Power Electronics

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Lecture 21

VSI PWM techniques-II

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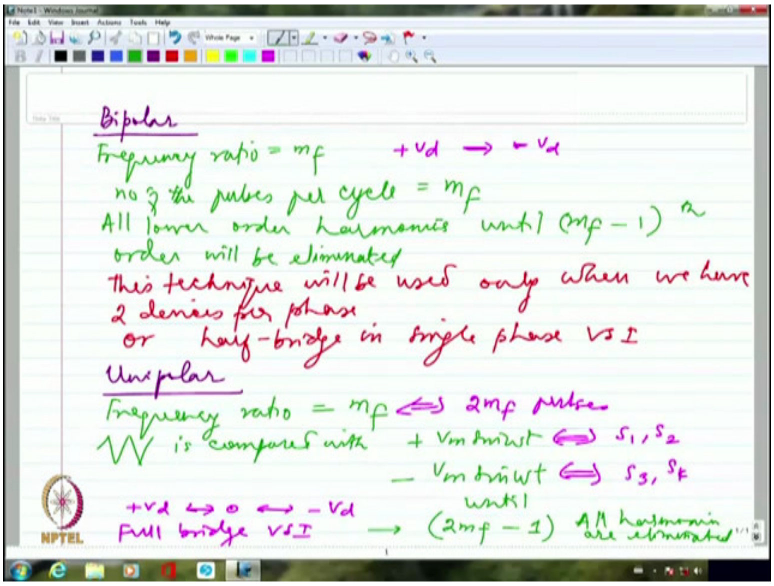

In the last class we had looked at various PWM techniques which are employed for single phase half bridge then single phase full bridge and subsequently for 3-phase as well. So, as I told you there is bipolar where if I am going to have the frequency ratio to be m_f then we are going to have the number of pulses per cycle will also be of m_f.

And we are going to eliminate all the harmonics, so all lower order harmonics until $m_f - 1$. If I am choosing m_f to be even then $m_f - 1$ until $m_f - 1$ all the harmonics will be eliminated, order will be eliminated. And we will have the variation of the voltage from $+V_d$ to $-V_d$ that is what we said.

That is why we call this as bipolar. And we said invariably this will be used, this technique will be used only when we have 2 devices per phase or half bridge kind of cell. Per phase or in a single phase case it is half bridge. We can you use this same technique even in full bridge case there is nothing wrong that means we can also fire S1 and S4 together and S2 and S3 together in bipolar configuration, but we cannot use unipolar so easily in the full bridge, I mean half bridge kind of configuration.

So, in this case, we are going to compare the triangular wave with $+V_m \sin(\omega t)$ and $-V_m \sin(\omega t)$ which are 180 degree shifted from each other. So triangular wave is compared with $+V_m \sin(\omega t)$ and $-V_m \sin(\omega t)$, this $+V_m \sin(\omega t)$ comparison will yield pulses for S1 and S2. They are NOT of each other S1 will be whenever $V_m \sin(\omega t)$ happens to be greater than the triangular wave. And the other one is just the opposite whereas this is going to give out pulses for S3 and S4.

So, in the same leg which are there S1 and S2 are there in the same leg, S3 and S4 are there in the same leg. They are not going to be definitely fired at the same time. So, this generally is going to have 2m_f pulses normally per cycle. Because we are essentially looking at S1 and S2, I mean S1 and S4 being fired by two different ways. So, we are going to have something like a freewheeling interval. So, we will have in this particular case, the level may be $+V_d$ to $-V_d$.

Whereas here I will have $+V_d$, 0 and $-V_d$ all 3 will be there. These are the 3 levels and we are going to normally use this in a full bridge VSI and if I look at the harmonic elimination, I am going to have $2m_f - 1$. Until this all harmonics are eliminated. So very clearly unipolar PWM technique is going to eliminate more amount of harmonics for the same frequency ratio as compared to the bipolar PWM technique. So, I will probably require smaller filter in the case of unipolar as compared to bipolar.

So, in that sense unipolar is definitely better but if you look at the switching frequency it will be almost similar. Because in the other case, S1 and S4 are fired together whereas here it is not that way. So, if you look at the frequency of firing of each of the devices it is almost the same. There is hardly any difference whereas because of the coinciding factor of S1 and S3 together or S2 and S4 together, I am going to have 0 voltages appearing here then there. So that essentially makes the number of pulses larger not because of larger number of switchings.

The switchings are still almost the same in bipolar and unipolar as long as I used the frequency ratio to be the same. So, so much so for recalling whatever we did in terms of bipolar and unipolar PWM techniques in the last class.

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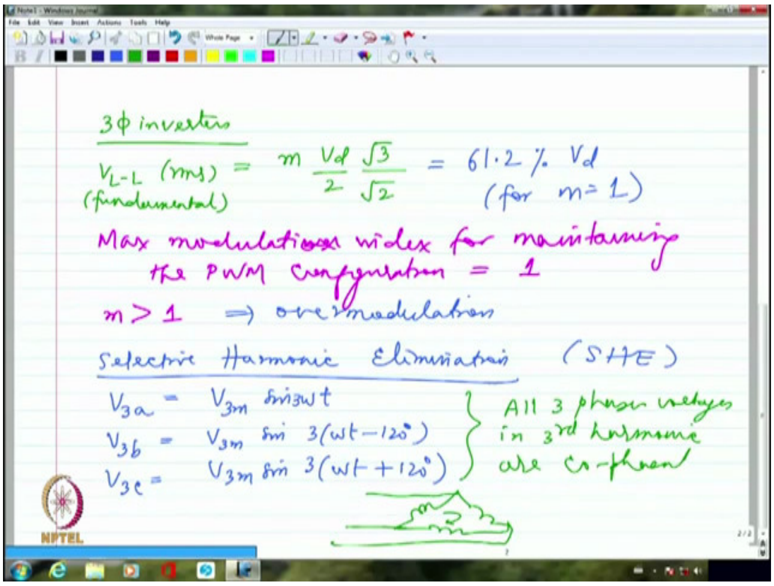

We ended with the fact that we can apply this directly to 3-phase inverters and then I had just mentioned that if I am looking at 3-phase inverters, I said that the line to line voltage RMS we get will be basically $m\frac{V_d}{2}\frac{\sqrt{3}}{\sqrt{2}}$. Because $\frac{V_d}{2}m$ happens to be whatever is the peak of the fundamental that I will be getting from which am looking at RMS value. So, V line to line RMS for fundamental of course.

