Pulsewidth Modulation for Power Electronic Converters
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Lecture - 30
Analysis of torque ripple in induction motor drives - II

Welcome back to this lecture series on Pulsewidth Modulation for Power Electronic Converters. So, we have been dealing with various pulsewidth modulation methods for power electronic converters. So, we are particularly looking at this dc ac converters, and domain modulation schemes like sin triangle or space vector and such kind of PWM methods, and how you would analyze the harmonic, I mean the waveform quality in such cases and so on and so forth.

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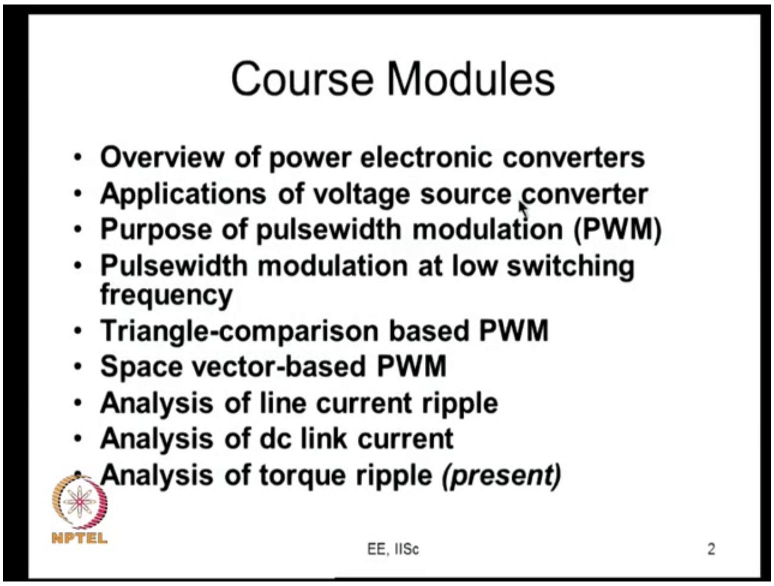

So, this V is course as had so many modules still now a few more modulus are yet to come 4 more to be precise. So, the initial module many of you might have seen the part of these are may be completely. So, this is got an overview of power electronic converters, where we discuss the various topologies dc-dc converters and dc-ac converters voltage source, and current source, multilevel and flying capacitor and so on. Then we looked at a few applications of voltage source converters, like motor drive and reactive power compensation and so on so forth.

Then we looked at some fundamentals of pulsewidth modulation, and then we looked at how to generate pulsewidth modulation at low switching frequency. Some times when the inverter operates at a very low switching frequency, how do you generate the PWM waveforms and we looked at some studies on that. So, we will looked at things like selective harmonic elimination for this purpose, and you know interestingly today we will be doing something very similar to that in this part of that.

So, in the last lecture we actually discuss down some low switching frequency PWM method, and we are trying to look at the pulsating torque produced by inverters I mean the motor drives, which are fit by inverters that switch at low frequency. So, today we will be dealing with that little bit of it. Again, and then you know these are the highest frequency PWM methods. That is, when the switching frequency is much higher than the modulation frequency, a fundamental frequency.

Let say fundamental frequency is 50 hertz, but the switching frequency is a few kilo hertz. So, in such kind of cases you use these triangle comparison methods are the space vector based PWM method. So, in triangle comparison you have things like sine triangle PWM third harmonic injection etcetera, in continuous and discontinuous PWM methods. So, in space vector you would normally use conventional space vector, and you would use bus clamping PWM methods.

So, all these methods as I mentioned before can be implemented either using a career comparison approach. That is, you can have three-phase carrier waves and compare them with I mean three-phase modulating waves, and compare them with carrier and produce the PWM waveforms. Or you can use the space vector approach, where the reference is provided as three-phase revolving I mean revolving voltage vector. And this voltage vector is sampled and you try to apply that, I mean apply a voltage vectors and use you know time averaging of different voltage vectors produced by the inverter to synthesis that. As I mentioned on the number of occasions there are there are some space vector based PWM schemes, which cannot be implemented based on triangle comparison approach. That is, space vector base PWM can do little more than what triangle comparison can do.

So, those we call them as advance bus clamping PWM methods in this course. And so, we have also discuses some of those methods earlier. And today we will be looking at them again briefly in the context of pulsating toque ripple. So, we would be looking at somewhat you know, on these things and particularly with an emphasize on higher switching frequency today in the context of torque ripple. That is, after we did the high frequency PWM we did the analysis of line current ripple, in some sense there is some similarity between the analysis of line current ripple and the torque current ripple, like we would see today.

So, as I mentioned. So, the last lecture our focus was on low switching frequency.

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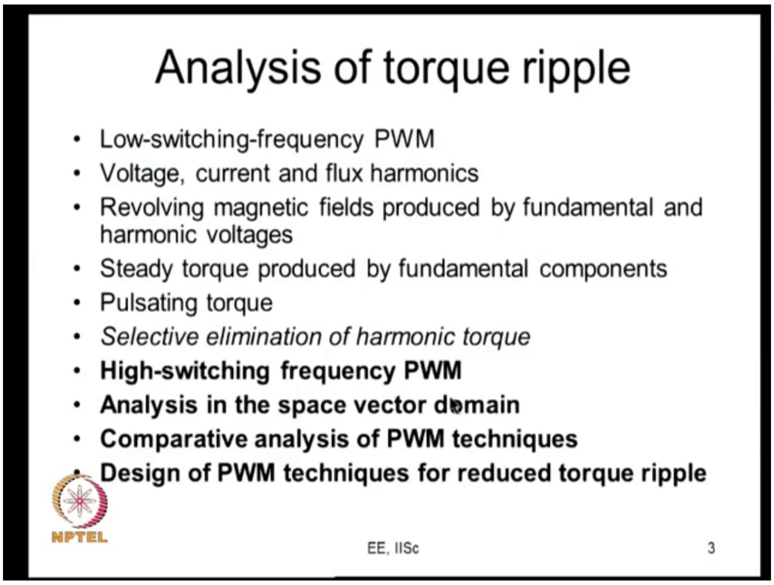

Now, it will be a review on the low switching frequency. So, like quick recap on low switching frequency PWM, and the voltage current and flux harmonics, and a revolving magnetic field is produced by the fundamental and harmonic voltages, and steady torque produced by fundamental components, on the pulsating torque produced by the rest, I mean mostly by the interaction of one fundamental magnetic field, and another harmonic magnetic field. And then we looked at selective elimination of harmonics torque. This we looked at it towards the end of the last lecture.

So, we I mean we would look at this once again today. And then we would move on to what is really the focus for today that is the high switching frequency PWM. So, we will look at it from the space vector point of view, because that is what is more general than the triangle comparison. And we will be dealing with certain space vector based PWM methods which really cannot be implemented from the triangle comparison mode, which are different from that.

So, we would look at a few high advanced bus clamping PWM schemes to here. And we would look at the analysis of that in the space vector domain. You try to do a quick comparative analysis of a few PWM techniques, try to get a feel for the relative performance of the PWM techniques in terms of torque ripple. And we would also look at a couple of design examples for how you design PWM methods for reducing the torque ripple right. So, let us get started with the todays lecture. I would just call it as analysis of torque ripple in induction motor drives 2. The last lecture was 1. So, this is a second lecture and this would be the concluding lecture on the analysis of torque ripple.

