Power Quality Improvement Technique
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Lecture – 25
PWM for Voltage Source Inverter – III

Welcome to our lectures on NPTEL and courses on the Power Quality Improvement Technique. Today will be our third class on the PWM technique for the voltage source converter. We shall start where we have finished in our previous class. That was the space vector modulations which will for the just sake of our recapitulation. We have discussed this thing.

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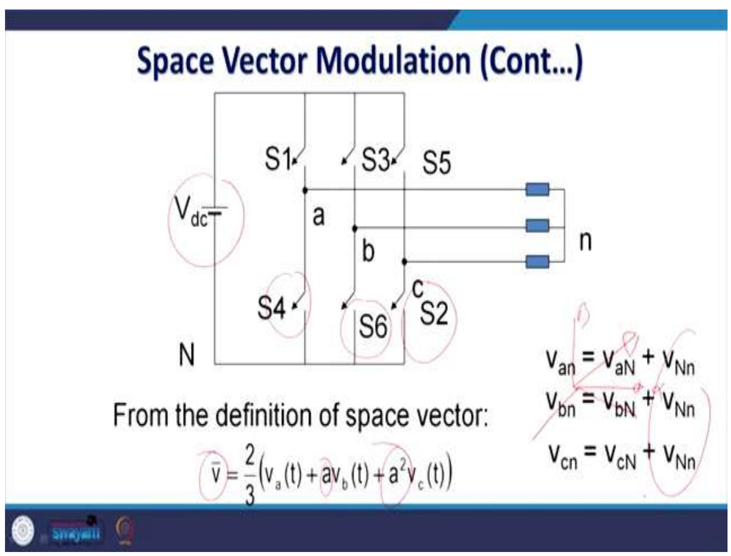

So, this is the V_{dc}, and upper three switches will be named 1, 3, 5, and lower three switches will be named 2, 4, 6 to maintain the difference of 3. Anyway, that is a same thing what we did in case of the full control converter t_1, t_3, t_5, and t_4, t_6, t_2 same thing will be used here and here formation of the voltage vector. We have seen that how to represent the 3-phase into the (r, theta) coordinate. First from 3-phase we shall take it to the alpha-beta frame and from alpha-beta frame we shall go back to the (r, theta) coordinate.

So, from the definition of the space vector it is 'v' that will be called 2 by 3 into v_a, 'a' gives you 120-degree phase shift and this 'a' square gives you 240-degree phase shift. So, we have discussed these things. Why this neutral voltage will not arise when you have shorted?

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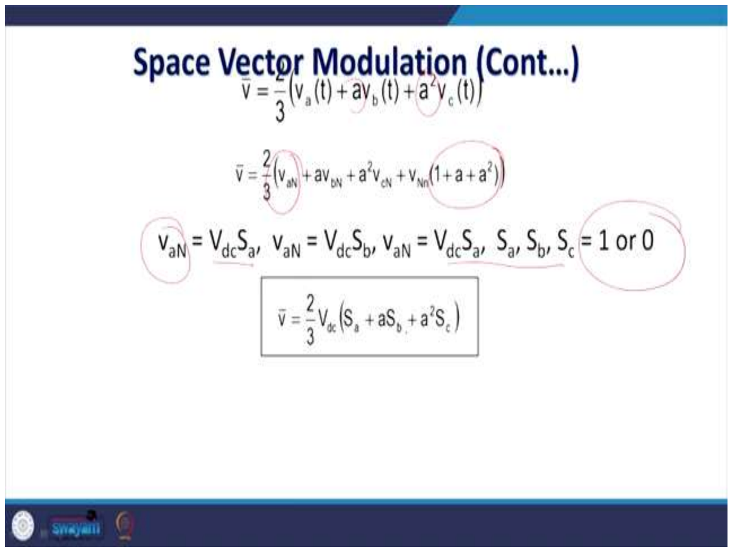

So, now we shall go to the next. That is the voltage which is given by two-third, v_a, v_b. v_a and v_a will be multiplied with the 'a' to make it a 120-degree phase shifted and v_c will be multiplied by 'a' square to get aligned with a particular vector. Now, you can say that v_a two-third that is we can go back. That is $V_{an} = V_{aN} + V_{Nn}$.