If I am talking about the fundamental value RMS. This will be roughly the value of RMS fundamental that I can obtain which means that if I say I do not want to go into over modulation where m>1. The modulation index I do not want it to be greater than 1 if it is greater than 1 and tending to square wave. Slowly I am going towards square wave. So the maximum modulation index for maintaining the PWM technique.

For maintaining the PWM configuration that is generally m equal to 1, I do not want to go beyond 1 greater than, m greater than 1 will indicate over modulation. And I do not want to go into over modulation because this will essentially reintroduce the harmonics. I wanted to eliminate the harmonics that is why I was actually using PWM technique. If I make over modulation prevalent then I am going to essentially, we introduce the harmonics which I do not want to do. So, for m equal to 1so this is going to be essentially about $61.2\%V_d$ for m equal to 1.

So, I will not be able to really get a good amount of DC voltage rather than the amount of fundamental voltage. Although I am applying 100 V of DC what I get as the fundamental value may be only 61.2 volts nothing more than that. So I am not utilizing the DC voltage very well. So this is 1of the problem we face with sinusoidal PWM technique and that is the reason I told you that we normally use 650 to 700 V of DC link voltage. If I want about 400 or 415 V of line to line RMS whenever we use the motor drive we normally tend to use the DC link voltage which is like 600 to 700 V.

So that is the reason why we never choose a device even if it is 450 RMS we never choose a device which is only corresponding to 600 V or something. We generally choose a device such as 1 kV or 1.2 k V. We never choose a device which is corresponding to just 600 V. We always choose a device which is having much higher voltage rating like 1 kV or 1.2 kV because each of them might be facing a voltage stress corresponding to that value. So that is the reason why we normally tend to choose devices which are all larger rating.

And that is also 1reason why multilevel inverters are more being used, I mean extensively being used there especially in large capacity motor drives. Because I am looking at multilevel inverters each of them may be having a V_d of say 600 V or 700 V. So, I will be able to cater to the needs of say 1 kV drive or 3.3 kV drive. So, I do not have to really increase the rating of individual devices which will increase the price also tremendously and the stresses could be very very large.

And if 1 thing fails, I have just essentially shut down my shop. Rather than that at least if I have 2 or 3 stages of cascading operation, if 1cascaded step is gone I may be able to operate a motor drive attractively at a lower voltage level if there is any need something like that. So multilevel inverters are becoming more and more popular because of this particular reason as well.

Many people call it as SHE, SHE PWM technique. So selective harmonics elimination essentially refers to eliminating particular harmonics if I know that some particular harmonic is going to be dominating and that is going to cause the havoc in my system. Then I may be able to eliminate those harmonics they are no effectively by using this particular technique. So, I may not be able to really have all the harmonics eliminated that I can try to eliminate for example sixth harmonic seventh harmonic.

Generally, we do not talk about third harmonic so much because if I look at third harmonic normally it is co-phasal if I am looking at the 3-phase conflagration, this we talked about when we were talking about the magnetizing current and its harmonics in transformer. So, if I am talking about the third harmonic I should write V_{3a}, the third harmonic I should write this as some $V_{3m}\sin(3\omega t)$ or $V_{3m}\cos(3\omega t)$. This ωt has to be $3\omega t$ now. Because ω was fundamental frequency if I am talking about third harmonic it will be $3\omega t$.

If I am talking about V_{3b} that the b says third harmonic it will be $V_{3m}\sin 3(\omega t - 120^0)$. And V_{3c} will be $v_{3c} = V_{3m}\sin 3(\omega t + 120^0)$. So obviously I am going to have 360 degree coming into picture in b phase as well as c phase which actually makes all 3 of them co phasal because of this 360 degree that come into picture 3 times 120. So, because of which I am going to have all 3 phases or 3-phase voltages in third harmonic or co phasal.

So, if they are circulating a current through a star connected system for example, then I am going to have essentially $I_{3a} + I_{3b} + I_{3c}$ will be a nonzero quantity. And unless I provide a path for that I will be able to really allow that to flow. So even if it is delta it will just circulate within the delta. So, if I am talking about the delta connected 3-phase winding it will essentially circulate only within this because this is co-phasal. It is like a mesh current, all of them are co-phasal and they are equal in magnitude, so they can happily circulate around and around within that mesh itself delta itself.

So, you would not see any of them in the lines, normally in the lines you will not see third harmonic current. The lines will generally be divide of third harmonic currents even though I may have some third harmonic component in the voltage because they are co-phasal. So generally when I look at it from the point of view of a motor drive which is being supplied from this delta. Or if I am looking at any other line that is if I am actually an electricity authority and I am looking at the lines how they are carrying? What kind of currents they are carrying? They will not carry third harmonic.

So, I would not see third harmonic here, so I do not have to worry about third harmonic so much as an electricity authority or utility industry. Or if I am looking at even the inverter generating from third harmonic ultimately it will not be supplied to the motor finally because the lines will not be having the third harmonic. So, when we talk about selective harmonic elimination especially in 3-phase case that is why we will never talk about third harmonic much. But if I am talking about single phase case, yes, I might have to talk about third harmonic as well. So, in selective harmonic elimination the basic principle is somewhat like this. Let us say I want to generate a waveform somewhat like this.

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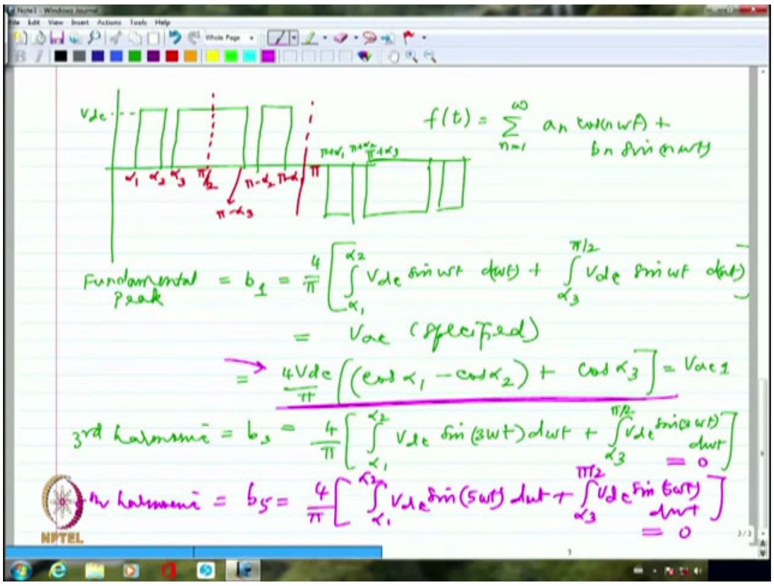

So this is actually 1 pulse and then I am going to have 1 big pulse and then again I am going to have a small pulse something like this. Let us say this is my positive half cycle that I want to generate from my inverter. I want to actually switch my inverter and these particular angles. So let us say I want this waveform to have quarter wave symmetry as well as half way symmetry.