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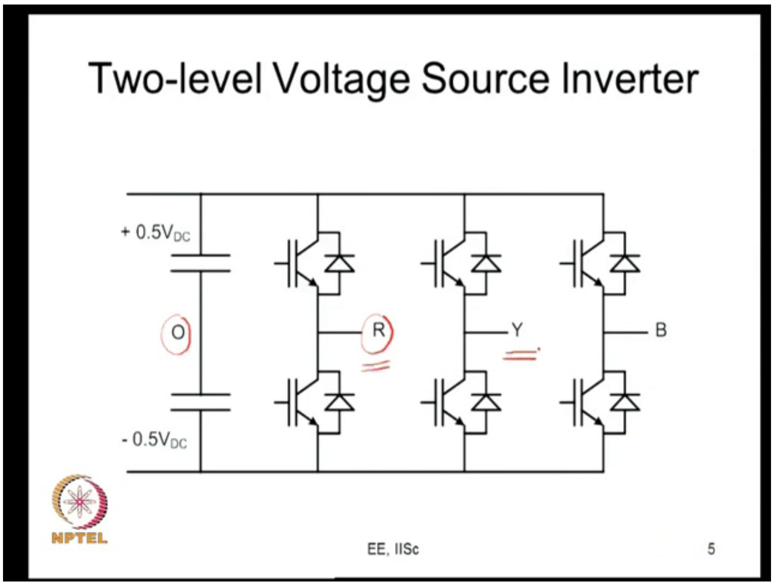

So, it is a usual three-phase voltage source inverter, and R Y B are the load terminals you have connected the motor here. And this is your dc bus, and this is dc bus midpoint. This dc bus midpoint is convenient for measurement of voltage at R Y and B. So, you call it V R O, I mean (Refer Time: 06:04) V R O is something we called as pole voltage. V Y O is Y phase pole voltage, and V B O, we call this as B phase pole voltage. And you subtract V R O and V Y O, you get V R Y, and so on so forth.

So, we looked at many of these. And the PWM is about how do you generate the pulses for these 3 legs.

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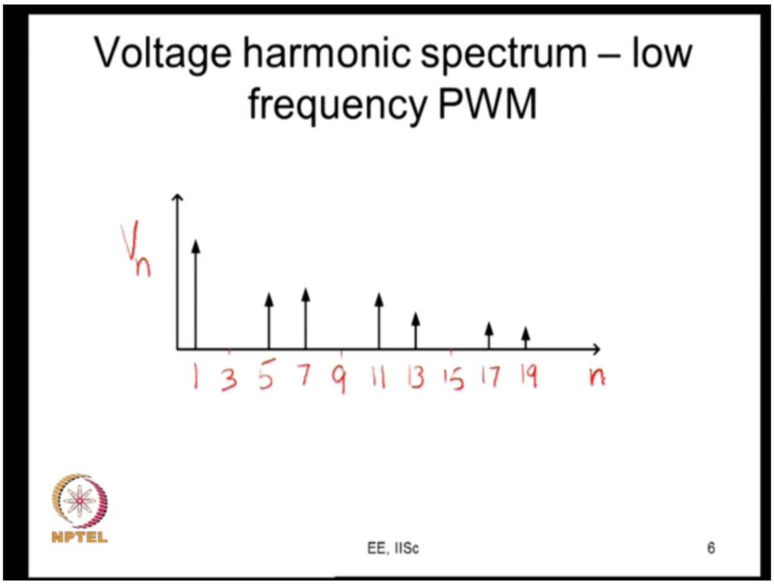

Now, let us say these 3 legs are actually being switch at a very low frequency. So, this is some typical harmonic spectrum of low frequency PWM method. So, let me indicate this is the magnitude of harmonic. So, what are the various higher frequency components there in the inverter output voltage, there is a fundamental component, which is most important, which is what you want. Then this waveform let us say presumably is having even I mean half wave symmetry in therefore, there no even harmonics now.

So, there would be the third harmonic, and the third harmonic is 0. The pole voltage might have third harmonic, but as I mentioned here, this pole voltage might have third harmonic. When you R with respect to O would have third harmonic, but when you subtract V R O minus V Y O, between V R and V Y you will not have third harmonic. So, those third harmonic would get cancelled. So, there will be no third harmonic in the line voltage spectrum. Then you have the fifth harmonic you will have seventh harmonic. Again, you are ninth would be absent, because you are subtracting 2 pole voltages, then this is 11 this is 13. So, this 15 is absent.

So, all the even harmonics are anyway absent. So, this is 17, this is 19 and so on, where this is the harmonic order n. So, let us say such a kind (Refer Time: 07:53) the waveform is being applied whose frequency spectrum is like this, so such a kind of frequency components are being applied on to that.

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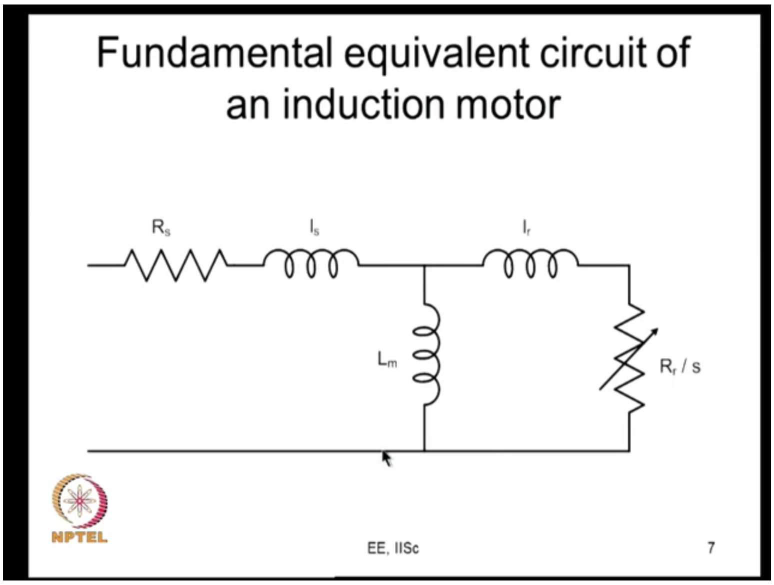

So, the fundamental component gets applied you know, on the motor, it is the one that produces the torque essentially, the steady torque. So, the current produce you know is can be calculated by this. This is the fundamental equivalent circuit. You want analyze the effect of the fundamental voltage on the motor, you can use this equivalent circuit now.

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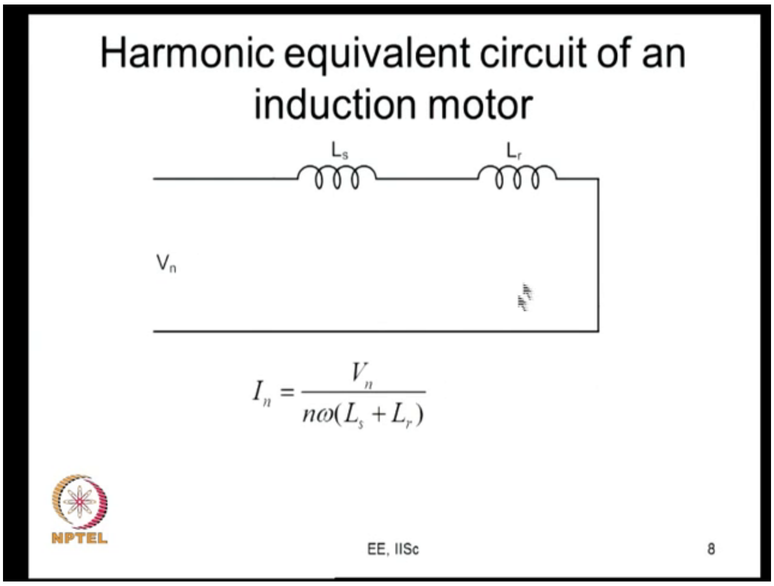

Other than the fundamental there are harmonics, for analysing the harmonic you can use this harmonic equivalent circuit, where this L s and L r are the stator and the rotor leakage inductions, as we discussed in the previous class now. So, if your harmonic voltages amplitude V n, V n upon n omega into L s plus L r would give you I n the harmonic nth harmonic current amplitude.