So, we can rewrite like this. So, $\bar{V} = \frac{2}{3}(V_{aN} + aV_{bN} + a^2V_{Nn}(1 + a + a^2))$, ultimately this summation generally gives you the 0. So, thus it will be '0' and thus, you are just left with this part of the value and thus what we can say that V_{aN} will be generated solely when you have $V_{aN} = V_{dc}S_a$.

So, similarly $V_{aN} = V_{dc}S_b$ and thus V_{aN} equal to we have V_{dc} into S_a, S_b, S_c depending on whether it is 1 or 0. Thus we can replace these values with V S_a, S_a into the switching state that is 'a' into S_b 'a' square into S_c.

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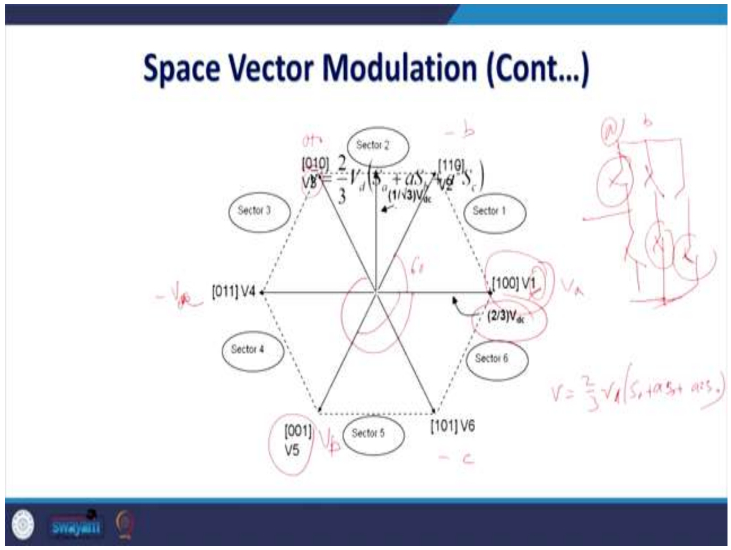

So, the switching logic comes into the picture. Thus, what you have is only this value. Thus, it is $\frac{2}{3}V_{dc}(S_a + aS_b + a^2S_c)$. Now, this is the typical two-level phase vector representations. First of all, if you want to have this vector which is said to be ‘a’ that means that is in upper leg of ‘a’. It is closed and it is opened and for the lower two leg this is open and this one is closed. Let us say this is ‘a’, and this is ‘b’, and this is ‘c’.

So, what happens? This upper leg is closed and these two legs are closed. So, ultimately voltage will be Va and this will say that it is [1 0 1] or it is Va. Similarly, ‘b’ phase will be lagging by 120 degree. For this reason, what will happen? Ultimately, this switch will be closed, and this switch will be open, and this switch and this switch will be closed.

For this reason, you get the this which is basically your minus this is basically your V_b. Similarly, another 120-degree lagging that is 240 degree and you will get your V_c. So, you will have [0 1 0]. So, from there you will start this convention and generally we have chosen this convention something like this and of course, you can rewrite this convention in some other form also.

Now, we will be splitting it into the sectors. Thus, what happen if it is V_a, it should be minus V_a. So, you can see that one correspondence to the switch. You know once you go back to this circuit, this is one and other lower switch are closed definitely and what we will get is a V_{an}. Similarly, others are followed.

Similarly, this one is 'b', and this will be minus 'b', and this one will be 'c' and this one will be minus 'c' and thus, and it is being splitted into the 60-degree sectors. So, if by these summations $V_b = \frac{2}{3} V_d (S_a + a S_b + a^2 S_c)$ and from there we require to calculate what should be the value of the theta?

This this radius is two-third of V_{dc} and of course, if you do the trigonometry this is the perpendicular and this value will be $\left(\frac{1}{\sqrt{3}}\right) V_{dc}$.