So quarter way symmetry is if I say this α_1 and if I may call this as α_2, if I may call this as α_3 this is clearly $\frac{\pi}{2}$. So I can say if this is π, this particular thing will be $\pi-\alpha_1$, this will be $\pi-\alpha_2$ and this will be $\pi-\alpha_3$. So, in which case I can very clearly say this has quarter way symmetry. So, whatever is before 90 degree that exactly reflected on the other side also until 180 degree. And similar thing has to happen in the negative half cycle as well.

So, I should have 1 pulse here, 1more bigger pulse here and one more smaller pulse here. And I should be able to write this as $\pi+\alpha_1$, $\pi+\alpha_2$ this is $\pi+\alpha_3$ that has to be $2\pi-\alpha_1$, $2\pi-\alpha_2$, $2\pi-\alpha_3$. So, I can say that this waveform completely has half wave symmetry as well as quarter wave symmetry. Now the problem at hand is 2 fold, one is I have to eliminate specific harmonics and maybe I have to get certain amount of voltage.

Whatever may be the voltage maybe normally I am going to get 60 percent or 70 percent, I want to get probably 50 percent only. So, I might like to reduce the voltage and I might like to eliminate certain harmonics. For this how do I determine α_1, α_2, α_3. This is essentially the problem at hand. How long I am going to determine α_1, α_2, α_3 such that I obtained a required value of RMS voltage at the output and also I am going to get essentially some of the harmonic, specific harmonic eliminated.

So, if I write actually what is the fundamental value for this? So fundamental component because I have eliminated essentially, I have half phase symmetry as well as quarter wave symmetry. All the even harmonics will be eliminated, all the cosine components will be eliminated. So if I try to get the fundamental value, I should be fundamental peak for example which I may call as b 1. Again, we are writing the Fourier expansion similar to $\sum_{1}^{\inf} a_n \cos(n\omega t) + b_n \sin(n\omega t)$. This is how this function will be represented.

No DC components so I am not written any DC components basically. So we are going to have the fundamental value b1 actually if I say this is V_{dc} that is whatever is available from my DC supply side that voltage is V_{dc}. I should be able to write this as first of all from $\int_{\alpha_1}^{\alpha_2} V_{dc} \sin(\omega t) d(\omega t)$. Then I have to write from $\int_{\alpha_3}^{\frac{\pi}{2}} V_{dc} \sin(\omega t) d(\omega t)$.

And this has to be averaged over $\frac{4}{\pi}$ because generally if it is done for, the entire the cycle then it is written as $\frac{1}{\pi}$. If it is done for half a cycle than it is $\frac{2}{\pi}$, it is done for now quarter cycle it is $\frac{4}{\pi}$. So this is going to be the b_1 value, b_1 is the P cost the fundamental way. According to whatever I have generated as this voltage waveform, if I try to calculate the fundamental, this will be the fundamental value.

This fundamental value I might like to have it as same DC voltages 100 Volts, I might like to have it as 50 Volts, I might have to have it as 40 Volts, I might like to have it as 60 Volts whatever. So, I can choose what kind of value I want so this is fixed at specified value of AC. This is 1of the demands or 1of the equations that need to be satisfied. So, I should be able to definitely write exactly whatever is the value, so I can write $\frac{4V_{dc}}{\pi}\left[(\cos\alpha_1 - \cos\alpha_2) + \cos\alpha_3\right]$ is 0.

So, I should write $\cos\alpha_3$, so this is equal to whatever is the value. So, let us say V_{ac} specified whatever this is the first equation. The second equation maybe I would like to eliminate third harmonic if I am talking about single phase inverter, I should say third harmonic which is b_3. That will be again $\frac{4}{\pi}\left[\int_{\alpha_1}^{\alpha_2} V_{dc}\sin(3\omega t)d(\omega t)+\int_{\alpha_3}^{\frac{\pi}{2}} V_{dc}\sin(3\omega t)d(\omega t)\right]$. Again, I can expand this like what I have done here. Whatever I have the near similar to that I should be able to expand this.

It will also have 3 α_1, 3 α_2 and maybe 3 α_3 this is what will be there. Then I can write fifth harmonic if I want to eliminate fifth harmonic. So, I can write similarly $b_5=\frac{4}{\pi}\left[\int_{\alpha_1}^{\alpha_2} V_{dc}\sin(5\omega t)d(\omega t)+\int_{\alpha_3}^{\frac{\pi}{2}} V_{dc}\sin(5\omega t)d(\omega t)\right]$. So now I have got 3 equations if I want to make them a 0, I have to make third harmonic this is equal to zero and similarly this also equal to 0. So I have got essentially 3 equations and in this case I have drawn as though have 3 unknowns which are α_1, α_2 and α_3.

So, if I want to eliminate more number of harmonics I might have to have more number of switching's. So, it here I have g1only with eliminating 2 harmonic contents, third harmonic and fifth harmonic and have specified a particular value of fundamental. So, corresponding to these 3 I have got essentially 3 unknowns. So, if I want to eliminate, more number of harmonics I should have more number of switching's.

So please note that all these equations will have cos and sin, cosine and sine. So, we will not be able to really solve for them directly like what we do for algebraic equations. So, we need to use some kind of iterative techniques. Newton Raphson method that kind of method whatever is your iterative technique we have to use iterative techniques. So, I hope you guys have studied Newton Raphson method, know.