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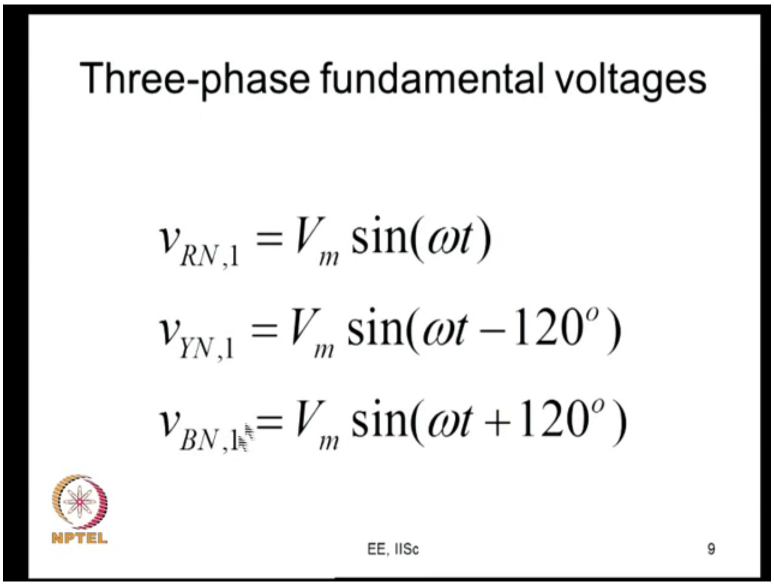

So, you have the three-phase fundamental voltages. So, this considers only the fundamental component. Let say the component here, this considers only the component here. Let us go one by one. So, let us call that amplitude as V m. So, it is V m sin omega t sin omega t minus 120 V m sin omega t plus 120. So, what are these? These are the fundamental components of the three-phase voltages that we have applied.

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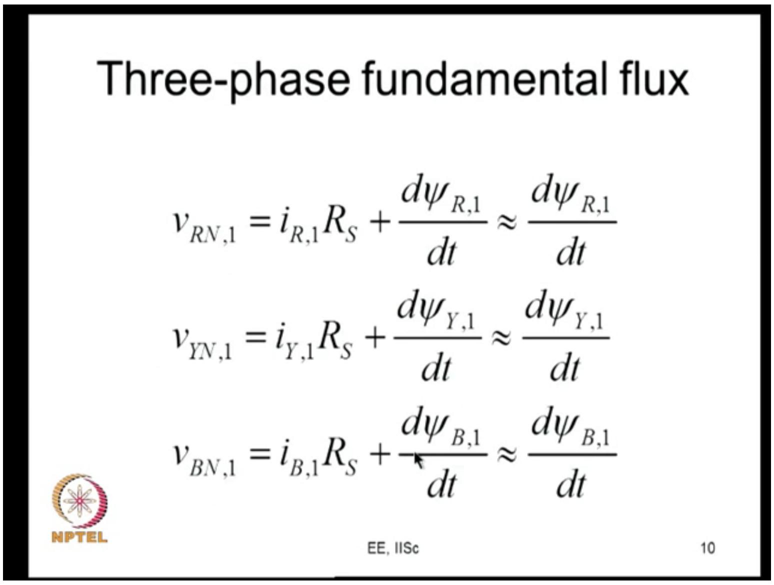

So, they produce flux, they produce a fundamental flux. So, the relationship V RN 1 is given like now. This is the I R drop, drop in the R phase winding. This R s is the stator resistance, and this is the resistance drop in the stator winding R phase stator winding. Plus, d psi R 1 by dt. So, this is really the rate of change of flux leakage now. And as we discussed in the last class, this could be negligible in most cases, and you can say it is approximately equal to d psi R 1 by dt; the same way V YN. So, you have d psi Y 1 by dt, you have again V BN 1 is d psi B 1 by dt. Now this psi R 1 is sinusoidal. Therefore, d by dt of that would also sinusoidal. So, it would be you know the amplitude of psi multiplied by frequency.

So, that is what you will actually get here. So, I mean you will have this equation as I was mentioning the other day. This is from where you draw that you know V by of ratio to be constant. If the voltage and the frequency the voltage to frequency ratio is held constant, then the amplitude would be constant.

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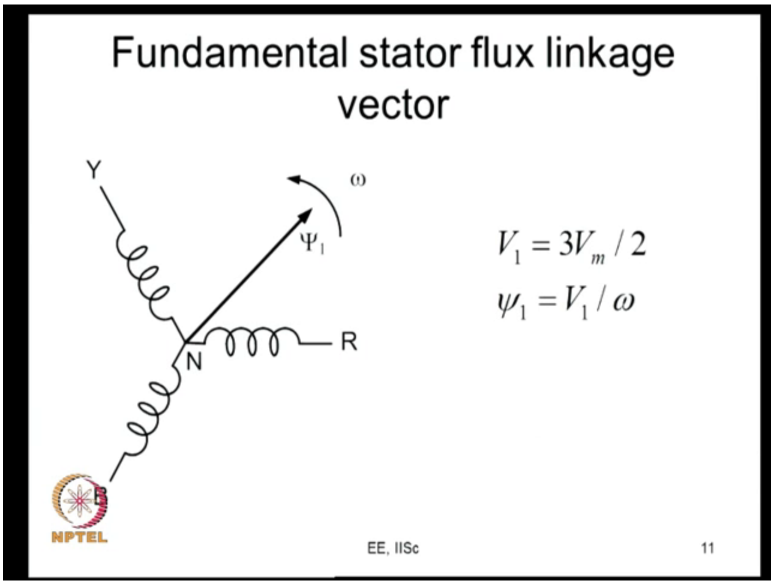

So, the fundamental one produces the fundamental flux. So, you have the three-phase voltages, they are transformed into space vector. You have a vector of magnitude V 1 and you could think of a corresponding vector, that is a stator flux leakage vector. The magnitude of the stator flux leakage vector would be V 1 upon omega. So, and this is a vector which revolves like this, this is produces a fundamental magnetic field. Let us move on to the next.

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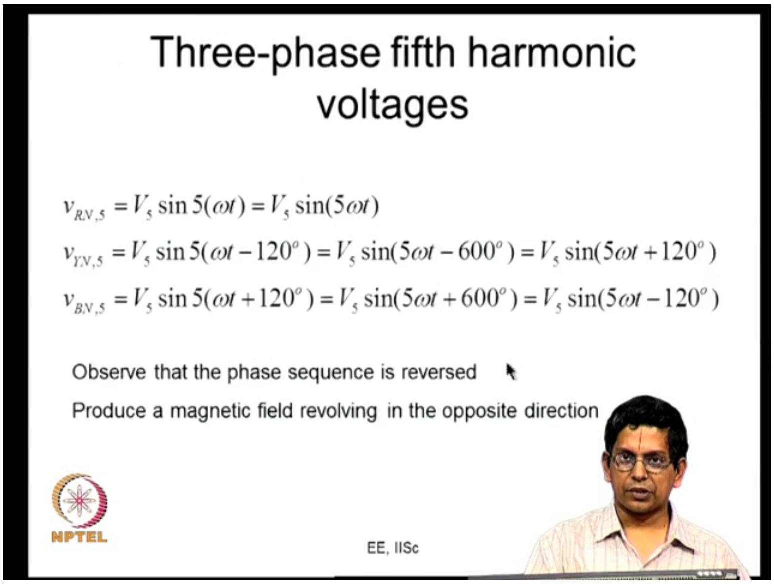

So, this is the fifth harmonic. As I told you other day, day the if you know this fifth harmonic sequence now reversed, where as for the fundamental if you look at the sequences it is omega t omega t minus 120 and omega t plus 120; where as for the fifth harmonic it is omega t omega t plus 120 and omega minus 120 the sequence is reveres. So, as I mention before and if the sequence is reveres what happens? Magnetic field it produces in the opposite direction.