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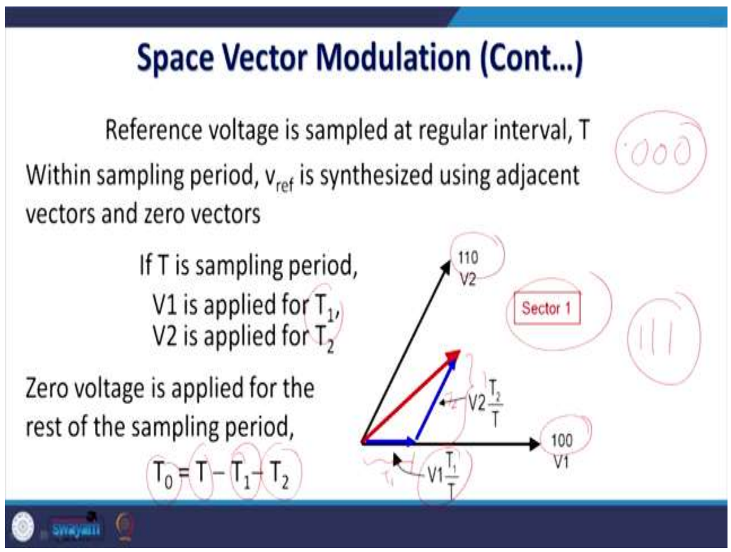

Now, we require to generate the switching logic for this inverter, so that we can accurately generate those reference. It is in a first sector and so, the switching will be [1 0 0] that mean in upper switch 'a' leg is short and minus 'b' and minus 'c' is short and in this case you know this is a one bit change. Upper legs are short and the 'c' phase is short.

Now, let us assume that this is the instantaneous voltage vector required to be generated, and it is in sector 1. So, we can make like this for this amount. If you apply the total voltage vector that is two-third V_{dc}. You will apply this much of this vector V_{a1}. Ultimately you have to match the area voltage curve. Similarly, let us consider for this will be applying for the T_1 of the total voltage, and similarly you will be applied for the time of T_2.

We require to have a task of computing T_1 and T_2 rightly. That is something we require to do and thus we can compute or generate this reference voltage. So, if T is the sample period and V_1 is applied for the T_1, then of course, you know you have to apply this. Ultimately it is $V_1 \, {}^{T_1}/_{T}$ will be this amount of this value. Similarly, V_2 is applied for the time T_2 and ultimately $V_2 \, {}^{T_2}/_{T}$ will be this reference voltage vector.

If you have that let us say it is switching at a 100 kilo Hertz that is 100 micro second. Sorry, extremely sorry. Just 10 kilo Hertz, then it is 100 micro second. In 100 micro second. It may be some value let us say 40 micro second. It may be 30 micro second. Then total brings you to 17. Then ultimately tip will be rest 30 micro seconds.

So, this is the way difference and generally this T_0 will be placed T by 2 0 and T by 2 0, at the beginning and at the end of the cycle and since that you know, there is a combinations that will start from [0 0 0] to [1 1 1]. [1 1 1] or [0 0 0] are said to the null vector, when all the lower switches are closed it is [0 0 0], so voltage will be null. Same way if it is [1 1 1] voltage also will be null. We will see that how switching takes place in this case?

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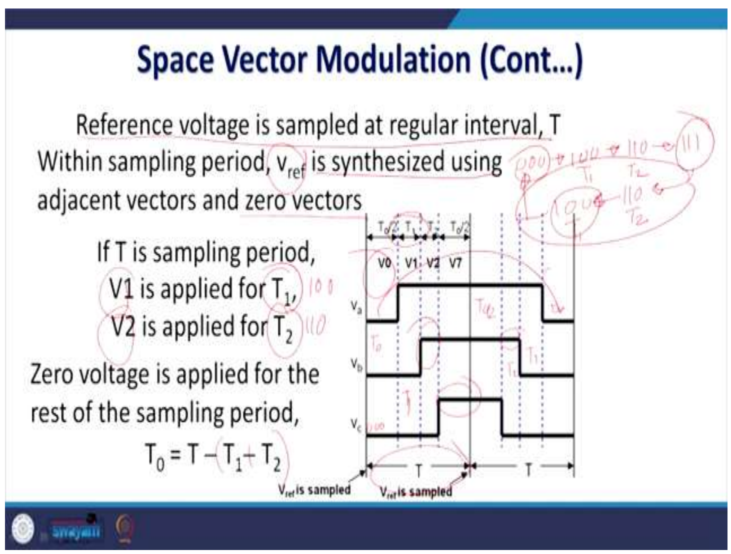

So, as I told you that you are generating the clock pulses from DSP or FPGA, and for this reason the reference voltage sample at a regular interval that is T with a sampling period of V_{ref}. It is synthesized with adjusting vectors and the zero vectors. If T is a sampling period, V_1 is applied for the time T_1, and V_2 is applied for the time T_2, and zero voltage is applied as I told you for the rest of the sampling period that is equal to T in between this.

