ratio. The second parameter is amplitude modulation index. This amplitude modulation index is defined as whatever is the sine wave peak amplitude divided by triangular wave peak amplitude, so if I have a triangular wave peak amplitude of 1 whereas I am going to have the sine wave peak amplitude of 0.8, we call the amplitude modulation index as 0.8 in this particular case. So, if I have a sine wave and the triangular wave almost coinciding with each other, the peaks then I call the modulation index to be 1, but at every point in the sine wave I will have intersection with the triangular wave.

So, for every cycle of the triangular wave I will have intersection with the sine wave, but if the magnitude is really high here, I am going to have a wide pulse which means if I bring down the magnitude of the sine wave I will have smaller and smaller pulses, positive pulses. So, the modulation index indirectly decides what is the overall RMS value I get out of my inverter. So, if I have the modulation index close to 1 I will get a good amount of magnitude of output voltage.

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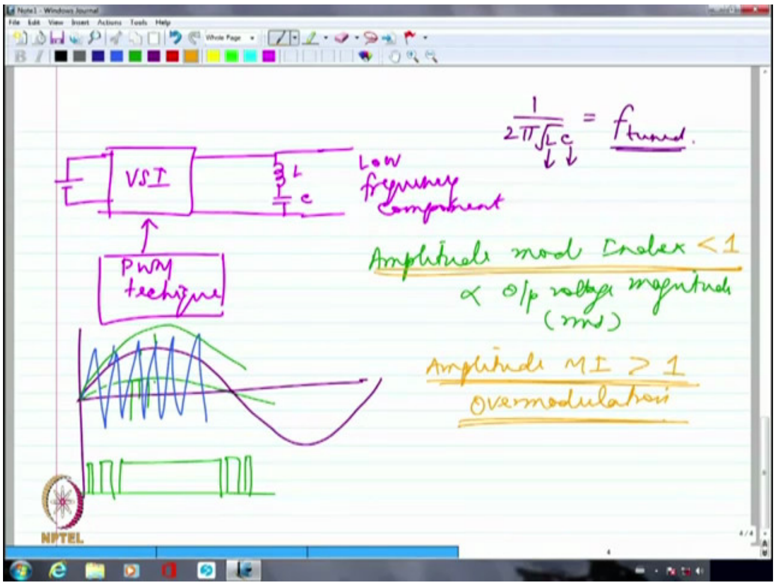

Whereas, if I bring down my modulation index what I mean is, if I am trying to look at the sine wave something like this. Initially let us say I have a sine wave like this, and I am going to have a triangular wave which is almost same as the magnitude of the sine wave. In this particular case I can say maybe modulation index is close to 0.9, okay. So, I would be able to get at least this width pulses.

Whereas, if I make the sine wave smaller, if I just make it smaller like this very clearly, I am going to get the pulse width here to be smaller as compared to what I got earlier. So, this particular green wave if I choose as my modulating wave where the modulation index becomes almost less than 0.5 I am definitely going to get a magnitude of the output voltage to be much smaller because the positive pulse is also shrink, you get my point.

So, this amplitude modulation index is going to be deciding rather whatever is the output voltage magnitude. So, I would say even if I calculate RMS, I am going to have reduction in the output voltage if I am looking at the amplitude modulation index coming down. Whereas, if I have a modulation index of 1 I will have definitely wider and wider pulses near the peak of the sine wave.

Now, if I am actually going to use a modulation index greater than 1 If I use a modulation index greater than 1, then I will not even see a lot of intersection. During the mid-portion I will hardly see any intersection. So, I will have wide pulse, during this portion I am going to have a wide pulse and I may have some intersections here.

So, whenever I use an amplitude modulation index greater than 1, we call this as over modulation. So over modulation will bring my waveform close to a square wave eventually. If I go to extremely large value of modulation index, then essentially all these things will also merge and then I will get a complete square wave, it is possible that I may have a completely a square wave.

So, during that portion I am going to again reintroduce the harmonics. Until now I was trying to eliminate the harmonics. I was trying to look at the waveform being closer and closer to sinusoid, only high frequency components could be there. But the moment I have eliminated all the switching's because of over modulation I am going to see that I have reintroduced the harmonics.