So, you all know that if you change the 2 terminals of an induction motor, R Y B you know you swap 2 of those terminals, the motor will turn on the opposite direction. So, this is what is V RN 5. Thus, it also produces magnetic field and those flux leakages are given by this equations now.

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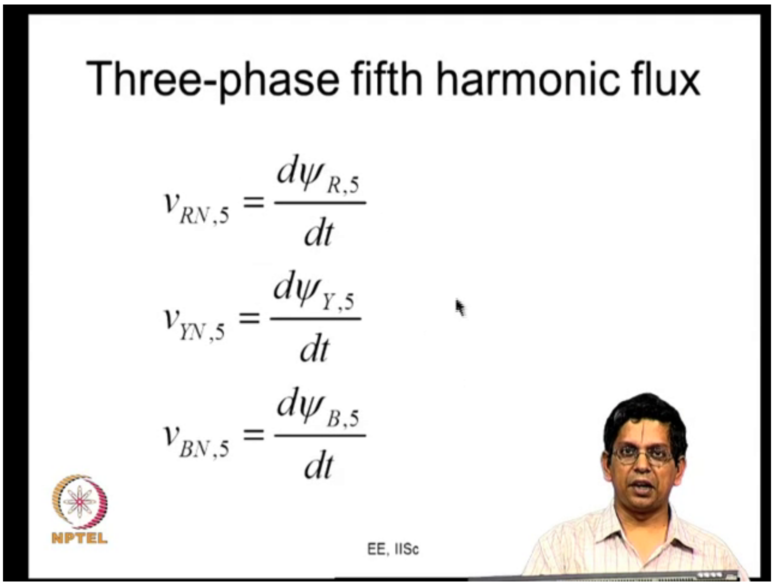

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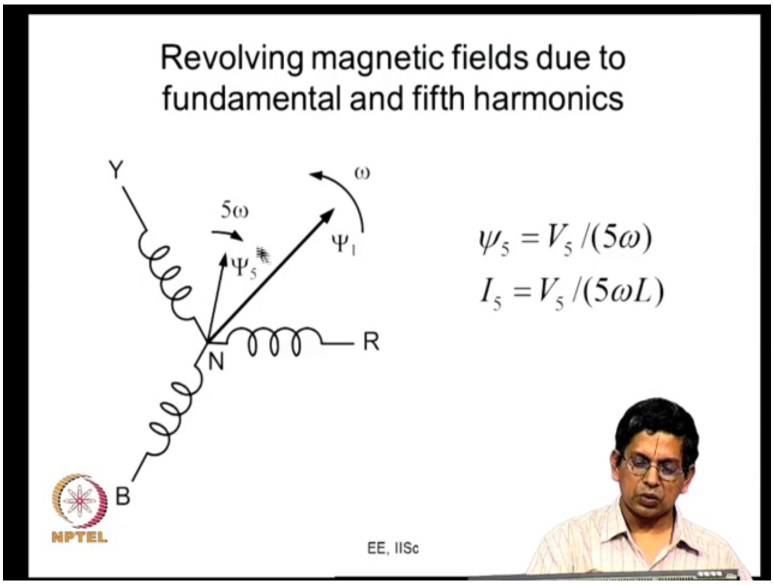

So, this produces one. What is the frequency? So, let us call it psi 5, and this psi 5 would be V 5 by 5 omega. So, this is a revolving magnetic field, but it revolves at a frequency 5 omega, and in the opposite direction compare to omega. So, the relative speed between the fundamental magnetic field and the fifth harmonic magnetic field is 6 times the fundamental frequency. And this is why it leads to what is called as 6th harmonic torque.

So, the fifth harmonic causes a fundamental vector like this; now psi s whose magnitude can be given by that. Again, it causes certain harmonic current, which can be given by this now; so where l is this leakage inductance now. So, this causes you know the fifth harmonic voltage causes certain fifth harmonic, current and fifth harmonic flux.

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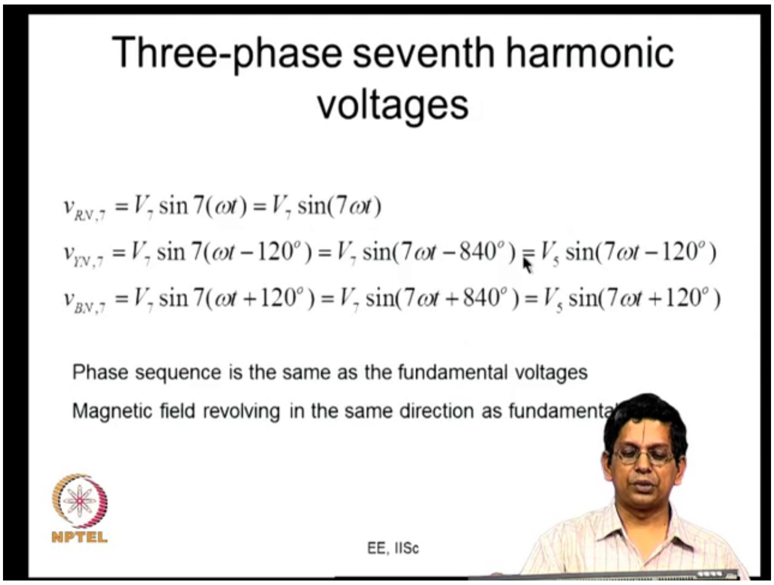

So, this is the same story about seventh harmonic, expect that the seventh harmonic as we saw the other day, it is the phase sequence as the fundamental it is 7 omega t. 7 omega t minus 120, then 7 omega t plus 120, or 7 omega t minus 240 or plus 120 (Refer Time: 12:20). So, you see that the phase sequence same as the fundamental voltages now. These also produce a magnetic field. This is also three-phase voltage, being applied to a three-phase winding. So, it produce revolving magnetic field, and in which direction is the same direction as a fundamental, because sequences same.

