Power Electronics

Prof. B.G. Fernandes

Department of Electrical Engineering

Indian Institute of Technology, Bombay

Lecture - 39

In my last class I discussed various types of pulse width modulation techniques, one of them being harmonic elimination technique. This method says that if there are N switchings per quarter cycle, N minus 1 harmonics can be eliminated and fundamental can be controlled. In the last class I did give an example, wherein there were 5 switchings. So, we eliminated 4 harmonics. There were fifth, seventh, eleventh and thirteenth and we controlled the fundamental.

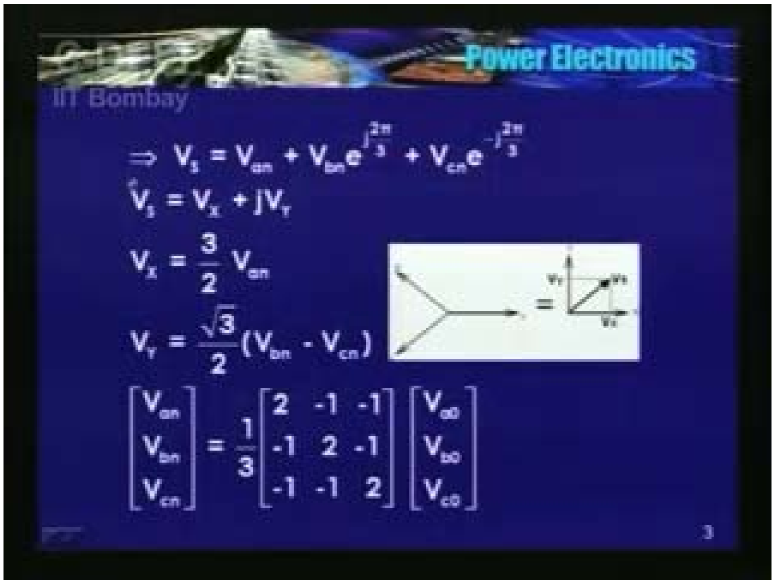
See, with 5 switchings per quarter cycle, you can have altogether different fundamental. See, in the last class we got, may be, around 0.985 or something like that. We can get much less than 0.985 and still you can eliminate these harmonics because when you write those 5 equations, you equate 4 harmonics to be eliminated to 0 and control the fundamental.

Another observation that we made was at any given time, there should not be simultaneous switching of devices of other phases. In other words, only 1 phase should be switching at a time. This is not ensured in the PWM techniques that you are studied so far because this PWM techniques, they treat one leg of an inverter as an independent identity unity.

So therefore, phase voltage is generated independently or pole voltage is generated independently, whereas, the space vector PWM technique, it treats the entire a 3 phase inverter as a 1 single unit. The space vector PWM technique treats the entire unit, entire inverter as a single unit. In this PWM technique, we will find that at any given time only one switch is being turned on or off.

In other words, one leg of the inverter is being switched. Other 2, remaining 2 phases are untouched at that particular time. So, I did define the space vector.

(Refer Slide Time: 04:04)

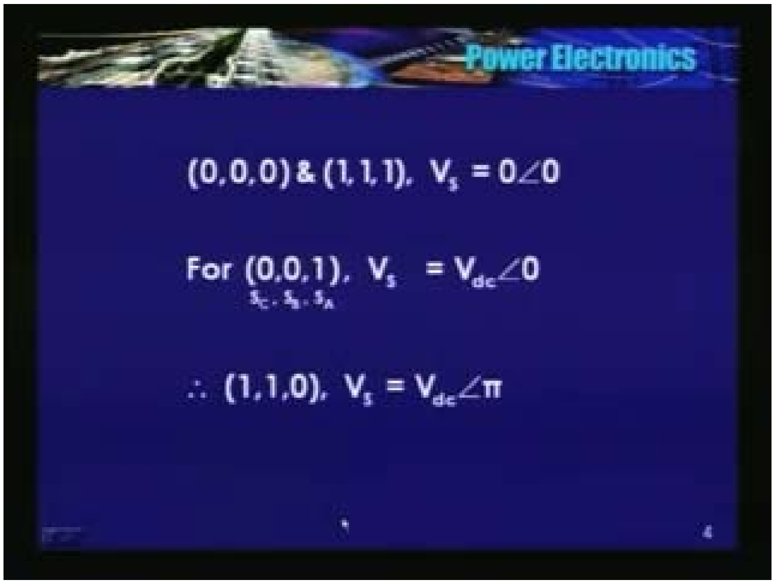


So, what is a space vector? V_s is given by this equation; V_{an} plus V_{bn} e to the power j 2 pi by 3 plus V_{cn} e into e to the power minus j 2 pi by 3. I told you that this 3 phase vectors can be represented by a space vector V_S and this space vector can be represented in 2 dimensional plane, wherein V_x is the X - axis component of or some of all X - axis components of these 3 vectors and Y is the sum of all the Y - axis components of these 3 vectors. We resolve these 3 vectors along X - axis and Y - axis and we found that V_x is 3 by 2 times V_{an} and V_y is root 3 by 2 times V_{bn} minus V_{cn}.

We also found a simple relationship between the phase voltages and the pole voltages because when the inverter is being switched, the pole voltages are known. But then the phase voltages are not known. We found that matrix to be very simple one. See, V_{an} V_{bn} V_{cn} is equal to1third. See these elements, diagonal elements are 2; rest all are minus1minus1minus1, V_{a0}, V_{b0} and V_{c0}.