So over modulation although will increase the output magnitude tremendously, it will reintroduce the harmonics, so it is not recommended especially when I want sinusoidal waveform in the case of motor drives or UPS and so on and so forth. So we basically have two regions of operation, amplitude modulation index being less than 1, this is one region which is preferred zone and the other one is the amplitude modulation index greater than 1 which is over modulation zone which is definitely not a very preferred zone of operation.

But if I probably want a larger magnitude of voltage I might try to kind of go into over modulation not too much maybe 1.2 or 1.3. So that, at least there are still some pulses left out. It is not like everything is merged together.

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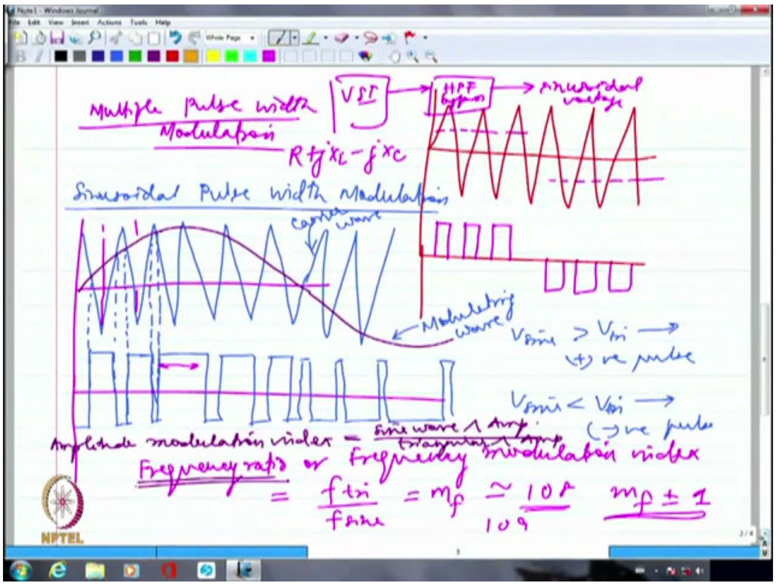

One more thing that we need to necessarily look at is that if I say that during the positive half cycle S_1 and S_4 are going to be fired and during the negative side S_2 and S_3 are going to be fired,

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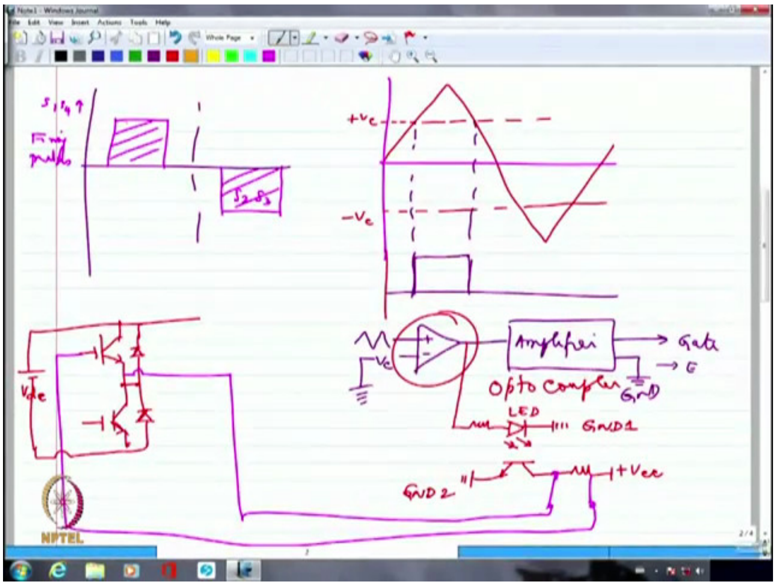

So, I am having actually, if you look at the circuit again I am having S_1 here and S_2 at the bottom.