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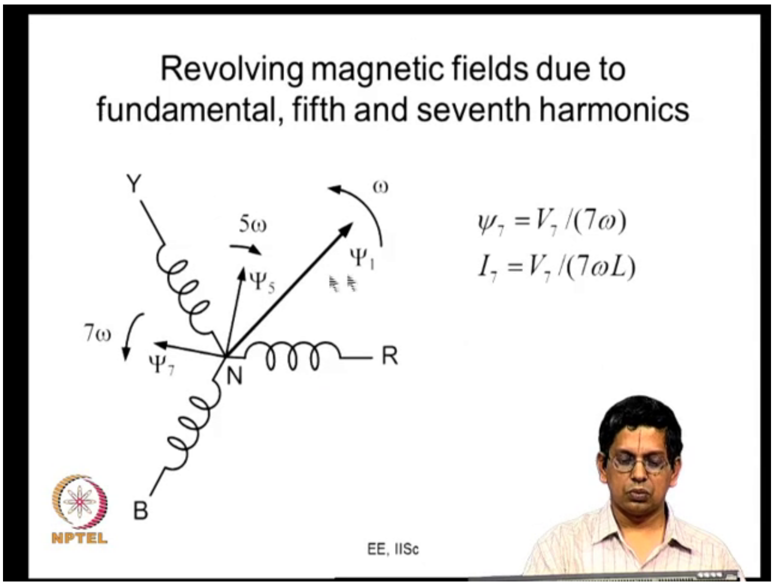

So, what does it do? You can see this here. This is all illustrated. So, fundamental this is the flux vector produce by the fundamental, this is a fifth harmonic, this is a seventh harmonic.

Similarly, every other harmonic component 11, 13, 17, 19 would all produce magnetic field which we are not showing them here all right. So, let us move on to the next part.

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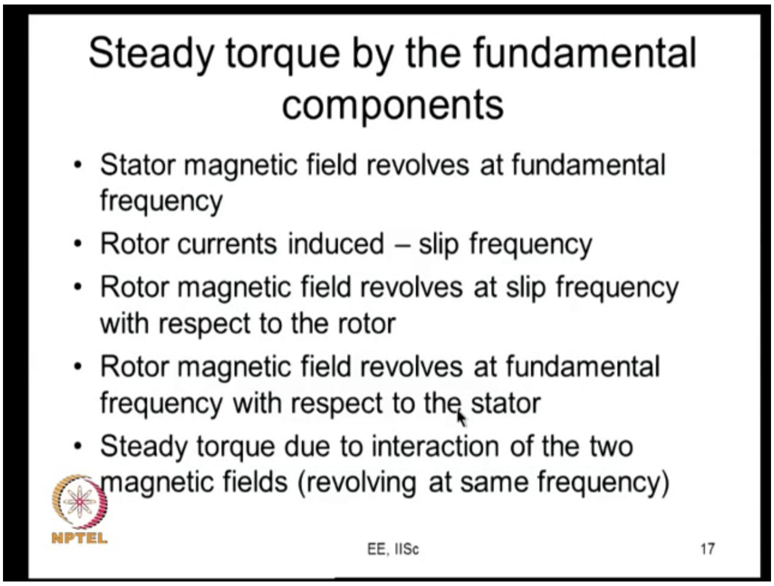

So, what happen because of that? So, the stator magnetic field revolves at fundamental frequency. These we are trying to look at the fundamental component alone, or simply the sinusoidal operation. So, the stator magnetic field produces a revolves at the fundamental frequency, the rotor currents there is some EMF induced the rotor. So, that is at slip frequency. So, this MMF wave it goes past the rotor at slip frequency.

So, slip frequency EMF are induced in rotor, and rotor produce shorted path and therefore, you are going to have slip frequency rotor currents. So, when you have slip frequency rotor currents. So, the rotor is going to produce magnetic field. Because it is rotor is also like a three-phase winding. So, it has currents flowing through that. So, there is it and this magnetic field revolves at slip frequency with respect to the rotor if the rotor magnetic field revolves at slip frequency with respect to the rotor. So, with respect to the stator, it is the slip frequency plus the rotor zone frequency; which add ups to the synchronous frequency itself.

So, the rotor magnetic field revolves at the fundamental frequency are synchronous frequency with respect to the stator. So now, you have 2 magnetic fields, one is this stator magnetic field and other one is rotor magnetic field. So, both of them are stationary with respect to one another, and that is the reason you are able to produce a steady torque. The torque is actually the cross product of these 2 magnetic fields. So, it depends on the strength of this magnetic field, and the strength of the second magnetic field, and the sine of the angle between the two. Since they are stationary with respect to each other, the angle between the 2 is constant, and the sine of the angle between the 2 is constant. And therefore, the magnetic I mean in the torque produce constant.

On the other hand, when you looking at harmonics, when you look at you know magnetic fields of two different frequencies, then they will produce a pulsating torque, because the angle between the two fields is going on changing, and therefore, the torque will also go on changing now. This is what we look at now.

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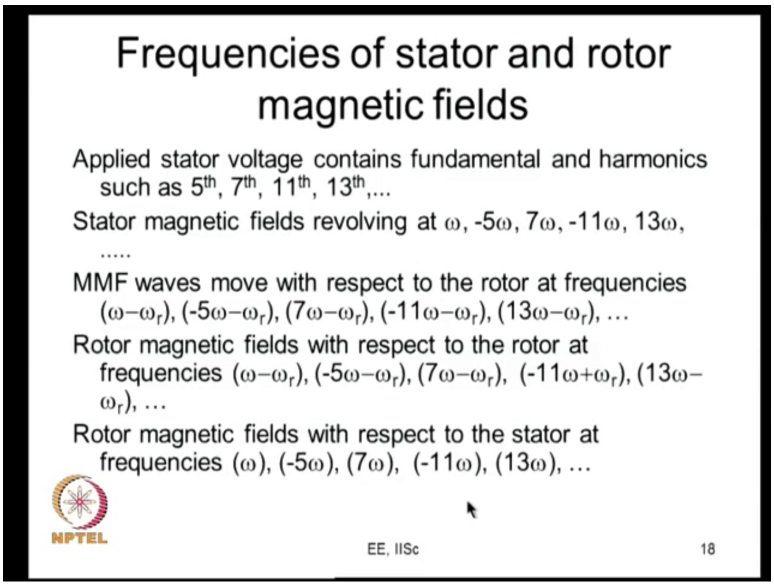

So, when you apply fifth harmonic voltage, it produces something revolving. That is at 5 omega, since it is in the opposite direction we make it minus 5 omega. So, the rotor is anyway rotating at omega r therefore, you know it sees an MMF wave moves pass the rotor at this frequency, minus 5 omega minus omega r all right. So, frequency you know EMF induced EMF in the rotor of this frequency 5 omega plus omega r. Such you know the rotor induced EMF is at this frequency 5 omega plus omega r therefore, the rotor induced currents are also at this frequency 5 omega plus omega r.

So, the rotor produce the magnetic field which revolves at this minus 5 omega I mean it is at 5 omega plus omega r, but the you know the direction is reveres and therefore, have indicated a negative sign here now. So, this is how the rotor magnetic field is with respect to rotate with respect to the rotor, and with respect to the stator it is back to minus 5 omega. So, what happens? You have the stator producing this fifth 7th 11th etcetera applied on the stator, consequently there are magnetic fields of 5 you know like 5 omega 7 omega 11 omega 13 omega etcetera.

There are magnetic fields corresponding to the various components of the stator voltage. And the stator voltage is in turn induced EMF in the rotor and currents in the rotor, and they produce magnetic fields. And once again those are at frequencies omega 5 omega 7 omega 11 omega 13 omega. So, what we can say is; the main torque is being produced by these 2. That is, what is revolving at omega and here what is revolving at omega. Any interaction between 2 here is pretty weak, because these magnetic fields is not very strong, and let us say some magnetic field here. This is also not too strong.

So, the interaction between these 2 is pretty small. So, what we need to consider is the interaction of these 2 fields which produces the fundamental torque, and the interaction between this field with any of these fields. Now if you take this field which is revolving at omega, and take this at minus 5 omega. So, the difference is 6 omega. So, there is an angle between this difference, and that actually varies at the 6th harmonic frequency. So, the angle between these 2 goes on changing in a cyclic fashion, at 6 times the fundamental frequency.