So, we have to see the timing diagram of this. So, V reference is sampled, and this duration may be T. So, what happens? This is the scale. What happens? After some interval of time, ok? Let us mark this at T_0. So, V_a or S_a, S_b goes high and it will continue to be high. Thereafter, as I see that this is [1 0 0]. There after [1 1 0], that mean after a time interval T_1 this V_b will go high and thereafter what happens? Since it starts from [0 0 0], we want to have a one-bit change.

So, it will start from [0 0 0], thereafter it will go to [1 0 0]. Thereafter, since it a one bit change it will be [1 1 0]. Thereafter it should go to [1 1 1] to incorporate as a null vector. Since you have end here and again you start. You should not start this shows the duration of T_1, and this was the duration of T_2. Since you start from [1 1 1], next sequence will be [1 1 0] and that will be T_2. Thereafter, you will be [1 0 0]. You will be again T_1. Then again you come to this point.

This is the cyclic order which you require to follow. Let us see here. That is what I was saying that this duration will be T_1 equal to V_1, and this duration is T_2, and for the voltage V_2 will be high. V_1, V_2 both are high. Thereafter definitely this voltage vector is V_0 and that given by [0 0 0] that is a null vector, where all the lower switches are closed and that duration will be $T/2$.

Similarly, at the end of that duration we will be again $T/2$. You will get this value and this is the way it will work. Now, what happens to this part? It will start from [1 1 1] and thus what happen? You continue to till '1'. Till it become [0 0 0] here. There after the interval of $T_0/2$, T_2 will be on. So, after this is T_2.

Thereafter what happen after T_1? You have to back calculate it and then it goes low and everything goes low at this point. So, this will be coming here. So, these cycles. This is called the cycle matching. This is the way this two-level space vector modulation works.

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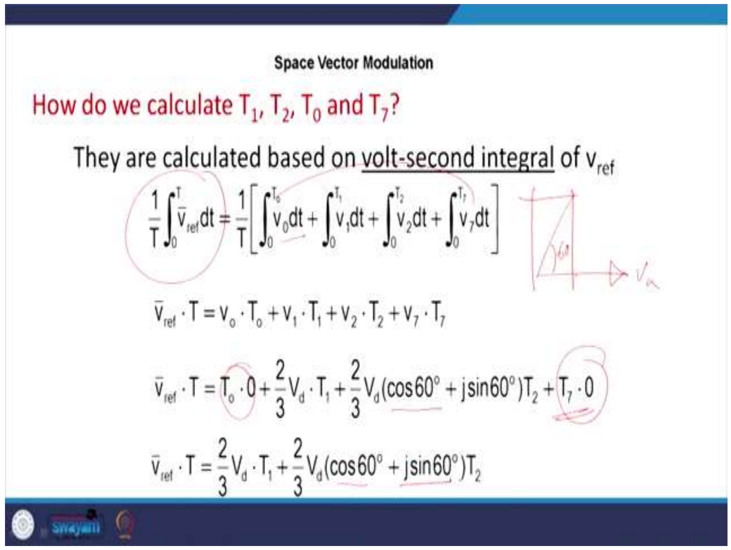

So, now question is how to compute or calculate the value of this times T_1, T_2, T_0 and the T_7? Generally, T_0 and the T_7 are having a same value and just put at the end or at the beginning of the switching cycle. So, if you do this voltage and the time integration of the voltage that is necessarily flux and you divide it by T, then it will raise the voltage only.

So, 1 by T, where T is the reference switching sequence frequency. That is 0 to T. v_{ref} dt which you know that you require to inject the voltage at 35 volt at an angle of 45 degree. So, then what happen? Generally, if you have a 45-degree injection of course, T_1 will be equal to T_2, because V_1 and V_2 magnitude wise this voltage are equal.

So, $\frac{1}{T}\int_0^T \bar{V}_{ref} dt = \frac{1}{T}\left[\int_0^{T_0} V_0 dt + \int_0^{T_1} V_1 dt + \int_0^{T_2} V_2 dt + \int_0^{T_7} V_7 dt\right]$. Generally, you know what we can do? We can keep them same and multiplied by 2 that is also possible. So, ultimately if you can withdraw the integration sign from the both side and thus what happen? $\bar{V}_{ref}.T = V_0.T_0 + V_1.T_1 + V_2.T_2 + V_7.T_7$.