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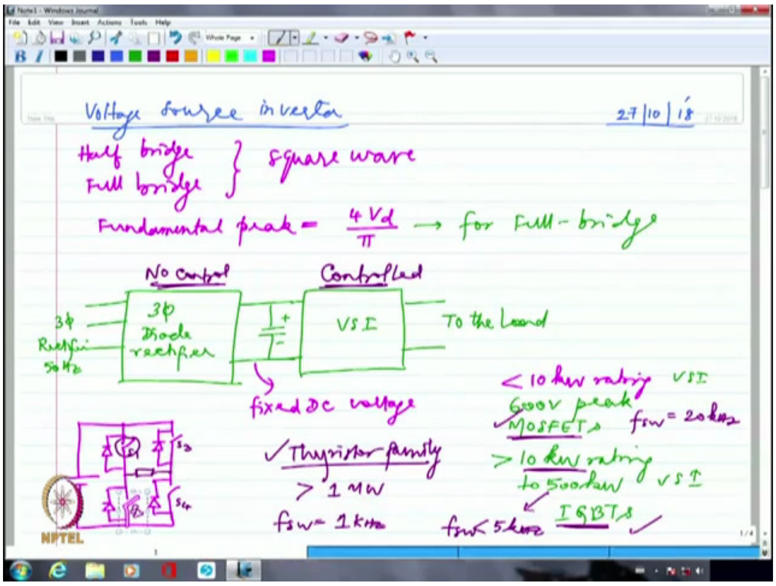

S_3 here and S_4 at the bottom. So, if I fire S_1 and S_4 for the positive side after sometime I am going to fire S_2 and S_3 when the negative pulse comes, but if I do not give any gap between the turning off of S_1 and S_4 and write away release the firing pulses to S_2 and S_3 I will definitely have a dead short-circuit across the DC supply. So, it is very important to give a dead band between S_1 and S_2 as well as S_3 and S_4.

So this dead band whatever I am looking at, so if I say that I am going to have pulses somewhat like this.

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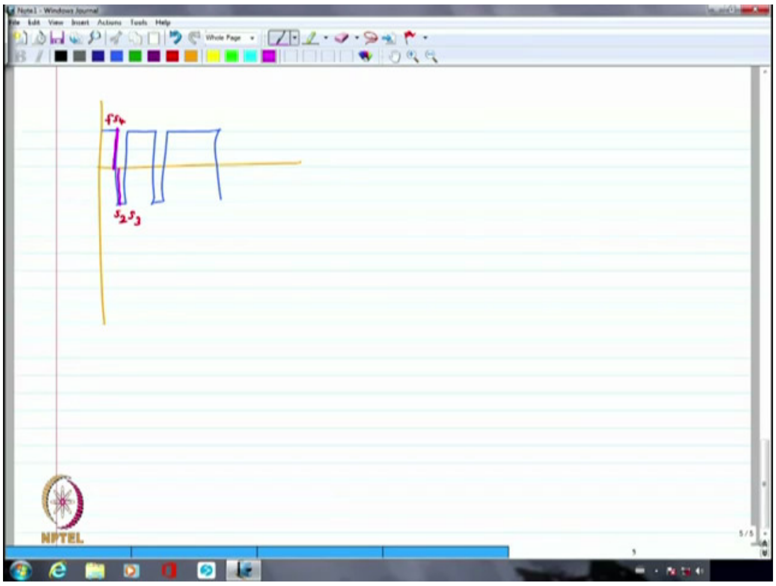

So, let us say I have the pulses going like this, something like this. So I would have fired S_1 and S_4 here. Whereas, I would have fired S_2 and S_3 here, so when these two go off at this instant S_1 and S_4 are supposed to go off at this instant. I necessarily need to induce or introduce a delay of a few microseconds depending upon what is the turn of time of my device.

So, I have to take into consideration what is the turn of time of my device. How long does it take to recombine? So, the recombination takes probably 5 µs, then I might have to introduce a delay of slightly higher than 5 µs. Generally, I will introduce a factor of safety maybe 5 multiplied by 1.5, 5 multiplied by 2. So, I might have to introduce a delay of 7.5 µs or 10 µs.

So, this, although the waveform is like this it may actually start only a little later. You can see that the blue and pink are not coinciding with each other. Although I had actually done sinusoidal pulse width modulation by comparing triangular wave and sinusoidal wave, this slide marginal increase in the delay that can again reintroduce some little bit of harmonics. This is a necessary evil that we have to live with there is no other way.

Unless we give a dead band, we will have shoot through, so to avoid shoot through we introduce this dead band which is probably going to kind of mess around with the harmonics that I wanted to eliminate. So, you may have small amount of harmonics being reintroduced because of this dead band. This is one of the necessary evils that come because of the shoot through being avoided, So, in general this particular way of generating firing pulses.