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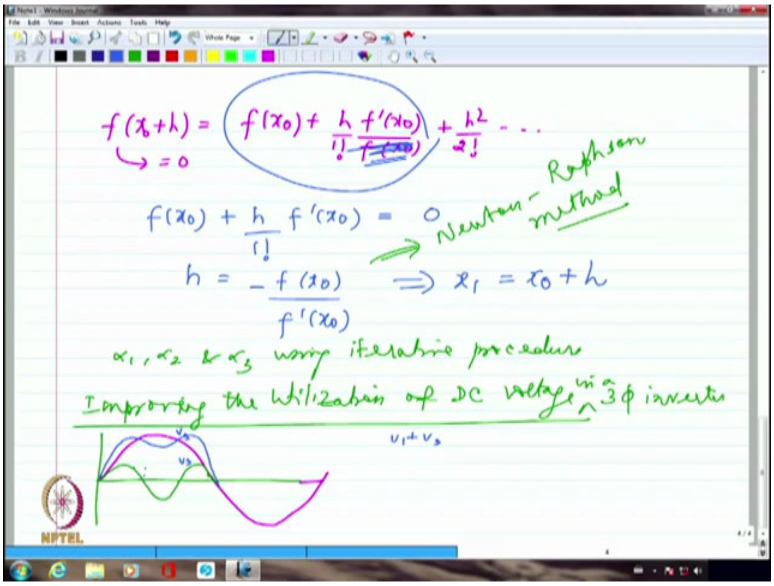

You guys know Taylor expansion, so Taylor expansion basically says $f(x_0+h)$. If I want to write, I should write f of x naught plus h multiplied by f dash of x naught divided by f of x naught divided by factorial 1 and so on, x square by factorial 2 and so on and so forth. So, if I say that this $f(x_0+h)=0$ is the function ultimately, I want to solve for where I do not know what is h? I do not know what is h?. So, I should say if I just take only the first order, I should say $f(x_0+h)$.

So we will get the type of x naught underneath here, $f^1(x_0)=0$. So, from here I should be able to solve for h, so h is whatever is the correction that I have 2 attributes to the original solution I have assumed. I have assumed x naught as the solution and if I have assumed x naught as the solution definitely it will not satisfy directly the equation $f(x_0+h)=0$. That is the equation that has to be satisfied. So, I can calculate what is f of x_0?

And I will be able to calculate what is $f^1(x_0)$ as well. From which I should be able to calculate what is h?. So $h=-\dfrac{f(x_0)}{f^1(x_0)}$. So, you get what is h, so this h is the correction that you're applying so you would be able to get x_1 the next iterative solution equal to x_0+h that is the next titrative solution. Now this you will use again for getting what is the next titrarive value of x which is x_2, x_2 will be x_1+ h the next h you calculate and so on and so forth.

So you would essentially assume initially certain values of α_1, α_2 and α_3. I can simply assume them to be maybe 30 or there 15, 45 and 75 or something like that arbitrarily. I can just assume those values and then slowly iterate them. So, I have to essentially iterate them with 3 functions, I have 3 functions here. 1 corresponding to third harmonic, 1 corresponding to fifth harmonic and 1 corresponding to fundamental. So, this has to be solved iteratively.

By solving them iteratively using Newton Raphson method. So, this essentially this particular calculation of h using Taylor's expansion, this is generally known as Newton Raphson method. So, Newton Raphson method is extremely useful where you start off with 1 particular assumed solution and then you iteratively solve it. And between the 2 consecutive solutions when the difference becomes less than some epsilon. Then you say you have already reached the convergence. That's how we generally do the iterative differential solutions generally.

So we actually will solve for α_1, α_2 and α_3 using iterative procedure. One thing you have to realize is that this α_1, α_2, α_3 because it is a long drawn process to solve for it, it is not a very simple thing. So we will not be able to do it online in the sense we will not be able to do it in real-time. Then I really want to control my inverter I was telling you that with analog electronic circuits with micro processes with digital signal processors I would be able to do this but not selective harmonic elimination.

You have to solve for it already and you should store α_1, α_2, α_3 inside your computer, inside your micro processor, inside your digital signal processor and correspondingly generate the pulses. For firing different devices that is the only way out. So selective harmonic elimination normally is not an online procedure, directly you can implement in analog electronic circuits or even digital platform, real-time implementation is difficult. So you have to pre calculate the values and then store them.

So sometimes we adopt lookup table kind of approach. If I want 80 percent of V_d, if I want 70 percent, if I want 50 percent and then if I want to eliminate these harmonics, these are α_1, α_2, α_3. We solve for it and then store it lookup table and then correspondingly we try to you now fire the inverter accordingly. So, this is definitely not possible if I want to do it with analog electronic circuits. It's very very difficult to implement selective harmonic elimination with analog electronic circuits.

We normally do it only in digital platform with the help of lookup table approach. But nevertheless, this has one major advantage with limited number of switching's. We will be able to eliminate specific harmonic if I want to eliminate specific harmonics. And then again use a high pass filter eventually to actually eliminate all the or bypass all the high order harmonics. So, if I want to specifically eliminate only particular order harmonic, it would be possible to use selective harmonic elimination that is one of the major advantages.

We told that in a 3-phase inverter what we get as the line to line voltage is about only 60 percent. If I want the modulation index to be one, I do not want to go into over modulation, but I want to utilize the DC voltage better if there any other way out. So, there is one particular method which is being used to improve the utilization of DC voltage.

If I want to really improve the utilization of the DC voltage specifically in the 3-phase inverter. If I am talking about the 3-phase inverter. So, in a 3-phase inverter what I can do is? I used normally the modulating wave to be a sinusoidal wave. Rather than using a sinusoidal wave, if I just use sinusoidal wave like this and then on the top of this if I add a third harmonic. Let us say we try to look at the third harmonic.

So, the third harmonic is going to be somewhat like this, this is how it will be. You understand because within half cycle I have to have one and a half cycle only then we call that as third harmonic. So, the summation of these 2 will essentially become, here I am going to have a little increased value. Let me call this as V_1, this as V_3. So V_1+V_3 I am trying to draw, so when I add this the pink color and the green color waveform it will increase initially and at this point it is going to start decreasing something like this.

And again, it will increase here and somewhat like this, this is how it will be. So that is essentially the summation of V_1 and V_3. So, if I use this as the modulating wave, I can afford to increase the fundamental magnitude further and further because third harmonic is pulling it down near the peak the third harmonic is pulling it down. Because the third harmonic is pulling it down near the peak, I can actually make the peak higher than what I have chosen originally with modulation index equal to one.