So, this fundamental magnetic field, and the fifth harmonic magnetic field interact to produce 6th harmonic torque. The same way the fundamental magnetic field and the seventh harmonic rotor magnetic field interact to produce the 6th harmonic torque. So, because again when you look at these 2 fields, the angle between these 2 field changes and it changes at the 6 times the fundamental frequency. The same way omega interacts with minus 11 omega to produce at twelfth harmonic torque. This field interacts with this field to produce again a twelfth harmony torque.

So, you can say that you know these are magnetic fields and they do this. And this is how the pulsating torques are actually get it produced.

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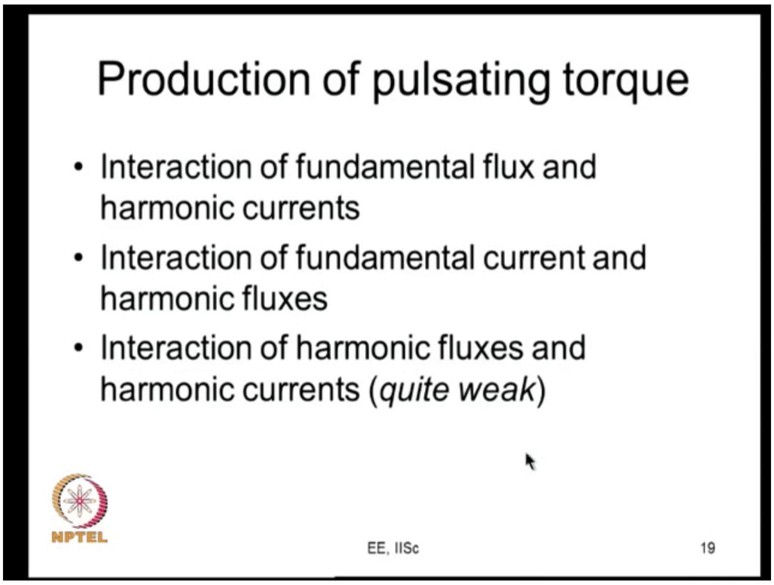

So now there are 2 magnetic fields. So, how do you represent a magnetic field? You can probably represent in terms of flux or in terms of current. So, let us say we look at the fundament the stator magnetic field the stators fundamental magnetic field. So, we can look at the fundamental flux of the stator, and if you want to look at a harmonic I mean now magnetic field produced by one of the harmonic rotor harmonic currents, I mean the harmonic fields of the rotor, then you can look at the harmonic currents.

So, like I want to say an interaction between the fundamental magnetic field produced by the stator, and one harmonic magnetic field produced by the rotor. I can possibly consider fundamental flux corresponding to the stator, and a particular harmonic current corresponding to the rotor. So, I can look at this as an interaction between these 2, we can also look at this is an interaction between fundamental current and harmonic fluxes. You look at things there, but the interaction between harmonious fluxes and harmonic currents is quite weak.

So, you know what we would essentially say is; we can actually look at what is the stator side fundamental flux are air gap flux, whichever way, and then you can look at currents the rotor harmonic currents, and you can actually evaluate the 6th harmonic or the twelfth harmonic pulsating torque.

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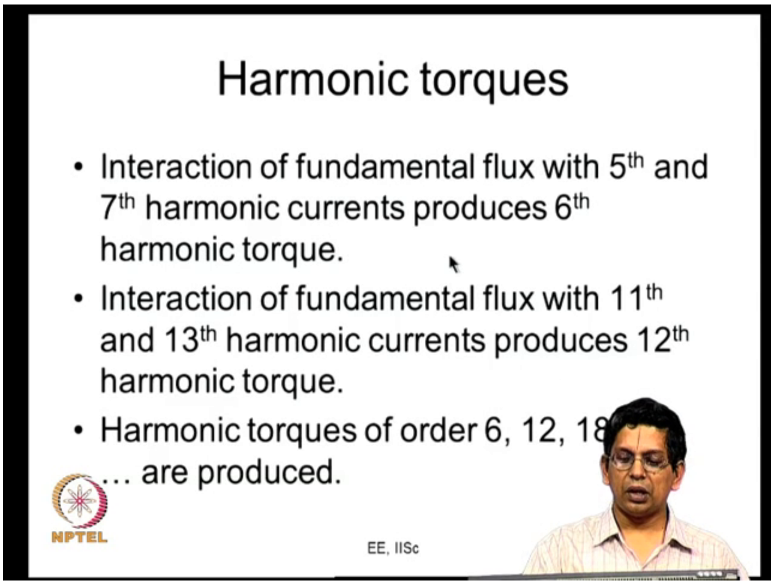

We didnt go through the detailed procedures for this; so this for interaction of fundamental with fifth and 7th producers 6th harmonic torque and similarly twelfth and all that.

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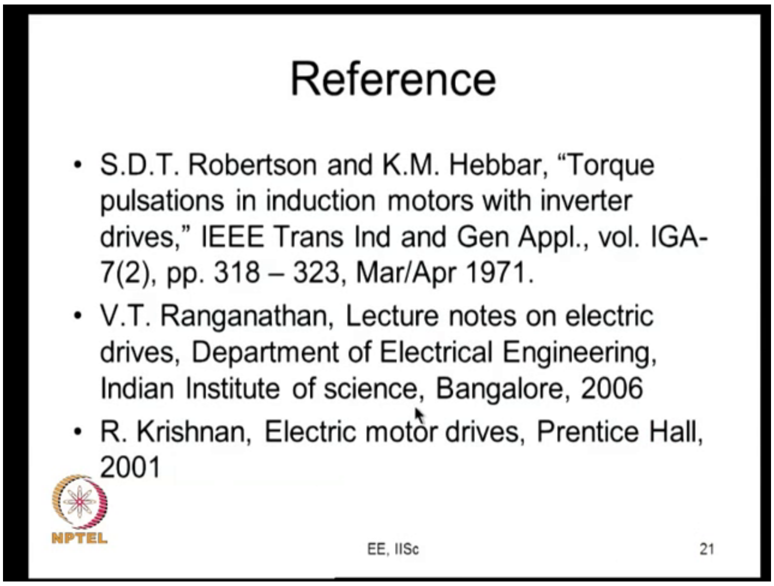

But, as I mention to you this the details are available in these references. So, you could always look at this references where you know you can they tell you how exactly to calculate this based on the parameters.

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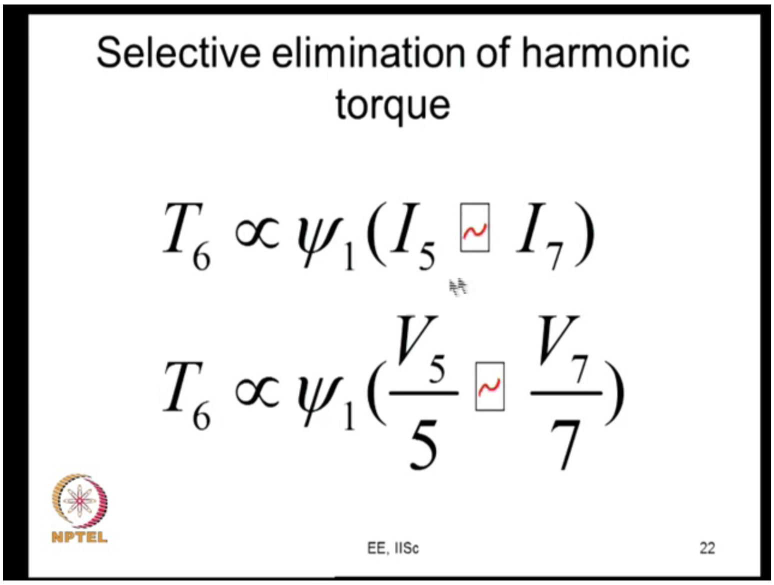

So, this is a difference between the 2. So, what happens here is; you have your torque, it is proportional to point fundamental flux and it is proportional to the difference of these 2 currents right. So now, this is fifth harmonic current, this itself is proportional to V 5 by 5 the fifth harmonic voltage divided by 5. And this is I 7 is V 7 by 7. Because the fifth harmonic voltage sees 5 times the fundamental leakage reactance, the seventh harmonic voltage see 7 times of fundamental leakage reactance. So, you have this as V 5 by 5 I V 7 by 7.