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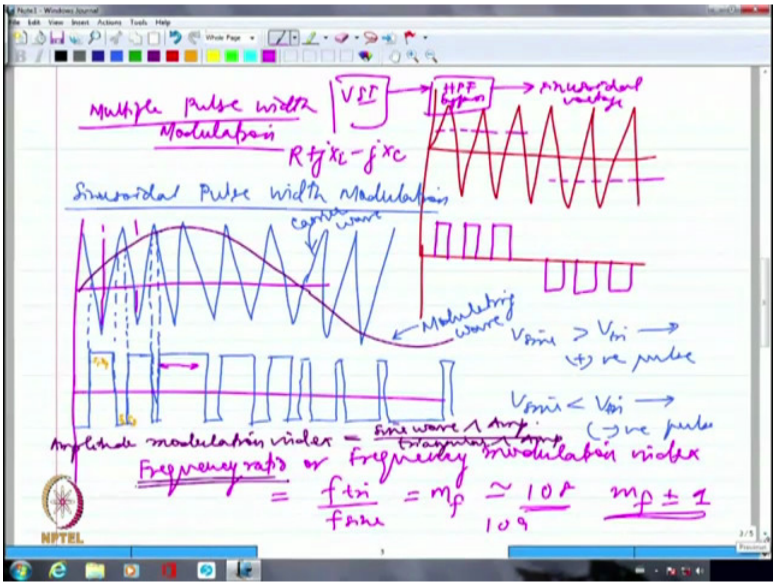

That is rare, I am just comparing one sine wave with a triangular wave and then getting the pulses which are corresponding to the positive side and negative side, so this is generally known as bipolar sinusoidal pulse width modulation, this we call as bipolar sinusoidal pulse width modulation technique which means there should be some unipolar. So, we look at unipolar also. What is a unipolar sinusoidal pulse width modulation technique?

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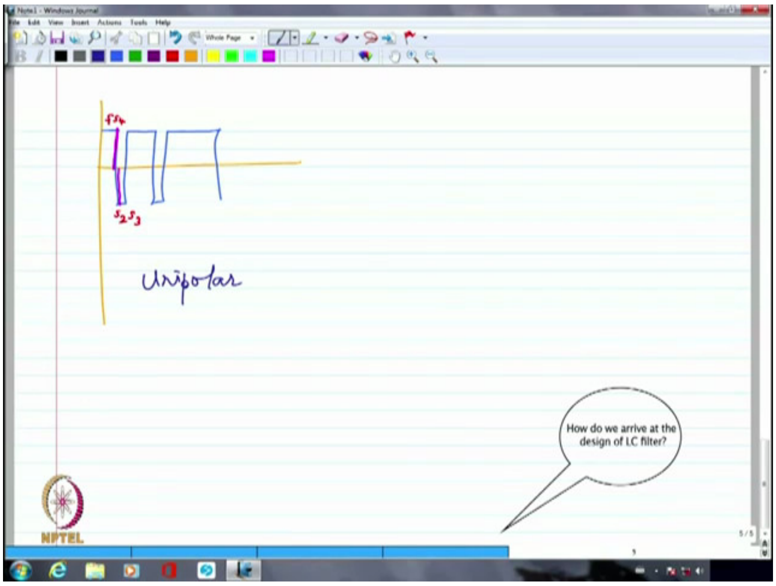

See if I have LC, it is essentially going to give me low impedance path for a particular harmonic’s frequency, if I am trying to tune it to that particular harmonics frequency. So it will essentially try to just attract or give low impedance path only to that particular harmonics frequency maybe for all the higher. So, I can make it as a high pass filter basically by tuning it for a bandwidth which is corresponding to 107 times whatever is 50 Hz to maybe 300, 400 times 50 Hz.

So, I can essentially make the band with accordingly by adjusting the quality factor, So this will not take definitely 50 Hz component because this will offer a very high impedance to the 50 Hz component. So, it is essentially looking at the parallel path of what is going to the load because here is the load and this is essentially not really a load, this is a bypass path. So this bypass path specifically is designed to bypass only the high frequency components, that is it.