So, if the conducting sates of the inverters, upper devices of the inverters are known that is1, 3, 5 or S_A, S_B, S_C. So, V_{a0}, V_{b0} and V_{c0} will be known. When upper switch is on, it is V_{a0} is is plus V_{dc} by 2. If the lower switch is on, it is minus V_{dc} by 2. So, I can calculate V_{an} V_{bn} and V_{cn}. In the last class, I did derive or I did find the Value of the space vector for 001 vector.

(Refer Slide Time: 06:40)

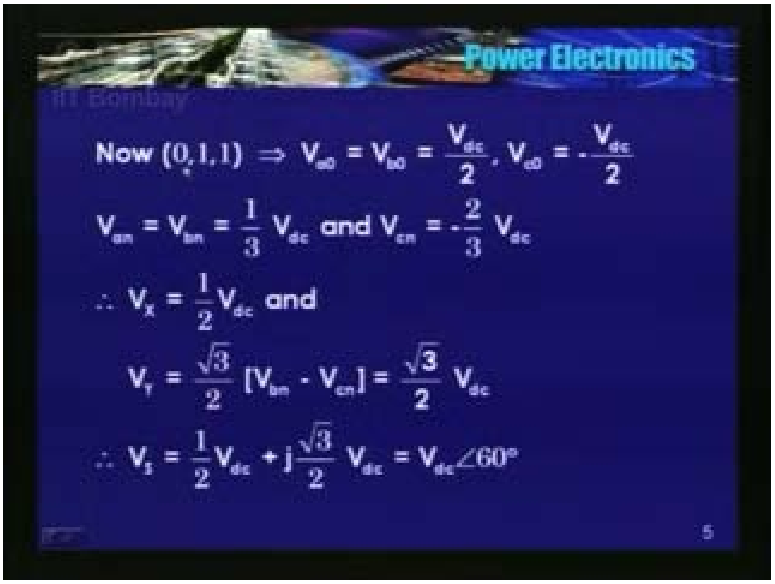


What is 001? I took upper device of phase A is on upper device of phase A is on and lower devices of phase B and phase C are on. So, for S_{A1} or A phase upper device of A phase is on and lower devices of phase B and phase C are known, we found that this magnitude of the space vector is the magnitude of the entire DC link, the whole DC link, V_{dc}; it has only an X axis component. Y axis component, we found that is to be 0. So, angle happens to be 0.

So, it is along V_S is along the X axis with the magnitude V_{dc}. So, for 001if it is V_{dc} at an angle 0, I told you that for 110, the complementary of this vector should be same magnitude at an angle pi. I told you, if you are not convinced, I said go back and do this exercise. I hope you have done it. And for the 0 vectors, 0 vectors or null vectors, wherein all lower devices are on or when all upper devices are on, magnitude of the space vector is 0 and the angle is also 0. In words so, in the XY plane, this is at the origin. So, if upper 3 are on or upper 3 off, the space vector that the magnitude 0 is at the origin.

Now, what about the remaining 4 vectors? I said 2 to the power 3, there are 8 possible combinations out of which 2 are null vectors and we already determined the the magnitude and the position of the space vector for 2 vectors, 2 active vectors. Why they are active? because, the magnitude of the space vector is non 0. We found that for 001and 110, the magnitude is V_{dc}. So, what is the magnitude for the remaining 4 active vectors?

(Refer Slide Time: 9:28)



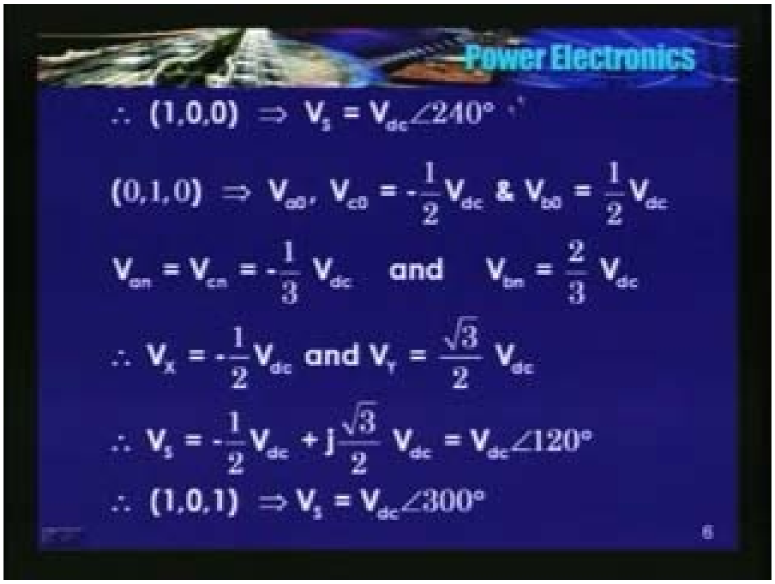
See, I will take 011. That means A phase upper device, b phase upper device; they are on and C phase lower device is on. So, V_{a0} is equal to V_{b0} is equal to V_{dc} by 2 because upper device is on, whereas, V_{c0} is minus V_{dc} by 2. Now, if I substitute these values in that matrix, we will find that V_{an} is equal to V_{bn} is equal to 1 third V_{dc} and V_{cn} is minus 2 by 3 V_{dc} because that is lower device is on.

So, from the switching position, we could determine V_{an}, V_{bn} and V_{cn}. Now, these this 3 vectors are known. So, I can calculate V_x, V_x is nothing but 3 by 2 times V_{an}. So, V_x is half V_{dc} and V_y is given by root 3 by 2 times V_{bn} minus V_{cn}. So, that is equal to you substitute these 2 values, you will get root 3 by 2 into V_{dc}. Now, what is the space vector? Space vector V_S is V_x plus j into V_y. V_x is half V_{dc}, V_y is root 3 by 2 times V_{dc} and it is positive.