So, what it is sort what is the end of last lecture was that; if we can actually eliminate V 5 by 5 minus V 7 by 7, or there is some phase relationship, but you know you can actually work that out, and when you take them like what you call as V 5 and V 7 (Refer Time: 20:57) then you can say V 5 by 5 minus V 7 by 7 can be eliminated. You can possibly eliminate 6th harmonic torque.

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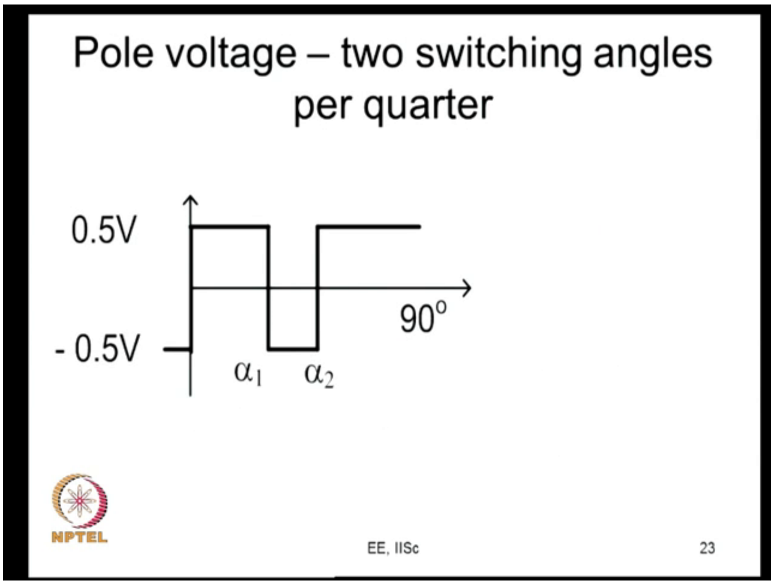

So, just as we could eliminate harmonic voltages. So, for the elimination of harmonics voltages, we had considered the simplest a case where we have 2 switching angles per quarter.

So, you have 2 independent variables. With only one independent variable you can control only the fundamental voltage, with 2 angles you can control one fundamental voltage and one other harmonic voltage, and you could. So, that controlling harmonic voltage means you know you could possibly eliminate that harmonic voltage, make it equal to 0.

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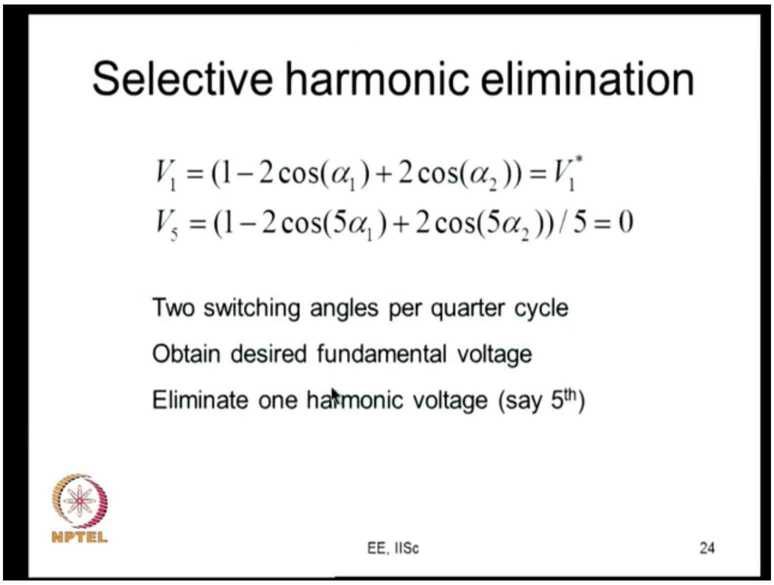

So now you have your V 1 and this V 1 is 1 minus 2 cos alpha 1 plus 2 cos alpha 2 is V 1 star is one of the equation now. So, you want to choose your angles alpha 1 alpha 2, such that your fundamental voltage is equal to desired fundamental voltage. Let us say 0.8 per unit, or 90 percent or 70 percent; something this is a desired voltage at you want. So, this is one equation for you. The second equation let us say you want to eliminate fifth harmony voltage. So, it is 1 minus 2 cos 5 alpha 1, plus 2 cos 5 alpha 2 by 5 that is your fifth harmonic voltage, that should be equated to 0.

So, by solving these 2 equations numerically, you will be able to find out some alpha 1 and alpha 2, which satisfy both these equations. So, you can get the desired fundamental voltage, you can also eliminate this. So, you can have 2 switching angles per quarter, you can obtain the desired fundamental voltage eliminate one harmonic voltage. This is one you have 2 switching angles. In general, if you have k switching angles, you could get your desired fundamental voltage, and it might be possible for you to eliminate up to k minus 1 harmonic voltages. So, that is selective harmonic elimination, selective elimination of harmonic voltages.

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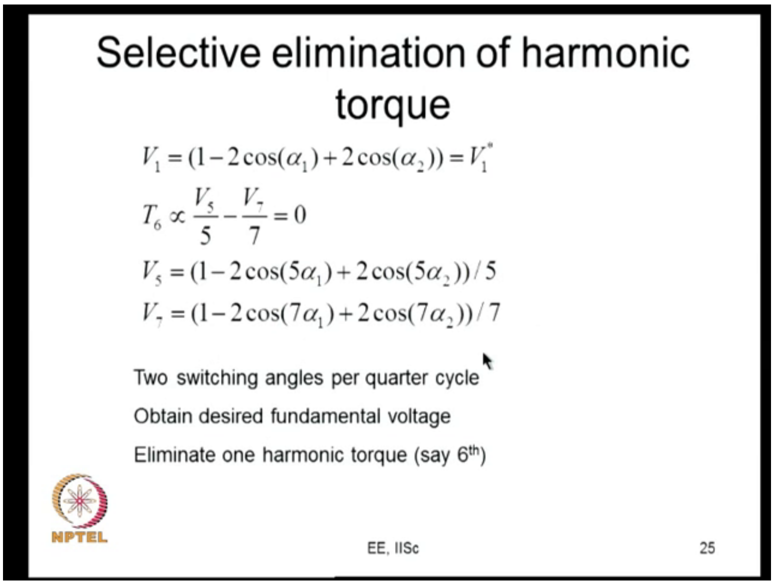

Now, we are talking of selective elimination of harmonic torque.