So, L and C what your design has to essentially go with this kind of equation $\frac{1}{2\pi\sqrt{LC}}$. So that is why L and C becomes smaller. Whenever I push the harmonics to the higher frequency this L and C will become smaller, I could have done this very well even in the sinusoidal I mean square wave inverter, no doubt. But in a square wave inverter necessarily I need to give third harmonic filter, 5th harmonic filter, 7th harmonic filter and so on and so forth and all of them are lower frequency, so L and C will become very large.

So, I can eliminate that problem by pushing the harmonics to a higher frequency that is what I am precisely doing in sinusoidal pulse width modulation technique.

See never is an inductance a pure inductance. We are happily relying on that. His question is, if L and C is tuned to 107 times 50 Hz will it not work like short-circuit? That the current will shoot up, but never is L, an ideal L, it will always have a resistance, in fact in many of the high pass filters we will also introduce a small resistance. Only thing is we have to make sure that the impedance offered by this bypass path is always smaller as compared to the load impedance.

So, filter design is again an involved area because of this because you do not know what is going to be your load impedance. Maybe you have to look at the worst-case scenario. So, if I know that always 20 percent load will be there, always it may not be 100 percent, 20 percent load is there that is when the impedance is maximum on the load side, so for that I have to design my tune filter for the worst-case scenario.

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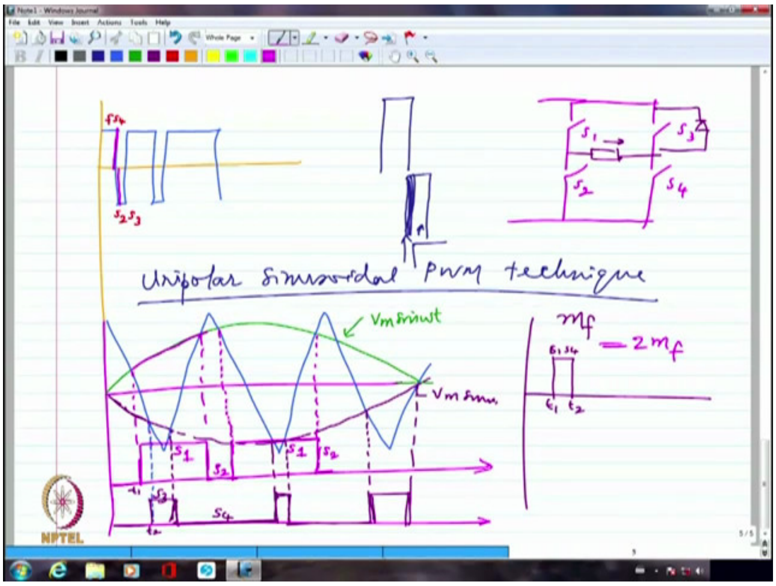

So, let us look at unipolar sinusoidal PWM technique. So, let us get into a little bit of hardware. How do you introduce dead band? These days whatever we have as microprocessors or digital signal processors what we use or what are being used by my students they all introduce dead band inherently in the programming. What they do is, they already compare a sine wave and a triangular wave inside at whatever frequency you require.

So, you just load into a resistor, what is the frequency output you require? What is the kind of frequency ratio you require? And then it just calculates inside because digital signal processes have immense computation capability. So, they clearly calculate what are the pulse widths and then they give out the pulse. So, you have several PWM pins that are available in DSP, at least 6. Minimum 6 is available because we always work with three-phase inverters, okay.

So minimum 6 pins will be available. So those 6 pins will give out the firing pulses for S_1, S_2, S_3, S_4, S_5, S_6, fine. When they give out along with the computation of the pulse width, they also compute the dead band, okay. And dead band you can again program, you can say I want 5 μs dead band, I want 100 ns dead band and I want so many nanoseconds dead band you can give that also can be given in a memory location.

So, it will generate the dead band and then give you the pulses. So, if you actually look at the CRO very clearly you will see between S_1 and S_4 there is a clear segregation, you will see that. In olden days we had a tough time, what we used to do is, if this is our pulse that is coming to S_1 and S_4 pulse comes like this we would try to introduce a mono stable multi-vibrator delay.

555 timer I do not know whether you guys have heard, 555 timer used to be our God literally. So, we will use 555 timer to first of all create a small pulse corresponding to in those days we used thyristors they required at least 50 μs or 100 μs delay. So, we will put an RC in our 555 timer which will work as a mono stable multivibrator and introduce a small amount of pulse.