So, V_S is I can substitute this for that equation for V_S. This is what I will get; half plus j root 3 by 2 half plus j root 3 by 2 - real component is half, imaginary component is root 3 by 2. So again, the magnitude of this is 1 at an angle 60 degrees: cos 60 is half, sine 60 is root 3 by 2. So therefore, for 011 the position of the space vector is at an angle 60 degrees with respect to the X axis, 60. Magnitude is the same, V_{dc}.

So, for 011 the magnitude of the space vector is V_{dc} at an angle 60 degrees with respect to X axis, for 100 which is the complementary of the previous vector, the magnitude of the space vector is still V_{dc} but at an angle 60 plus180. That is at 240 degrees. So, that is what I have written here.

(Refer Slide Time: 13:04)



For 100, V_S is V_{dc} at an angle 240. So, we found the position as well as the magnitude of the space vector for 4 active vectors. The magnitude happened to be the same. Now only the angle, see, the position of the space vector seemed to be changing. So, we will find out for one more case and I can use the complementary of this vector and I can get the get the the position of the space vector. So, the last one being 010, only upper device of B phase is on; A phase is off and c phase is also off.

So therefore, V_{a0} equal to V_{c0}, both upper devices are off. So, magnitude is minus half V_{dc} and V_{b0} is plus half V_{dc}. So, what will be the V_{an}, V_{bn} and V_{cn}? For this combination, A phase is also off, c phase is also off. So, V_{an} is equal to V_{cn} that is equal to minus 1 third V_{dc} and V_{bn} is equal to 2 by 3 V_{dc}. Straight away you can write, you do not need to write, substitute this in that matrix.

See, for 001we found that V_{an} is 2 by 3 V_{dc} and V_{bn} and V_{cn} are minus1third V_{dc}. So, in other words, if only1switch is on; I will repeat, if only1switch is on, the magnitude of that voltage is or magnitude of phase voltage is 2 by 3 V_{dc}. If 2 switches are on, magnitude of the phase voltage is 1 third V_{dc}.

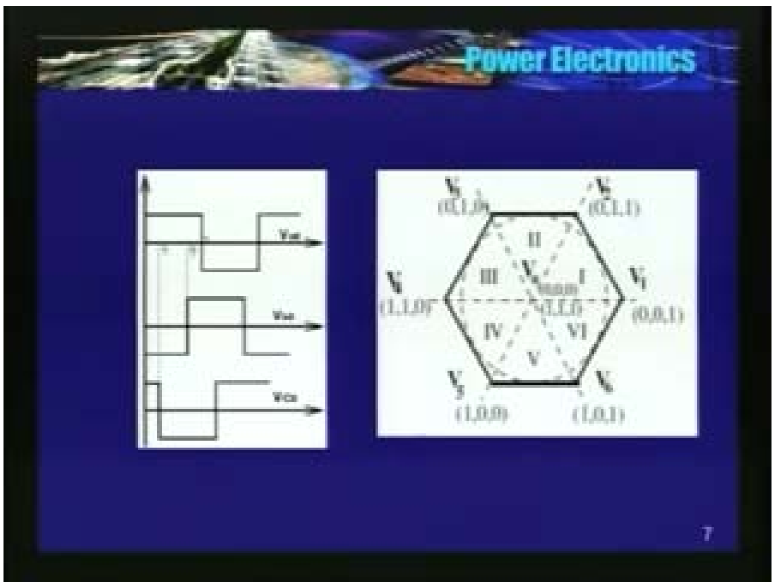
The sine depends on whether it is upper device or lower device; that is all. If lower device is on, it is minus. If upper device is on, it is plus. That is a sine convention. So, I will repeat; if only1device is on, magnitude is 2 by 3 V_{dc} of that phase and the remaining 2, it is it is1third V_{dc}. If 2 are on, magnitude is 1 third V_{dc}. The sine depends on whether the upper device is on or lower device is on.

So, what is V_x? Now, V_x is V_x is given by 3 by 2 times V_{an} or 1.5 times V_{an}. So, V_x is minus half V_{dc}. I will substitute for V_{an} for V_x is 0.5 V_{dc} and V_y is root 3 by 2 V_{dc}. So, I will substitute for V_{an}. I will substitute for V_{cn} and V_{bn}. So, it is again root 3 times V_{dc}.

So therefore, the space vector is minus half V_{dc} plus j root 3 by 2 times V_{dc}. So, again minus half plus j root 3 by 2 magnitude is1.But then angle is120 degrees. Cos120 is minus half, sine 120 is root 3 by 2. So therefore, the position of this phase vector position of this space vector for 010 it is at120 degrees with the respect to the X axis. So therefore, for101 it is120 plus180 that is at 300 degrees. So, it is here for 101 V_S is V_{dc} at an angle 300 degrees.

So, for all the remaining 6 vectors, we found that magnitude of the space vector is the same. Now, let us plot these 6 vectors. In fact, all 8 vectors in the xy plane. What sort of a figure that we get?

(Refer Slide Time: 18:14)



See, 000 or 111, we are at the origin; 001 - only phase A is on. So, magnitude is V_{dc} and it is along the X axis, angle is 0. For 011, vector is making 60 degrees and for 010, vector is making 120 degrees and so on. So, so if I try to because all the magnitudes is all the sides of all the sides are of magnitude V_{dc}. So, I can join them. So, I get a hexagon.