So, let us say that triangular wave peak is hundred volts. The sine wave peak also I would have chosen as hundred volts if I am talking about modulation index equal to one. But if I am choosing the third harmonic with the peak which is corresponding to let say 15 V, 15. Then I should be able to choose this sine wave rather than having hundred volts peak it can have 115 V peak. So that the third harmonic even if it pulls it down, it is bringing down to 100 volts.

So, it will look as though at every point my triangular wave will have an intersection with the summation of V1 and V3. So, my fundamental voltage will increase by about 15 percent if I am actually adding a third harmonic wave which is having about 15 percent of the peak magnitude of the fundamental, original fundamental wave. So, I would be able to enhance the fundamental wave by a certain magnitude provided I add actually to the original fundamental whatever is the new third harmonic.

If I add them together and use them as the modulating wave. Please understand that whatever is my modulating wave the output produced would essentially emulate my modulating wave with the, modulating wave is sinusoidal I will have a sinusoidal output. If the modulating wave is rectangular, I will have a rectangular output, so here my modulating wave is summation of fundamental and third harmonic. So, what will be produced that output will consist of third harmonic as well as fundamental, but it is a 3-phase inverter.

So, I could not care less if there is third harmonic. So, this particular methodology essentially allows us to utilize the DC link voltage better than what we utilized in the sinusoidal PWM technique. This is essentially addition of the third harmonic component to the original sinusoid so that I can enhance the amplitude of the fundamental wave. But the presence of third harmonic will not affect the output of the inverter especially in the 3-phase case because anyway third harmonic component are co phasal and those currents will not exist at the output.

So, this is very very commonly used in many of the 3-phase motor drives. If I want to really enhance the output of the 3-phase fundamental wave then I can summation of this single phase, I mean fundamental and third harmonic together to make that as a modulating wave. So that is one of the applications where we’re trying to enhance the output of the inverter yeah.

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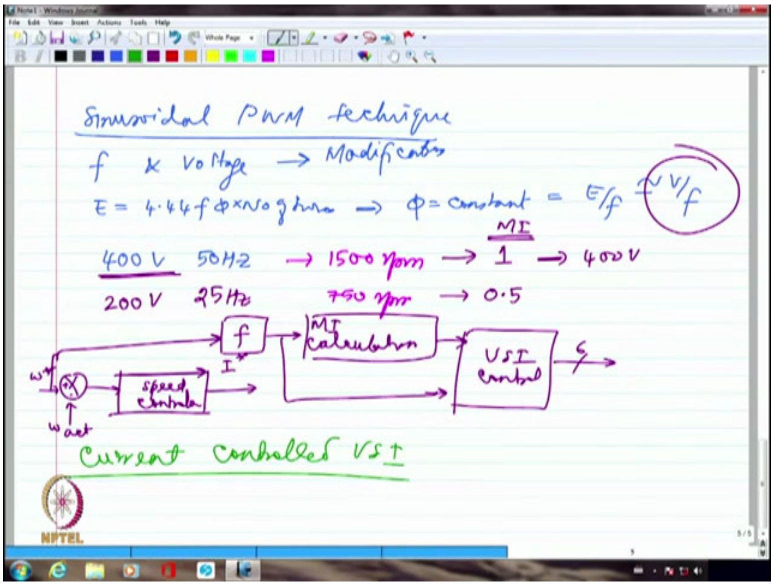

Student: Can we add sixth harmonic instead of third harmonic for enhancing the output voltage?

Professor: Fundamental yes, you can add sixth harmonic, but sixth harmonic is even. Most of the times what we do not want to do is to enhance the even harmonic at any point in time. If you look at the power quality considerations normally, if you look at any of the regulation that are imposed by power quality authority. They generally at least will give some amount of lenience towards odd harmonics. Even harmonics they will take very stringently.

No even harmonic can be present they will say it cannot be more than 0.05 percent, 0.07 percent so there extremely stringent about even harmonics. That is one reason why generally we use m_f that is the frequency modulation ratio as an integer because otherwise you can have something like sub harmonics. What you mean by sub harmonics is? For 50 Hz we generally expect 150 Hz maybe there then 250 Hz maybe there and so on and so forth. It is all integer multiple.

But if I use frequency ratio of 1.27, 1.5 something like that then I may have suddenly 50 Hz then suddenly 70 Hz might appear then some 85, 90 Hz might appear, and it will be too difficult for us to deal with all those sub harmonics. Sub harmonics are those which are not integer multiples of fundamental so that is 1reason we do not generally use frequency which are, and we never use a wave which is not having halfway symmetry generally because we do not want even harmonics or DC value top here.

And DC values generally are deadly for any AC machines, for transformer. For example, it can lead it to saturation completely because fluxes in one direction and it is going to the keep on increasing if at all. There is nothing like defluxing that is happening in alternating current you are having flux developed in a particular direction and flux is developed in the opposite direction. So, it is fluxing and defluxing if you may call it but in this particular case if it is DC you're not going to essentially, you are going to allow the transformer to saturate that is the problem.

So even harmonics are generally never added you may say ninth harmonic, but ninth harmonic magnitudes are generally much small. As the harmonic order increases, generally the magnitude of the harmonic content will decrease. The thumb rule is as if I have something like a square wave, if I say fundamental is hundred percent. Generally, third harmonic will be one third, 33 percent, fifth harmonic will be about 20 percent, seven harmonics will be one seventh and so on that is how it is. If you actually calculate the furrier coefficients this is how they will be. Normally it will be for a square wave.

So generally, as the harmonic order increases it's going to become less and less. But when used sinusoidal PWM, I told you that frequency ratio we are going to have the peaking of that particular harmonic, yes it will happen in sinusoidal PWM. How do we actually modify the frequency and voltage simultaneously especially when we are feeding a motor drive? If you may recall you guys have done one experiment in induction motor where we used an inverter, that inverter was having basically voltage and frequency both were controlled.

And if you may recall we wrote actually for transformer as well as induction motor this equation is valid for 4.44 f Φ multiplied by number of turns. This is the equation we normally wrote, if you may recall. So, if I want to hold flux as a constant, I have to essentially hold $\frac{E}{f}$ ratio as a constant. And E, I will not be able to measure because it is internal voltage. In the induction motor whatever I apply as a voltage minus the stator drop, what is coming across the air gap that is E.