So, the mono stable multivibrator can be triggered at a rising edge. So originally whatever comes out of our comparator that rising edge will be used for triggering the mono stable multivibrator which will generate a delay of 50 μs or 100 μs pulse width, that pulse width we will note it, AND it with the pulse that came out of the comparator itself. So, we will have actually the pulse out of the mono stable multivibrator something like this.

This and this will be ANDed together. So, what is unipolar sinusoidal pulse width modulation? So, let us again take it for just one half cycle. So, let us say this is going to be my sine wave for the first half cycle. So, this is $V_m \sin(\omega t)$, so we are going to have the reverse of this also being utilized in the control circuit. We have $V_m \sin(\omega t)$, we have generated this using may be an oscillator.

We can always use an inverting amplifier to get the $-V_m \sin(\omega t)$, okay. So, this is my $-V_m \sin(\omega t)$. Now I am going to have let us say a triangular wave, somewhat like this. So I am just showing a triangular wave as though it is somewhat like this, Now I will compare the triangular wave, the same triangular wave with both $V_m \sin(\omega t)$ and $-V_m \sin(\omega t)$.

So, if I have a triangular wave compared with $V_m \sin(\omega t)$, let us say during this portion, this entire portion I am having the sinusoid dominating over the triangular way. So let me probably call this as the positive portion for one of the pulses. So let us say during this portion I am going to have positive. During this portion I am going to have zero and similarly, unipolar that is why I am calling it as unipolar and during this time I am going to have again negative, zero and during this portion am going to have positive.

So, I am comparing $V_m \sin(\omega t)$ with that of the triangular wave like what I did in bipolar and whenever this is positive, let me redraw the circuit again, so that we know exactly what we are talking about. So, this is S_1, this is S_2, this is S_3 and this is S_4. So, the first comparison that is $V_m \sin(\omega t)$ and triangular wave comparison is going to provide the firing pulses only for the first leg only for the first leg. So, they are essentially not of each other.

So, I am going to have essentially S_1 being fired here, S_2 being fired here. Again, S_1 being fired here and S_2 being fired here and so on, you get my point. I have still not come to S_3 and S_4. So, in the same leg both of them will not be fired at the same instant. Please note that S_1 and S_2 are in the same leg. So S_1 will be fired whenever $V_m \sin(\omega t)$ is greater than the triangular wave.

And S_2 will be fired whenever $V_m \sin(\omega t)$ is less than the triangular wave, so this is one set. The second set would be I am going to compare $-V_m \sin(\omega t)$ with that of the triangular wave. That is going to provide the firing pulses for the other leg, the second leg. So, if I actually look at comparison of these two, first of all during this portion, this is smaller, the sine wave is smaller, let me probably use, so the sine wave is smaller than the triangular wave.

The sine wave, I am talking about this dark color whatever I have drawn that is smaller than the triangular wave. So, I am going to have a negative, And if I look at this portion only during this portion I am having the sine wave greater than the triangular wave. Triangular wave is smaller, so I am going to have positive pulse, Similarly, from here, I am having the triangular wave being bigger as compared to the sine wave $-V_m \sin(\omega t)$. So I am going to have this pulse.

And from here to here for a very short duration I am going to have again positive and it is going to be negative until this portion, so this is all negative. And from here it is going to be again positive. I have taken a very-very low frequency triangular wave just for demonstration, you get my point. So, during all this positive I am going to fire S_3, whereas during all these negative I am going to fire S_4.

Now please look at what happens when I am having S_1 and S_3 both being fired, this is actually my load. If S_1 and S_3 both are fired it is as good as freewheeling nothing else, you get my point. It depends upon in what direction the current is flowing. If the current had been flowing in this direction and if I fire S_1 and S_3 this diode will take over. Although I am giving a firing signal to S_3.

S_3 will not conduct if the current is flowing in the particular direction there will be a freewheeling through the diode and S_1. If the current had been flowing in the opposite direction it will be S_3 and the diode parallel to S_1. So, I will have essentially either I will have positive voltage, or I will have zero voltage or I can have negative voltage. So unipolar PWM technique where I am going to compare the sine wave as well as the reverse or 180 degrees shifted sine wave with that of the triangular wave gives me essentially three level kind of output I can have $+V_d$ or $-V_d$ or zero.