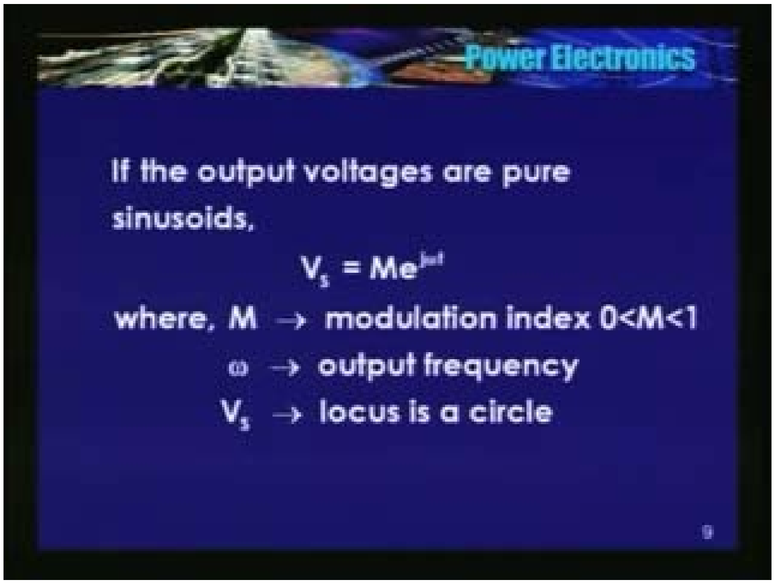
So, what conclusion that I can draw? Out of 8 possible vectors, 2 are null vectors which are at the origin. The remaining 6 are at or the angle between any 2 vectors is 60 degrees and all the 6 vectors, they occupy the vertex of a vertex of a hexagon. See here, 6; I am calling these vectors as V_1, V_2, V_3, V_4, V_5, V_6. Please, these are not if the binary equivalent; I am just calling as V_1, V_2, V_3, V_4, V_5, V_6. V_0 and V_7 are at the origin.

See, now take the pole voltages for 180 degree conduction. V_{a0}, V_{b0} and V_{c0} for each position or for each active vector, the space vector is occupying one of these 6 places one of these 6 places.

See for example, see it is A phase is 1, B phase is 0, C phase is 1. So, if I take 101, where are we? Here, 101. See, next is 100. A phase is 1, b phase is 0, C phase is 0. So, this is pi by 3 that is 60 degrees. Another 60 degrees we have. A is 1, B is 0, C is 0. So, we are here. What happens from 2 pi by 3 to pi? A is 1, B is 1, C is 0 C is 0. C is 0, B is 1, A is 1. So, so V_2 vector.

Definitely, see next is I will just repeat for 1 more. A is 0, lower device is on. B is 1; see, for another 60 degrees another 60, before V_{c0} becomes 1, 010 010. See, we are somewhere at this point. So, even if I use 180 degree conduction, in other words, each device is conducting for 180 degrees; for each positions I have a space vectors and a magnitude remains the same but the position shifts by 60 degrees.

(Refer Slide Time: 23:32)



Now, if V_{an}, Vbn, Vcn are sinusoids V_{an}, Vbn, Vcn are sinusoids, so I can write the space vector V_S as M into e to the power j omega t. In that 2 axis in that 2 axis plane, V_x plus jy we wrote. Now also I can write that V_S is M into e to the power j omega t where M is some modulation index and omega is the frequency of V_{an}, V_{bn} and V_{cn} which is same as the frequency of the space vector.

What is the locus of the space vector? If V_{an}, V_{bn}, V_{cn} are sinusoids, what do I what will be the locus of V_S? Locus of V_S is a circle is a circle. So, what should be the ideal locus or trajectory of V_S? I said we need to have an ideal 3 phase sinusoidal voltages. So, only then may be when I apply them to a machine or 3 phase balance load, it will draw a sinusoidal current. But then unfortunately it is just not possible to have a pure sinusoid. But then it is always desirable to have these 3 as sinusoids. So, if these 3 are sinusoids, locus of V_S is a sinusoid.

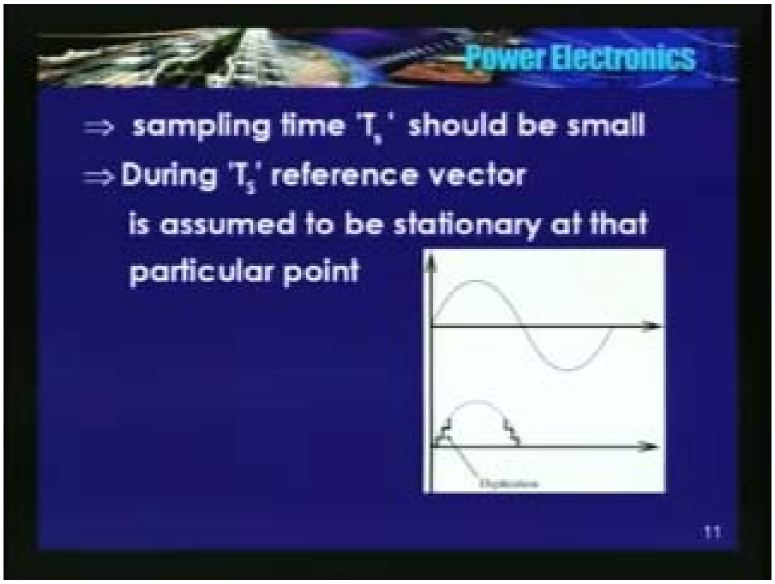
So therefore, the locus of V_S is sinusoid if the magnitude of V_S is less than less than the diameter of the inscribed circle or in other words if magnitude of V_S lies within this hexagon or within this circle, I am sorry, if it is lies within this circle, I have V_{an}, V_{bn}, V_{cn} are sinusoids. But then if

I use 180 degree conduction, if I use 180 degree conduction, at every 60 degrees one switch is being turned on or off here. We find that the space vector moves by 60 degrees. See here, A was on, B is off and C is on. We are here. May be after 60 degrees when I turn off the upper device of C phase, immediately we jump here or space vector jumps here. Then after 60 degrees, B phase is being turned on; the space vector jumps here.