So, let me write this is approximately equal to $\frac{V}{f}$. So, if I am talking about a 400 V 50 Hz induction motor, if I am talking about a 400 V 50 Hz induction motor maybe it's normal traditional velocity is 1500 rpm close to, I am not saying exactly closed to 1500 rpm 4 pole induction motor. So, if I am talking about running it at 750 close to 750 rpm I have to apply essentially 25 Hz. And if I want to keep the flux almost as a constant, I have to apply only 200 Volts not 400 Volts close to 200 Volts line to line nothing more than that.

So, I have to adjust the frequency and the voltage magnitudes simultaneously which means I necessarily need to have an oscillator which will actually generate maybe 25 Hz, maybe 50 Hz whatever is the value of the frequency I want it to generate then the triangular wave frequency also needs to be adjusted. Because if I want to hold the frequency ratio as a constant that are triangular wave frequency also needs to be adjusted which is actually very difficult in analog electronic circuits, we have faced the music all the time.

So, I know that it's not easy to generate a triangular wave so easily at variable frequency because you have to change smoothly. You cannot say I am rotating the motor at 25 Hz, I want to jump it to 50 Hz away that not possible. So, you have change it smoothly which means both the oscillators, the triangular wave oscillator as well as the sinusoidal oscillators have to change their frequency smoothly. This can be very nicely, very easily done in digital.

All you need to do is to give the numbers, you get 25 Hz, you get 50 Hz, you say this is the frequency ratio I want it will very nicely generate all the pulses. So, in digital implementation it becomes much simpler but how do I adjust the voltage magnitude? That is done by the modulation index, so if I assume that the modulation index in this particular case is 1. I would try to choose the modulation index in this particular case, amplitude modulation index to be 0.5. So, when we generate the sine wave not only the frequency needs to be adjusted, I will very clearly adjust the amplitude, peak amplitude because I will keep the peak amplitude of the triangular wave as a constant.

So, once I vary the peak amplitude of the sine wave keeping the peak amplitude of the triangular wave as a constant, I am modifying the modulation index. So if I am having the modulation index here as 1and if I am getting 400 Volts obviously the output is proportional to the modulation index because of which automatically I am going to have the amplitude of the output or RMS value of the output being decreased to half the original value. So I have to do multiple things simultaneously, first of all adjust the frequency of the modulating wave, adjust the frequency of the triangular wave if I have to do it in analog it's not going to be easy. And adjust the amplitude, so that amplitude only of sine wave not the triangular wave.

Triangular wave I would like to keep the amplitude as a constant. So this is how we normally do it when we really want to control a motor drive. So we actually are going to adjust all of them simultaneously. So, if you actually look at the normal if I say this is the speed I want then this is the actual speed, so I will compare these two it is like a control system very clearly I will compare these two. The output whatever I have got this is going to decide really what is the kind of current or torque or whatever needs to be generated from the motor drive so that the gap in the two speeds is bridged.

The reference speed and the actual speed whatever is the gap that will bridged. So, I necessarily need to hear decide what is, so this is the speed controller maybe it can be PI controller or whatever. The output what is coming out of the PI controller will reset where I need a particular current because $\frac{3I_2^2R_2}{s}$, for example is your torque. So, I can directly control what is the current.

So, this will actually give me $I_{reference}$ but from here from omega whatever is a set value this will set my frequency. Because if I know this is probably going to be my synchronous speed closest so I can definitely decide what is the kind of frequency I will require roughly. So this will set my frequency from omega star I will be able to set the frequency. And if I know frequency because I want to keep $\frac{V}{f}$ ratio as a constant, I should be able to say what is the kind of voltage that I need to generate from my inverter that will set the modulation index.

So, from the frequency I can calculate modulation index. Once these two are calculated the frequency will go independently, modulation index will go independently to the VSI. Of course, VSI control circuit, I will have a control circuit which will generate all the firing pulses which will go to the VSI. So, let me probably show this as control, so from this I will have six pulses coming out. Now this is essentially independent of the current so I may not be able to control the current very nicely in this particular case.

But if I want to control the current very often what we try to do is to merge voltage control and current control together. At that point we call that as current controlled VSI. So, we may like to actually monitor the current also in this particular case we will not be able to monitor the current at all because I have already given the pulse it is going the inverter. Inverter generating the voltage and it is simply going to the induction motor. I might have to sense the current feedback, I have to give the feedback and then I might have to stop the firing pulses with the current is going to high.

So, in current control VSI, I would like to take a feedback from the motor drive or the inverter because they are connected in series the output current of the inverter or input current to the motor drive I will monitor. And I would like to put that as one of the inner controls within the firing pulses generation circuits. So, the firing pulses generated whether I release it or not it is going to continue or not is decided by whether the current is within the threshold or whether it is beyond the threshold.

So apart from voltage source inverter or current source inverter this is a third category. A voltage source inverter where there will be a current control which will be build in and this is essentially used in many of the motor drives. VSI with no current control is not used very commonly in motor drives. UPS can use it not really motor drives. So, these are different categories of inverter it is just a matter of detail, I am mentioning because these are actually employed in the field. Direct VSI with the sinusoidal PWM technique without current control is not used very commonly, with current control it is used along with motor drive. So, a half bridge inverter, yeah.

Student: How do we implement current control in VSI fed drive?

Professor: Yeah, if it has to go if I have to show this not as a VSI control without current control. So, I have to essentially compare this with whatever is the I actual and I actual generally will be sense either from this on the motor or one more way of sensing it is I will definitely have a rectifier here. And I will have essentially a current here which is going into the inverter I can sense that, so this has to be taken at this. Now the output of these has to either block or I can say if I have device number one and device number 4.

If I give firing pulses to device number one the current of A phase is going to increase. If I give the firing pulses to device number 4 the current will start declining because it is connected to the negative. So, I can switch between the 2 devices 1 and 4. So this will work as an override, over whatever is the PWM scheme even I am employing because this will protect the motor drive against current increasing beyond a particular value. So this has to actually override whatever your PWM technique is do.