So whenever I am going to have a freewheeling interval I will have necessarily zero voltage. Whenever I am going to have S_1 and S_4 both conducting together then I will have $+V_d$ and whenever I am going to have S_2 and S_3 conducting together I will have $-V_d$. So, I can have three level output with the help of unipolar PWM sinusoidal PWM technique, And second thing is if am going to have S_1 and S_4 conducting during this portion, let me write probably this instant as t_1, this instant as t_2.

Between t_1 and t_2 I have S_1 and S_4 conducting together, so I will have $+V_d$, this is S_1 and S_4 conducting together between t_1 and t_2. After that I am having S_1 and S_3 conducting together. So, I am going to have zero voltage. So, I will have multiple switching's now, almost double the switching off what I got in bipolar. Compared to bipolar I will have double the switching in this particular case, but if I try to look at the devices individually, they are still not switching at a higher frequency.

Because I have segregated, S_1 and S_2 are being fired with the help of one sine wave. S_2 and S_3 are being fired with the help of another sine wave. So, the rate at which they are switching is still almost the same, but it looks as though I am going to get more number of pulses than what I got earlier for the bipolar. For bipolar, the number of pulses I got was equal to the frequency ratio itself.

Whereas here, the number of pulses I will get because in between I will have zero voltage interval. So, I will have necessarily the number of pulses doubled as compared to what I got in the bipolar switch which means although here the frequency ratio is m_f it will behave as though the frequency ratio is $2m_f$. So, this is essentially going to reduce the high pass filter size even further.

So, the unipolar switching is generally preferred if I am looking at something like a full bridge inverter, but whenever we use a bipolar, we are essentially looking at maybe one device is firing and opposite of that is the other device. So wherever only two devices are used, bipolar becomes a vouge that is one which is being used normally. So, whenever I have four devices sitting like a full bridge inverter I can go for unipolar.

Whereas, whenever I have only two devices sitting, where one is the NOT of the other as simple as that. In those cases, generally bipolar will be used as a rule and if I look at three-phase inverter. Three-phase inverter is only two devices per phase. So invariably we use only bipolar PWM technique for three-phase inverters, where I am going to use only two devices for every phase. So S_1 and S_4 will be for A phase, S_3 and S_6 will be for B phase and S_5 and S_2 will be for C phase. So essentially bipolar switching is used in these cases.

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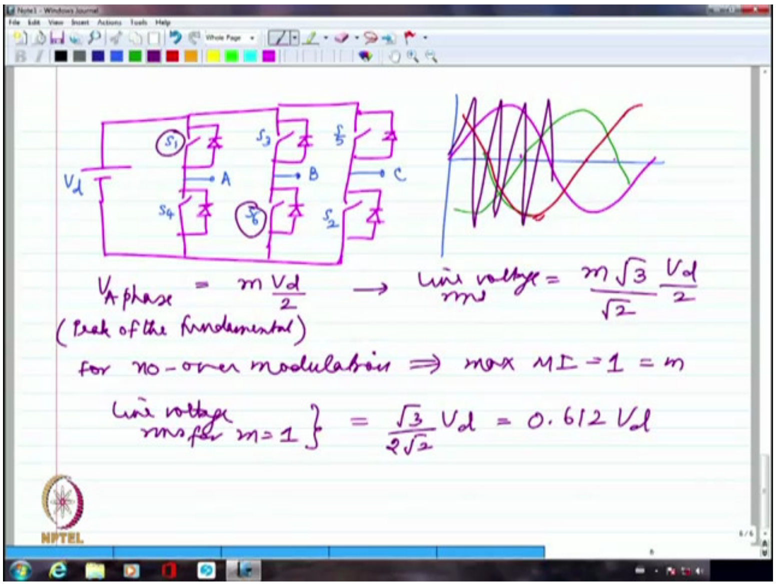

$$V_{A\,phase} = m\frac{V_d}{2} \longrightarrow \text{Line voltage rms} = \frac{m\sqrt{3}}{\sqrt{2}}\frac{V_d}{2}$$

(Peak of the fundamental)

for no-over modulation $\Rightarrow$ max $MI = 1 = m$

$$\left.\begin{matrix}\text{Line voltage}\\ \text{rms for } m=1\end{matrix}\right\} = \frac{\sqrt{3}}{2\sqrt{2}}V_d = 0.612\,V_d$$

So, coming back to the three-phase inverter. We just looked at 180 degree and 120 degree conduction mode I hope you guys drew the waveform for Delta connected load because I did it only for star connected load, I hope you guys have done it. So, in the case of three-phase inverter, so this is S_1, this is S_4, this is S_3, this is S_6, this is S_5 and this is S_2.