So, in one cycle is completed after 360 degrees. In fact, there are 6 combinations, the space vector moves in discrete steps, remember. The space vector moves in discrete steps of 60 degrees. So, when you apply this space vector to a machine or these voltages to a machine, the field produced by this space vector V_S also moves in discrete steps of 60 degrees.

See, after all these voltages are being connected to the machine. We are generating 3 phase voltages and they have to be connected to the machine and we found that at every 60 degrees, one switch is being turned on or off though the space vector is moving in 60 steps. Sorry, space vector is moving at an angle by an angle of 60 degrees. So definitely, the magnetic field, the resulting magnetic field produced by this space vector is also moves by or moves in steps of 60 degrees. So definitely, the magnetic field produced does not rotate at a uniform velocity inside the air gap. It moves in discrete steps.

(Refer Slide Time: 28:51)



See, here is a pure sinusoid. That is what we want. Say, call it as V_{an}. If we use 180 degree conduction, V_{an} has 6 steps or cycle. There has there has 6 steps; each of 60 degrees, height is 1 third V_{dc}, 2 third V_{dc}, again 1 third V_{dc}.

Now, of course, there are it is rather impossible to get a pure sinusoid. Can I increase the number of steps and try to achieve a sine wave which is very close to this sine wave? In other words, can I have a large number of steps in 1 cycle? It is something like this; digitizing a sine wave. This has a large number of steps in half a cycle. So similarly, in the negative half cycle. See, if you give this sine wave to an ADC, how do I digitize it?

Digitizing means I have an analog signal; I need to convert it into a digital signal. So, I need to give it to an analog to digital converter. Now, this analog to digital converter has its own conversion time. It cannot there may be very fast ADCs but definitely conversion time cannot be or will not be 0. It has a finite conversion time. So, what I will do? I will or if the ADC we will first will sample it. Sample the instantaneous value of the sine wave, convert it to an equivalent the digital value and depending upon the sampling frequency, the ADC digitizes the given analog signal and and then if I plot it, I will get a stepped sine wave because for this time for during the sampling time, we are assuming that sinusoid does not a value of the instantaneous value of the sine wave does not change. It remains constant.

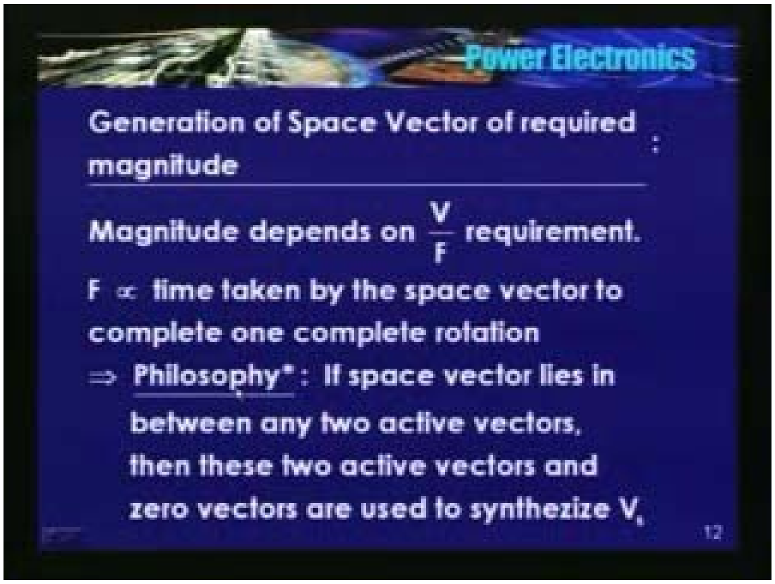
So, larger the number of steps better will be the sinusoid or waveform is superior. So definitely, I need to have a large number of steps or in other words, I need to sample this sine wave at a very fast rate and what will assume and in that sampling time; the instantaneous value, the sine wave remains constant and the vector the reference vector or whatever the sine vector is stationary at that particular point.

So now, how do I generate the required space vector of some frequency and magnitude? Who decides the magnitude of the space vector? It is the load or the V by F curve decides the magnitude of the space vector. After all, it is an inverter. It is being switched using a space vector PWM technique, output of the output of the inverter is connected to a load and how do I decide the frequency? The time taken by the space vector to complete one cycle decides the frequency of operation.

Now, how do I generate this space vector of some magnitude and some frequency? Because we found that there are only 6 active vectors, magnitude of magnitude of space vector is constant and for every position, space vector moves by 60 degrees. I told that this is not acceptable. Then I showed that the sine wave should be digitized. I cannot have a continuous sine wave, it is not possible. Best way to have is you divide a half cycle into large number of steps. But here is an inverter where there are only 6 vectors are available. Now, how to get this space vector of required magnitude required magnitude.