So, ultimately, we required to see that this voltage vector is in is aligned to v_a, but this is this and this magnitude is one-third of 60 degree. So, you have to take the component of it to its direction. For this reason, it is $\bar{V}_{ref}.T = T_0.0 + \frac{2}{3}V_d.T_1 + \frac{2}{3}V_d(\cos 60^0 + j\sin 60^0)T_2 + T_7.0$. So, this one is 0 and this one is also 0.

So, what happen? You just reduce this null vectors. So, $\bar{V}_{ref}.T = \frac{2}{3}V_d.T_1 + \frac{2}{3}V_d(\cos 60^0 + j\sin 60^0)T_2$.

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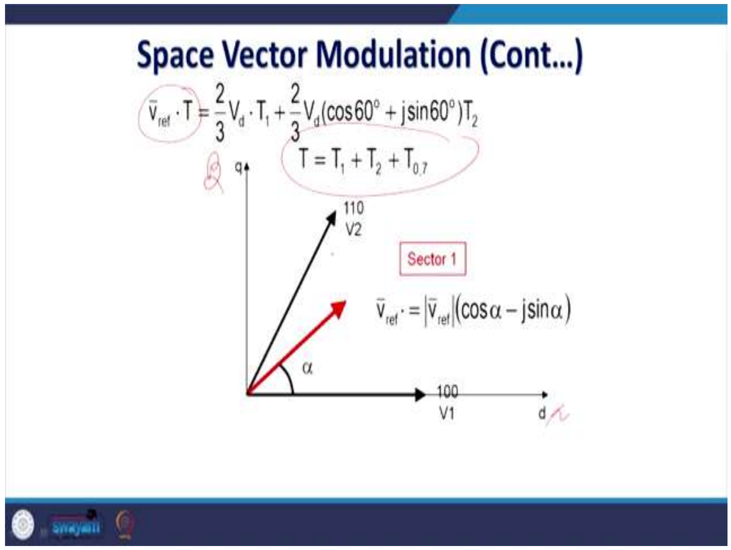

So, what happens now? We can rewrite these equations, where $T = T_1 + T_2 + T_{0,7}$ and we can rewrite this like this. So, this is the angle alpha ultimately $\bar{V}_{ref} = |\bar{V}_{ref}|(\cos\alpha + j\sin\alpha)$ you can equate them in alpha beta axis and later if you rotate this by the synchronous frame, this alpha beta become dq frame of reference.

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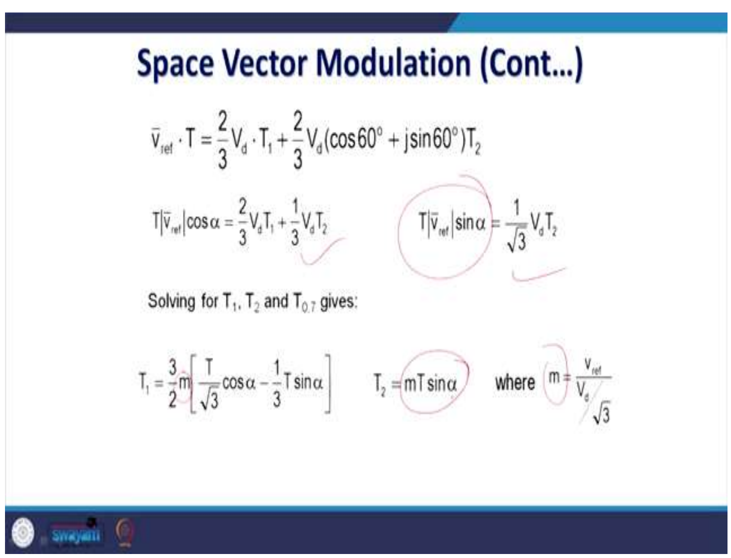

Thus, splitting in x and y axis which is equivalent to the alpha and beta. We can write that is v_{ref} into T like this. So, equating the real and the imaginary part, we can write like this you know $T.\left|\bar{V}_{ref}\right| \cos\alpha = \frac{2}{3}V_d.T_1 + \frac{1}{3}V_dT_2$. Similarly, $T.\left|\bar{V}_{ref}\right| \sin\alpha = \frac{1}{\sqrt{3}}V_dT_2$. This is the equation.

From there you can calculate the time. So, T_1, T_2 and T_0, you can directly substitute where 'm' you can give. Write it like this. So, m is v_{ref} what is the magnitude of it the 40-degree, 40 volt, 30 volt and V_{dc} maybe 100 volt whatever may be and that reference is called the effective modulation index.