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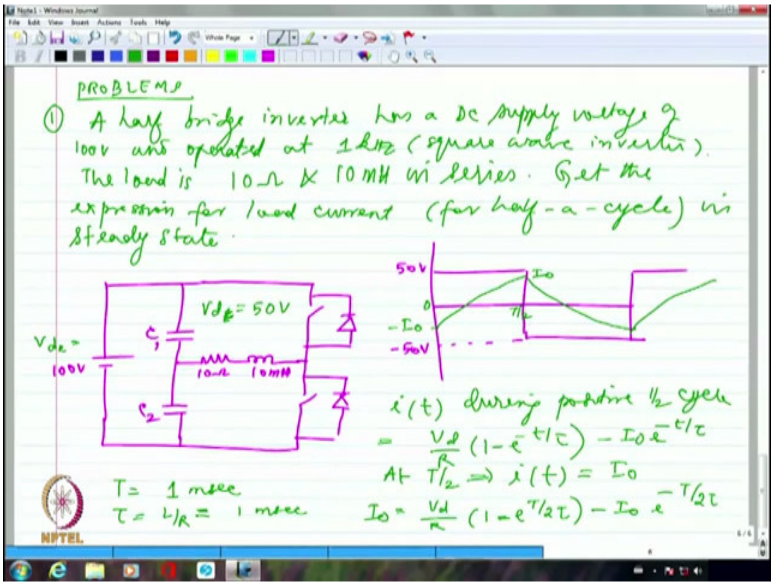

The problem statement goes as follows a half bridge inverter as a DC supply voltage of hundred volts and operated at 1 kHz. 1 kHz is not switching frequency, 1 kHz is the output frequency itself, so it a square wave inverter. The load is 10 Ω and 10 mH in series, get the expression for load current for half a cycle in steady-state.

So, we will have two capacitors and we are having RL load and here is one switch and here is the other switch and we are going to have diodes so this is 100 volts and these are 2 capacitors and this is 10 Ω, this is 10 mH. They are asking for steady-state expression, so we might have to solve for the initial condition also that is what it is.

So, if you may recall I think we actually drew the waveform somewhat like this if we are going to get the voltage like this, so this will be 50 Volt and 50 Volt across the load. Because the capacitor will have only half the voltage and then you have to essentially show as though a current might come from the negative side and it will go like this and then again it will go like this and so on and so forth. This is how the current is going to be.

So, what is being asked is to get the expression for half cycle of the current that's it because it is RL load. So you can say that this is 1 kHz so the period is going to be 1 ms and time constant also we can get $\frac{L}{R}$ which is $\frac{10mH}{10}$, so that is also 1 mille second. Time constant of the circuit is also 1 mille second. So, you can calculate basically, let us write expression in terms of if we say V_{dc} is V_d is 50 V. So, this is V_{dc} which is 100 volts.

So, we have to write i(t) during positive half cycle will be what? It will be $\frac{V_d}{R}(1-e^{-\frac{t}{\tau}})$ that is one portion. The other one will be whatever is the current that it is starting of with, if I may call this as I_o, so it is going to be and if I say this is $-I_o$ this will be $+I_o$. In steady-state both have to be the same when once it reaches the steady state, I should have positive peak and negative peak magnitude should be equal to each other that's when you call it as steady-state.

So, I should say $\frac{V_d}{R}(1-e^{-\frac{t}{\tau}})-I_o e^{-\frac{t}{\tau}}$. This is what will be the expression for the current for current differential equation solution. And to solve for I_o I should be able to say that when it is a half cycle. I should be having again i(t) to be I_o itself. So, at t/2 if I assume that this is 0 and this is t/2. At t/2 i(t) is equal to I_o.

So, I should be able to say $I_o=\frac{V_d}{R}(1-e^{\frac{T}{2\tau}})-I_o e^{-\frac{T}{2\tau}}$. So, t and τ were exactly the same 1 ms, so e power minus half we will have to substitute and then we should be able to get what is the value of I_o. Once we have the value I_o you have the entire expression with you. 50 divided by 10 which is 5 multiplied by e power minus t by tau, τ is 1 ms so minus thousand t.

Minus I not value you can solve for from whatever we have written, so the expression is there get my point. So, it is essentially your second transition solution nothing more than that. So, this will be the expression during the positive half cycle. So, this is true only ones the circuit reached its steady-state, so initial state if you have to solve initial few cycles definitely you see you will get the positive half is dominating over the negative half if it is has started with the positive half cycle. So, you would see that is the current is dominating over the negative.

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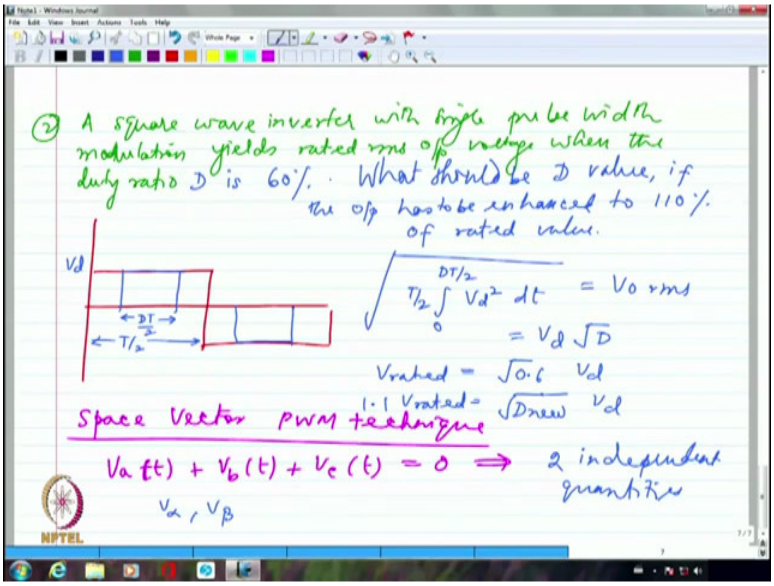

A square wave inverter with single pulse with modulation that is only one pulse being modulated. Modulation yields rated RMS output voltage when the duty ratio you may call that as duty ratio that is for example, if I am having this as a complete positive half and this as the complete negative half. If this is conducting only for 50 percent of the time.

So, I am calling that duty ratio as 0.5, so out of the total duration how long each of the devices conduct. So, they are supposed to conduct 100 percent of the duration if a square wave inverter rather than that I am probably making it on only for 50 percent of the duration. So, if I say that this is essentially $\frac{DT}{2}$, this entire thing is $\frac{T}{2}$.

So the duty ratio we define as this, so when the duty ratio D is say 60 percent. What should be D value if the output has to be enhanced to 110 percent of rated value? Very simple though only thing I want to emphasize is we have to take $\sqrt{D}$, you understand the point. Because when we are actually looking at the output it will be RMS value. So I should say if this is V_d, I should say $V_d^2 D(t)$ and $D(t)$, I have to essentially take it from 0 to $\frac{DT}{2}$ and I have to average it over $\frac{T}{2}$.