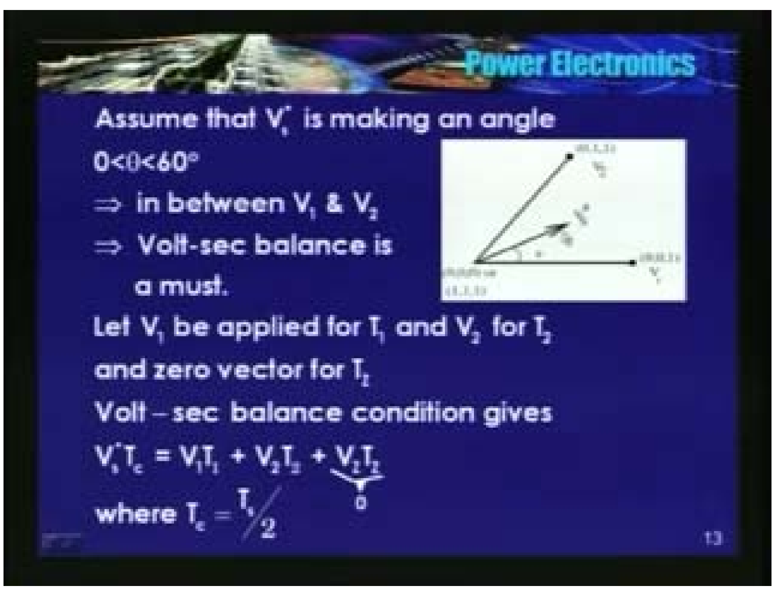
Now, let me recall one of the qualities that a good PWM technique should have. What is that? At any given time, the switches of one phase should change its state. In other words, there should not be a simultaneous switching of other phases also and I told you that space vector does this. How this does how the space vector manages to switch one switch at a time or how this is being done? So, here is a philosophy of the space vector PWM technique.

(Refer Slide Time: 34:54)



What it says is if the space vector lies in between any 2 vectors if it lies in between any 2 vectors, you need to use only these 2 active vectors and the 0 vector to synthesize the space vector of required magnitude. I will repeat; if the space vector lies in between any 2 vectors, at any given time if it lies in between 2 vectors, we need to use only these 2 vectors and the 0 vector or at the origin to synthesize the space vector of required magnitude. I will give an example.

(Refer Slide Time: 35:57)



Assume that V_a star; in the sense, I put a star here because the magnitude is very small compared to compared to the V_{dc} because depending upon V by F or depending upon the frequency of the space vector, magnitude also changes in order to keep V by F constant. Looks like the frequency of operation is less than the rated. Therefore, the magnitude of the space vector is also less than the rated and it is lies in between sector 1 and sector 2 or it is in sector 1.

I am calling I just I might have explained; see, this is sector 1, sector 2, sector 3, sector 4, sector 5, sector 6. So please remember, sector 1 is from 0 to 60 degrees and sector 2 is 60 to 120 and so on. So therefore, I will assume that the space vector lies in sector 1 now and the magnitude of the space vector is less than the rated. How to synthesize this vector? The condition to be satisfied is that there should be a volt second balance. I will repeat; there should be a volt second balance.

By the way, what is this volt second? Volt second is nothing but flux or incremental flux because d pi by dt is equal to e. e is the unit of e is volt. So, volt into second is nothing but d pi. Therefore, see, here is this space vector V_s. When it is apply to a machine, definitely it produces some flux at some direction. See, I am not going to discuss about the direction of flux produced by V_S. Now, I have to synthesize this Vs using this 3 vectors; 2 active vectors and one null vector and I said volt second balance should be there.

In other words, incremental flux produce by V_S or flux produce by V_S when it is in this position when it is in this position should be same as the flux produced by this space vector when you are in this position and this position.

I will repeat; the incremental flux or the flux produced by a total flux produced by this space vector when it is in this position; magnitude and position both should be same as when you switch this as well as this.

See, when V_1 when when I am switching 001 or when you use this vector, the space vector is along X axis and magnitude is again constant V_{dc}. So definitely, it will produce some flux or incremental flux that direction again definitely different from the direction of incremental flux produced by the V_S or required position. I will repeat; see, when you switch 001, space vector is along X axis, magnitude is V_{dc}. So, incremental flux again depends on the position of this vector. When I apply this, the position is going to be different. Magnitude of V_{dc} is constant or magnitude of space vector is equal to V_{dc} which is constant.

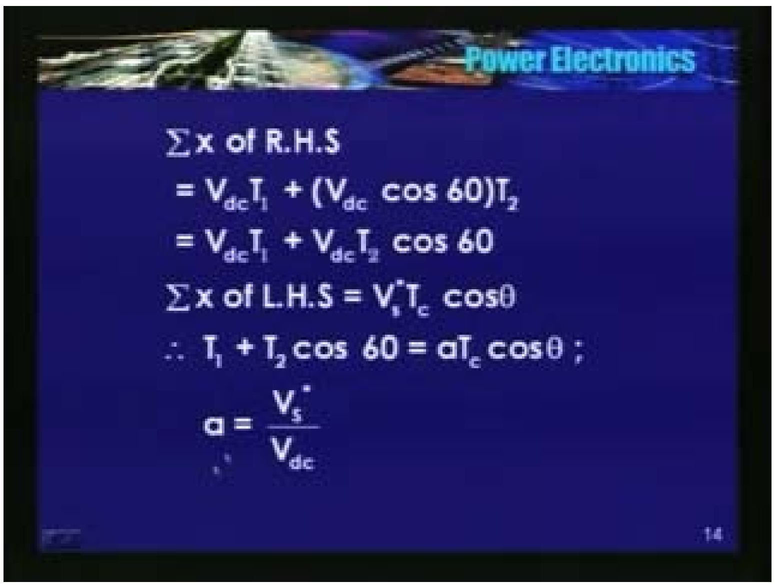
So, direction of incremental flux when I apply this vector and this vector, they are different. What I what I want is here, the V_S vector. The net effect net effect should be the same as this space vector. Volt second of this space vector. See, I will repeat; so therefore, therefore if V_1 is applied for sometimes, say T_1 seconds and V_2 is applied for some seconds or some T_2 seconds and 0 vector for T_z seconds, what is the volt second balance condition gives? V_1 into T_1 plus V_2 into T_2 plus V_z into T_z should be equal to V_S into T_c. Sometime T_c which is equal to the sampling time by 2 sampling time by 2.