Thus, what happens? You can write it $\frac{3}{2}m\left[\frac{T}{\sqrt{3}}\cos\alpha - \frac{1}{3}T\sin\alpha\right]$. Similarly, we can calculate for the T_2. $T_2 = mT\sin\alpha$. So, thus we have calculated T_1 and T_2. Subtract it from the total time T, and you divide it by 2 and that become T_0 and T_7.

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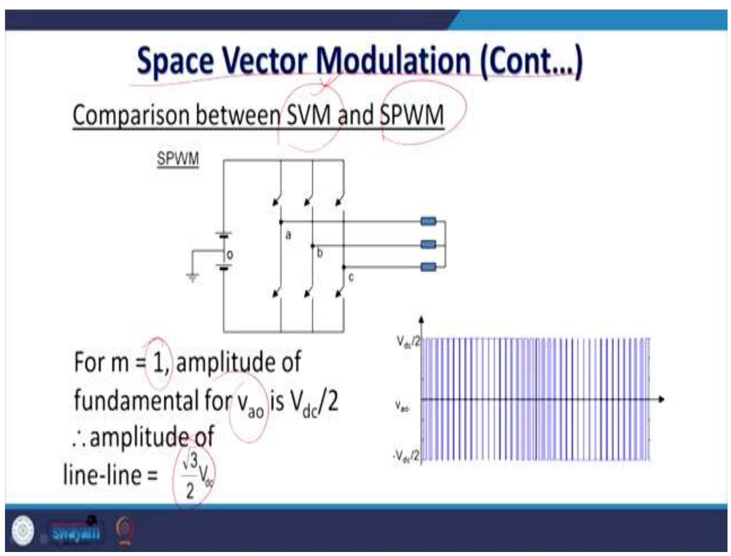

So, this is the way to calculate the times for the two-level space vector modulation. Now, we required to understand that what is the benefit of it or a comparisons of the sin triangle PWM with the space vector modulations. One aspect is that we just say one thing that sin PWM is simple to implement. We can implement this sin triangle PWM very easily.

There is no computational burden. Every time we require to calculate this timing of the switching. So that require a processors and the digital programming is require in a digital domain. This complexity burden is more in case of this SVM. But with the arrival of the digital age and the soft first processes, it takes the gain over the accuracy like exactly generating the particular THD, what you require from this vector control.

For this reason, the space vector modulation has gained much attention and what are the other advantages for $m > 1$ and m 1, that I will come later. Amplitude of the fundamental for V_{ao} is $V_{dc}/2$ and amplitude of the line voltage is essentially $\frac{\sqrt{3}}{2}V_{dc}$. So, what happens? We know that possible phase angle without over modulation is $\frac{1}{\sqrt{3}}V_{dc}$.

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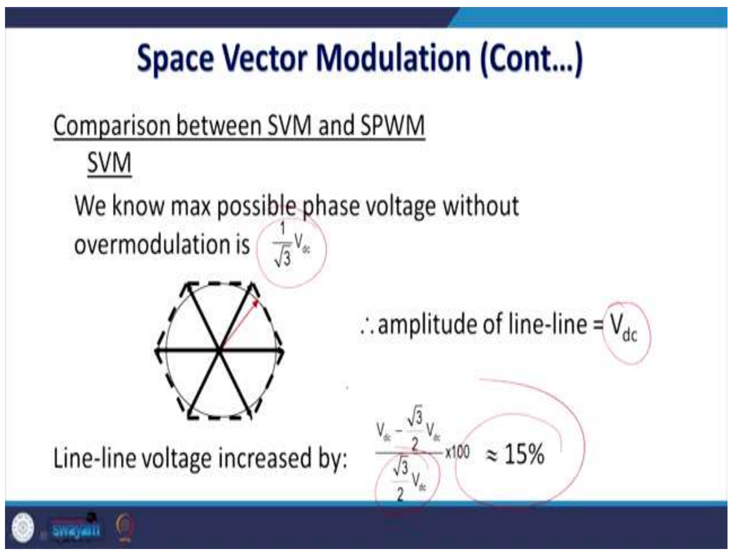

An amplitude of line-to-line voltage can be up to V_{dc}. Thus straight away you know you can see that the line-to-line voltage in case of the space vector modulations is $\frac{V_{dc}-\frac{\sqrt{3}}{2}V_{dc}}{\frac{\sqrt{3}}{2}V_{dc}} \times 100 = 15\%$ hence 15 percent increased in the utilizations in the line-to-line voltage for the output of the inverter, and thus we can transform into the better utilization of the dc bus voltage. So, this is the one opportunity of it.