So, I will get essentially whatever is $V_d\sqrt{D}$ as the RMS value that is what I wanted to emphasize. That is why I just took this; the same thing holds good for AC voltage controller you remember. When we did integral cycle control, we said it is route of m by m plus n. The same thing holds good here because it is going to conduct only from let us say from 0 to $\frac{DT}{2}$.

But it has to be averaged over $\frac{T}{2}$ and we have to say $V_d^2 DT$ and then it has to be taken as square root this will be my V_o RMS. So essentially what I get will be $V_d\sqrt{D}$. So, in this case I have to simply say $V_{rated} = \sqrt{0.6}V_d$. So $1.1V_{rated} = \sqrt{D_{new}}V_d$, so you should be able to calculate what is D_{new}? So, space vector modulation technique normally we have in 3 phase cases, 3 independent quantities to be controlled.

We generally say v_a, v_b, v_c but we also know that normally in any 3-phase configuration we will have $v_a(t)$, instantaneous voltage $v_b(t)$ and $v_c(t)$ together will make up for 0 at any point in time. So you cannot say all the 3 are completely independent quantities. They can be definitely represented by just 2 quantities they are only 2 independent quantities. So normally what we trying to do is to transform these 3 quantities into 2 independent quantities.

And we call them as α and β. The first of all transform the 3-phase quantities into two independent quantities which are α and β. And we generally take them as perpendicular to each other if α is along a phase axis we take β perpendicular to it. Some books take this as leading, some books take this as lagging, I take this normally as leading because that is the way I have learnt completely my transformations. So, I generally go with the leading, beta leading over alpha. So, I will essentially let us say this is v_a, v_b, v_c and I am going to take essentially α along this and β along this.

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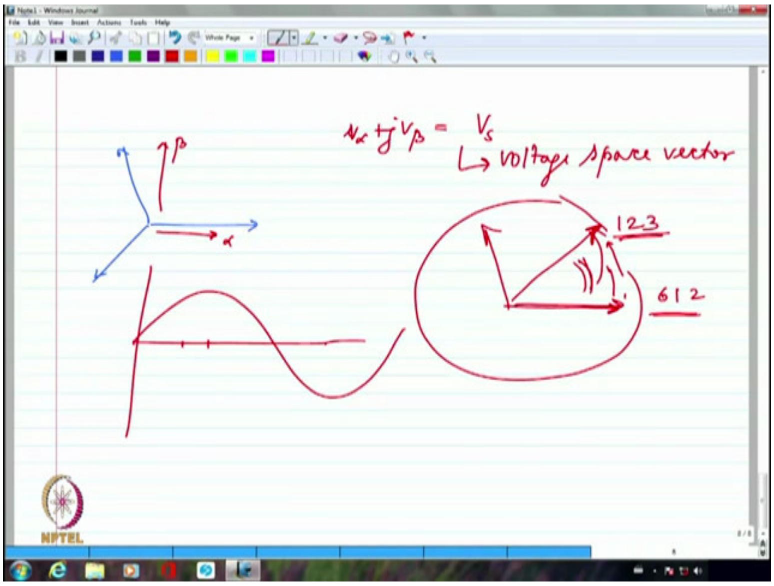

Once I transform the voltages that are independent of each other or the currents which are independent of each other which are in 3 phases into α and β. I should be able to write this as a complex number representation, I can always write $V_\alpha + jV_\beta$ is what is the overall voltage of all the 3 phases. So instead of having 3 independent voltage quantities, I can merge them into a single vector I call this as the space vector.

So, this particular vector which is actually combining all the 3 phase quantities into a single complex quantity. We call this as the voltage space vector. It's very difficult to actually give a physical meaning for the voltage space vector but for current we may be able to give it better. If you may recall in induction motor, we said we have i_a, i_b and i_c passing through space distributed winding which gave rise to a revolving magnetic field. So, when a current is flowing through an inductive coil, we are able to at least give it a physical meaning saying that it is actually showing a particular value of probably the flux combined together.

When you actually combine all the 3-phase fluxes together. And that is showing a revolving magnetic field that is what we said. So essentially for voltage it is very difficult to give a physical meaning but for current at least they would be able to say it is showing a flux vector which is visualized in a space maybe in air gap or whatever. So, what actually the inverter control using space vector modulation does it is if I have v_a, v_b, v_c which are sinusoidal in nature normally. We say that at a particular situation maybe my flux vector or the current vector is this way.

After some time, it rotates like this, after some time it goes on rotating in anticlockwise direction if I keep applying a 3-phase quantity to a 3-phase winding. So, whenever I am going to have only 3 switches of the inverter on, maybe it is 612, maybe 123, maybe 234 and so on. Can we say that the voltage occupies this particular position, maybe it occupies this particular position, maybe it occupies this particular position whether can be correlate a particular situation or the on state of different switches with a particular position of the space vector.

So, what actually people who had worked on space vector modulation did was to rather than jumping from say 612 to 123 directly, can I make a movement which is slow and steady. Then it will essentially emulate exactly a sinusoidal transition. It will not jump from 612 to 123, 123 to 234 and so on. If I can do it slowly maybe if I can get something in between, in between states how do I get? I am not sure because 612 is a discreet way of turning on 3 switches and again from that you can jump to 123.

But how do I achieve in between the 2 states? So that is what space vector modulation technique addresses. How do I really get into anywhere in between because if I say discretely this is corresponding to 612 to being on, this is 123 being on. How do I achieve any of the states in between? If I can decipher that I would be able to make my inverter function in such a way that it generates some wave very close to our sinusoidal. And that is the flux of space vector modulation.

So, what we will do by stating about space vector modulation is first of all we will try to map each of the inverter states that is whether it is 612 or 123 or 234 to a particular space vector position. Once we do that then we would try to find out if I want to generate a voltage which is corresponding to somewhere in between. How do I do that? Really by making use of these finite states of the inverter, I have only the finite states because I have only six switches. So, using that I have only finite states of switching.

So how do I really generate any voltage which will be mapped somewhere in between and among these discrete states by adjusting the switching combinations? So, this is what we are going to look at for space vector modulation and this actually allows us to utilize the DC link voltage also much better. So that is why I would like to conclude the PWM with this space vector modulation.