So, we have assume that V_S; the position as well as the magnitude will remain constant during this time T_S or during T_S time. So, during T_S seconds, V_S is at this position and it is held and assumed to be stationery and constant magnitude. So definitely, V_c V_S into T_c is the incremental flux. That I need to get by switching V_1 for sometime and V_2 for some other time and using this.

But then in this equation, V_z into T_z is 0 because 0 vector. So, the vector itself is 0; definitely, incremental flux also will be 0.

Now, how do I determine or how I calculate T_1 and T_2? I said volt second balance has to be satisfied or if this is the resultant or this is what is to be synthesized or this is the incremental flux due to the space vector in T_c seconds; somehow, I need to get using these 2 vectors. Now see, when I apply V_1 and along the X - axis, it has no Y axis component. When I am in when I apply V_2, it has X axis component as well as Y - axis component. So, what I will do is I will add up the X - axis components as well as Y axis components. The resultant should be is equal to V_s into T_c, see here.

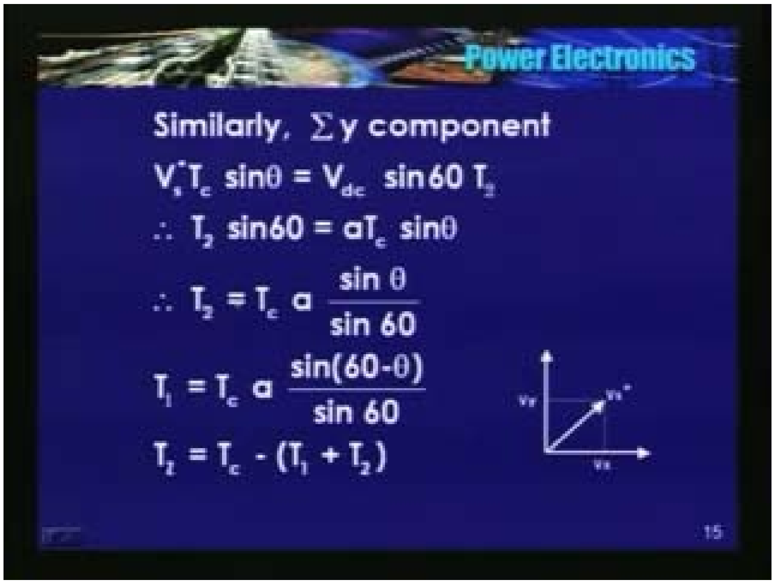
(Refer Slide Time: 44:21)



So therefore, the sigma the sum of X axis components of the right hand side; what is that right hand side? Magnitude is V_{dc}, V_{dc} into T_1 because I am applying V_1 for T_1 seconds. So, V_1 V_{dc} into T_1 is a X axis component. V_{dc} into T_2 into cos 60, cos 60 is the X axis component of V_2 into T_2. So here, V_{dc} into T_2 into cos 60 is equal to the sum is the sigma X of the right hand side. What is the sigma X of left hand side? See here, it is V_S into T_c and angle is theta. So, this is it. So, V_S into T_c into cos theta is a sigma X of the left hand side left hand side. So, I need to equate them. X - axis components are same, Y axis components are same. Therefore definitely, I have I have synthesized the space vector.

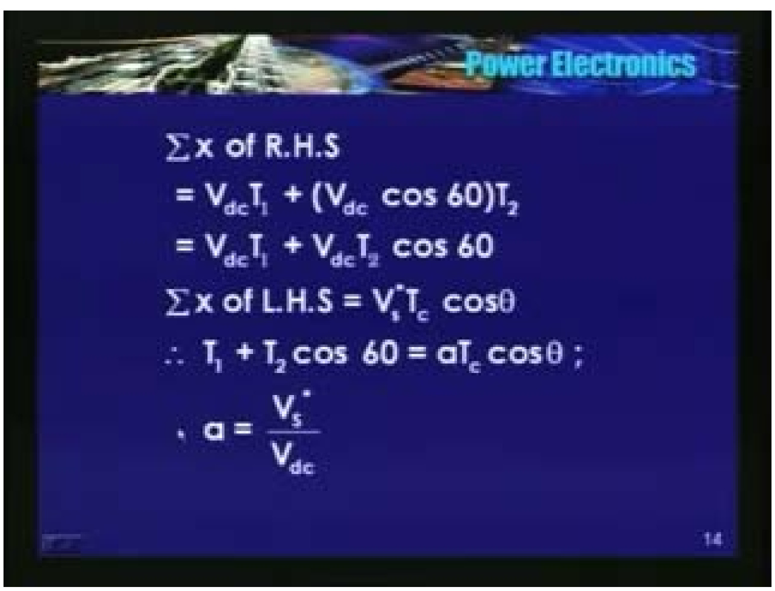
So, T_1 plus T_2 into cos 60 is equal to a into T_c divided by into cos theta where a is V_S star into V_{dc}. See, I need to equate this equation on this; V_S star into T_c. Left hand side should be equal to the right hand side. So, T_1 plus T_2 cos 60 should be equal to V_S star divided by V_{dc} into T_c into cos 60. So, I have one equation. Similarly, I will equate the Y axis components.

(Refer Slide Time: 46:43)



So, Y axis component is V_S star into T_c into sine theta should be equal to V_{dc} into T_2 into sine 60. See in this figure, Y axis, this has no Y axis component, whereas V_2 has both X axis as well as Y axis component. So, V_2 into sine 60 into T_2. So therefore, T_2 sine 60 equal to same; V_{dc} divided by sorry I will equate them, so T_2 sine 60 is equal to V_S star divided by V_S into T_c into sine theta. So, I call it V_S star by V_{dc} as a. So, T_2 sine 60 is equal to a into T_c into sine theta. So, T_2 from this equation T_2 is equal to T_c into a into sine theta divided by sine 60.