So, this is A phase, this is B phase and this is C phase. And what we have is V_d, the DC voltage that we have given as input. The same kind of modulation technique can be used for the three-phase inverter as well. Only thing is the modulating waves will become A phase, A_n and then B_n will be 120 degree shifted from A_n and C phase will be shifted again 120 degrees away from B_n, this is what is going to be the modulating waves for each of the phase.

So I will have to have three different waveforms completely, this is for A phase and for B phase I am going to have maybe the second one, somewhat like this and I am going to have the third one somewhat like this which is going to be the third phase and each of these have to be compared with the triangular wave. So, I may have to use the triangular wave which is of very high frequency like this.

So, I can compare the triangular wave with A phase, B phase and C phase respectively independent of each other and I should be firing device number S_1 and S_4 or S_3 and S_6 corresponding to B phase and C phase and so on. So, what we use in this case will be normally bipolar that is what I want to underline again. Normally what we use in this case will be bipolar unlike what we do in the other case.

So, if I am going to have two devices conducting simultaneously maybe S1 and S6. So what I get will be $\frac{V_d}{2}$ in this portion, another $\frac{V_d}{2}$ in this portion that is what I will get because that is what will be A phase voltage with respect to the neutral of the load. If I assume that the load is balanced than V_d is applied across.

So V_d is applied across A phase and B phase load. So, I am going to get A phase voltage to be $\frac{V_d}{2}$ and B phase voltage to be $\frac{V_d}{2}$. We already said that if I use sinusoidal PWM technique in bipolar modulation technique we are going to get the output to be proportional to the amplitude modulation index. So, if I try to look at what is A phase voltage it will be whatever is the modulation index multiplied by $\frac{V_d}{2}$.

This will be proportional to this and this is essentially the peak of the fundamental because essentially, I am using this as the modulating wave. My modulating wave is essentially a sinusoidal wave and the peak of the sine wave divided by the triangular wave peak is my modulation index. So, if I try to look at what is the A phase peak of the fundamental voltage that will be close to m multiplied by $\frac{V_d}{2}$.

So, this is going to be peak of the fundamental A phase voltage or phase voltage. So, if I want what is line voltage? RMS not peak, what I need to do is $m\sqrt{3}\frac{V_d}{2}$ this will be the peak of line voltage and if I want RMS I have to divide by $\sqrt{2}$. So I am going to get the light voltage RMS to be $\frac{m\sqrt{3}}{\sqrt{2}}$ roughly and if m is 1 at which I do not want to drop any pulses I do not want to go into over modulation the maximum voltage I will get for no over modulation.

The maximum modulation index is equal to 1. So, I can say line voltage RMS for m equal to 1 or modulation index equal to 1 will be $\frac{\sqrt{3}}{2\sqrt{2}}V_d$. If you calculate this it will come out to be about 60 percent or 61 percent, so it will be only about 0.6 times to be precise it is 0.612 or something multiplied by V_d. So, if I have 564 or 600 V as the DC voltage and if I use a bipolar sinusoidal PWM technique I will not get more than about 60 percent of whatever is my DC link voltage.

So, if I want about 360 V or 400 V I need to essentially say the DC link voltage has to be 400 divided by 0.612 that is the reason why we normally use a very-very high DC link voltage for most of the three-phase inverter configuration. We use something like 650 or 700 V all the time. So, whenever we try to use a three-phase inverter at 400 V level, RMS line to line voltage level, the DC link voltage as a rule in sinusoidal PWM technique has to be as high as 700 V, close to 700 V.

So, this is one of the major problems of sinusoidal PWM technique where we underutilized the DC bus. We design it for a very large value and ultimately what we get the output is much-much smaller this is one of the problems of sinusoidal PWM technique. We will look at how to improve this situation. How to utilize the DC link better in the next couple of classes.