Generally, what happens? You can do the same thing. You get this kind of thing in case of the third harmonic injection, but in third harmonic injection stress of the dc bus voltage were higher. But with the less dc bus voltage that mean less stress on your component you can achieve 15 percent more than line voltage. For this reason, this method is preferred even though it got a computational complexity.

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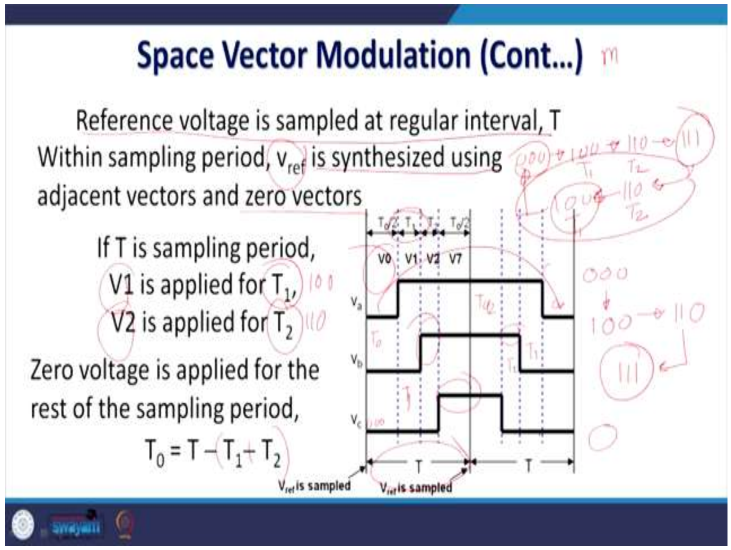

So, we shall start. We are not able to finish because you know just 2-3 minutes are left. So, let us revisit this part again. Now, how it can be used these values to compute your T_0 T_3 and all those values when it is there? So, how it will be more superior than sin triangle PWM? What happened in case of the sin triangle PWM? Essentially your switching does not have a sequence.

Please see that. What we have done here, I can go back to this figure. You can see there this is a one-bit change. What happens? One switch goes on [0 0 1 1]. We are not going for [1 1 0]. We have a control and thus we make it [1 0 0]. But this kind of control in case of the PWM is difficult. Because it will be turning on depending on whether this modulation index is more than the carrier wave.

If carrier wave is less than this modulating wave. That is fine. Otherwise if modulating wave is more than the carrier wave it is going to turn on and it will not consider whether it is a one bit change or a two-bit change. But you can ensure that there is only one bit change to generate any reference. So, it is [1 1 0], thereafter it will be the [1 0 0]. Thereafter will be [1 1 0]. Thereafter it will be [1 1 1].

So, in that way, you can reduce the switching losses also by this technique and also you can control the duration of iteration. Let us come to that later. So, how much duration it will be turning on and all? Thus, you can have a control and it is required to have this control for minimizing the losses.

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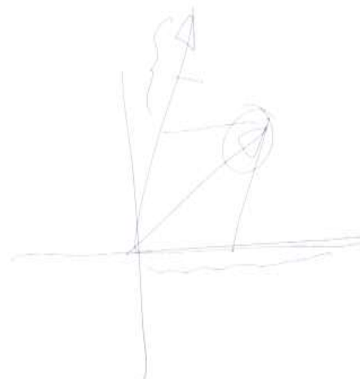

Also, what happens? Since you have converted this frame then what happen? Here you have 3-phase voltages and you have converted to the alpha-beta frame, then you go to the polar form and ultimately you have exactly calculated the voltage. What happens there? You essentially try to mimic this voltage by the space vector. So, of course, you apply this and you apply this to generate this voltage for this duration and this duration.

Ultimately it average outs and this fills up by the harmonics. For this reason, it is not a scope of work here. We generally prefer this. We generally prefer this three-level or the multi-level inverter. So, that it can have more number of space vector to generate a particular voltage and thus it will be more accurate to generate that voltage.

Thank you for your attention. I shall continue this discussion of PWM technique in our next class.