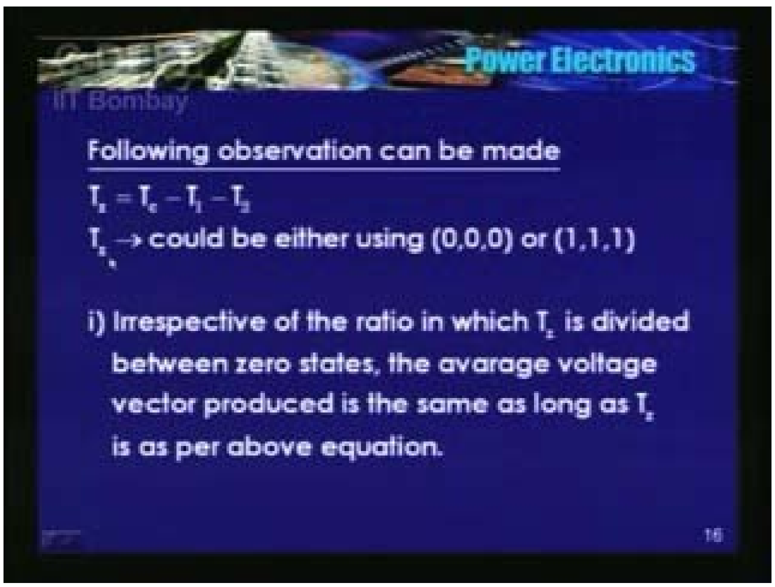
(Refer Slide Time: 48:05)



I will substitute this or substitute the value of T_2 in this equation and solve for T_1. So, I will get another simple equation; T_1 is equal to T_c into a sine 60 minus theta divided by sine 60. What is theta? Theta is the position of the space vector of the XY plane. So see, every only theta should be known here, position. The magnitude of the space vector that should be realized is known from the V by F curve. V_{dc} is also known. So therefore, a is known. T_c is the sampling time that is also is decided. Again, so I need to know the position of the position of the space vector in the XY plane. So, if I know theta position, I know T_2. I can calculate T_1.

So, T_1 and T_2 are known. So, remaining period should be T_z that is nothing but T_c minus this. So, so it is so time for which vector V_1 and vector V_2 should be applied can be determined if I know the position of the space vector in the XY plane. That is all. So, what are the observations that I can make from the analysis that I did so far? T_z or 0 vector period is given by this equation.

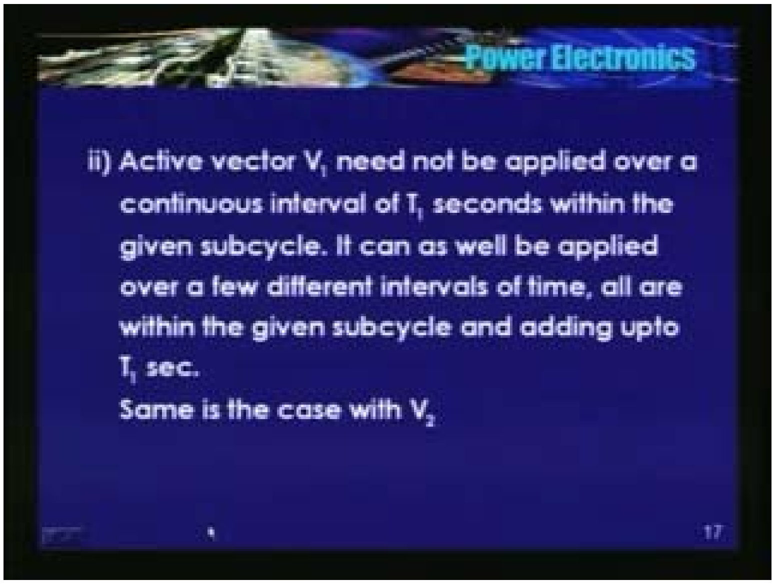
(Refer Slide Time: 50:16)



It could be or T_z could be realized using either 000 or 0 vector or 111 or both; it does not matter because voltage the magnitude of the space vector when I apply these vectors is 0. So, so T_z could be 000 or 111 or I can use depending upon the stability. I can use any one of them. So, I will make another statement irrespective of the ratio in which T_z is divided between the 0 states. I said this could be either this or this or both. The average voltage vector produced is the same as long as T_z is as per the above equation.

I will repeat; what does it mean, in what ratio you divide the 0 vector into this and this, it does not matter. I will repeat; in what ratio you apply 000 or 111, it does not matter as long as as long as you satisfy this equation. So, if you satisfy this equation, it is does not matter, how long you use this or this?

(Refer Slide Time: 52:05)



And, what is the second observation? I said active vector V_1 should be applied for T_1 seconds and vector V_2 should be applied for T_2 seconds. So, I am not saying that V_1 should be applied in a continuous interval of T_1 seconds within a sub cycle. So, it is means this that you do not need to apply V_1 continuously for T_1 seconds. You can divide this T_1 seconds in as many parts that you want. But that should be within a sub cycle. Is that okay?

So, V_1 need not be applied continuously for T_1 seconds. You can divide T_1 depending upon depending upon of or what sort of a harmonic spectrum that you want because there are large number of different PWM techniques that have been proposed by dividing this T_1 period into the large number of different parts. Similarly, it is true for the V_2 vector. So, more about it, I will explain in the next class.

Thank you.