So, we want the fundamental voltage like before. V 1 is 1 minus 2 cos alpha 1 plus 2 cos alpha 2 equals V 1 star, but what we want is also that; instead of the fundament being I mean particular harmonic voltage being eliminated, we want the particular harmonic torque to be eliminated. That can be achieved in in certain cases by ensuring that V 5 by 5 minus V 7 by 7 is equal to 0. So, what is this V 5? It is 1 minus cos 5 alpha 1 plus 2 cos 5 alpha 2 divided by 5. And what is V 7? 1 minus 2 cos 7 alpha 1, plus 2 cos 7 alpha 2, the whole divided by 7. So, this V 5 by 5 minus V 7 by 7 you want to make it 0.

So, you once again have 2 2 equations in 2 unknowns, you can solve them. But I say some of you might recall from my lectures on low switching frequency PWM selective harmonic PWM. So, you have 2 equations 2 unknowns. It is not necessary that you should have a solution. In fact, you will not get solutions, when you are very close to 6th step operation when you are modulate desired a voltages close to one per unit where one per unit stands for the square wave fundamental voltage. So, like 0.95 to 1 per unit or so, you know there some small range where you may not get any solution at all. And in some range, you will get some solution, and there are also a few rangers where you get multiple solutions, we have looked at all these right. So now, this is just an example of selective elimination of harmonic torque, you know with 2 switching angles.

So, that you can control the fundamental voltage and you can eliminate let us say the 6th harmonic torque. If you want you can also eliminate the twelfth harmonic torque. In general, you know what you do is; you try to eliminate the harmonic torque which might come close to your resonant frequency. The system might have some resonant frequency. So, you will have particular harmonic torque which might come close to that. So, one approach engineers would use actually to eliminate that particular torque now.

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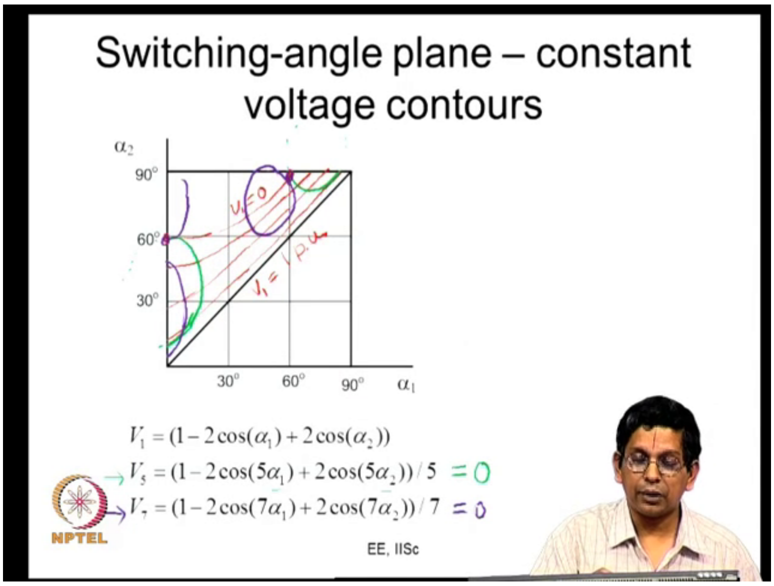

So, to get a feel for this, we know let us do a recap of what we did before. That is, this switching angle plane we had this 2 angles alpha 1 and alpha 2. So, this 2 angles alpha 1 and alpha 2, let us consider one of them along the x axis, and another one along the Y axis now. So, this is your plane. Now you are looking at this plane, alpha 1 cannot exit 90 alpha 2 cannot exit 90 degree. Because it is within one quarter, and alpha 1 has to be less than alpha 2. So, you are essential looking at this upper triangle. You are essentially looking at this upper triangle. So, this is the area, within which you are looking at all your possible PWM waveforms are within that now. So, if you are looking at V 1 is equal to 1 minus you know some you know particular fundamental voltage. Let us say you consider this one, what is that line? This line is alpha 1 is equal to alpha 2, when you say alpha 1 is equal to alpha 2, you can see from this equation that it is 1. So, this corresponds to V 1 is equal to 1 per unit.

So, it is a square wave operation, there is nothing more than that. If you want to take V 1 is equal to 0, you can see that this point would correspond to V 1 is equal to 0. You would fine that this point alpha 1 is 16 alpha 2 equals to 90 also corresponds to you can put these numbers in c, we have done this all we know good detail earlier. So, actually you will get a set of all points. Like, this along this line you will get V 1 is equal to 0. What does it mean? You are producing a PWM waveform which has 2 switching angles as shown here, but the fundamental voltage is 0.

So, it is not unique. There are several pairs of switching angles available for you. Each of these pair can actually give you V 1 is equal to 0. So, let us say you want V 1 is equal to 0.2 per unit or so you will get some other curve like this. You might get some other curve like this. If you want to look at V 1 is equal to 0.5 or so you might get some other curve, which may be like this. And we want something like V 1 is equal to 0.8 per unit or. So, you may get some other curve like this. So, this are all different values of V 1. So, this are what we can call as constant fundamental voltage contours on this alpha 1 verses alpha 2 play. Now we are interested in seeing the harmonics.

So now there are so many options for you. That is, if you want a particular value of V 1, let us say this is V 1 is equal to 0.2 per unit, you can use any of this points here, along this curve. Which point do you use? It depends on which want to choose. That depends on your criteria for a selection. Now let us say you want your criteria for selection is that fifth harmony should not exist. So, you want to see where fifth harmonic is. So, it is actually possible to plot the fifth harmonic currents also, I mean the wait a minute. So, we can see where all fifth harmonic is 0. That is, you can consider this equation and based on this equation, like you know you can look at several values of alpha 1 and alpha 2, which would satisfy this equation V 5 is equal to 0. So, if you try this. You can plot this we have also done this before, in case you have not done this it is a nice exercise for you to do it.

So, you would actually get certain angles like this. You would actually get a curve like this. This is, but not the only once, here also you will get a curve like this. This is within this range. This is actually is a part of a larger curve. Again, this is also part of a larger curve. This curve can be obtained by shifting this contour by 72 degrees, and shifting further up by 72 degrees. This 72 degrees is 360 by 5, which is really the fifth harmonic frequency. Now you can also look at; where are the seventh harmonic components are there. So, I can consider this equation, and you can equate this to 0. And you can see the set of all points where seventh harmonic is 0.

You will once again see that this point seventh harmonic is 0. You will see that at this point seventh harmonic is 0. So, those are actually the points at which the PWM waveform is a triplen frequency square wave. It is a third frequency square wave. So, you will not have any components other than the third harmonics there. So, if you look at that this 6th harmonic you know, there will be another fellow here, you may have it as like this. You may have some V 7 is equal to 0 curve here. You may have another V 7 is equal to 0 curve, which is going up it is not within our interest, you will have another V 7 is equal to 0 curve like this. You may have some other curve like this. So, we have done this all before, we are just trying to do this is a recap. So, these are also constant volt constant voltage contours. But while these are constant fundamental voltage contours, these are constant harmonic voltage contours. This green line is for example, V 5 is equal to 0, this line is V 7 is equal to 0.

So now if you choose this point for example, you get at this fundamental voltage, you will get your fifth harmonic to be 0. So, you choose this point, you are going to get seventh harmonic to be 0. So, it is possible for you to eliminates. So, it is depending on where you choose like here or here, you can actually operate with 0 fundamentals fifth harmonic or 0 seventh harmonic. Similarly, it is also possible to look at where 11th harmonic is 0 where 13th harmonic is 0, it is also possible to look at a certain combinations of harmonics, and see you know square root of V 5 square plus V 7 square is low. Many a times what is done is the weighted t h d of voltage is considered to be low. That is also done at times now.

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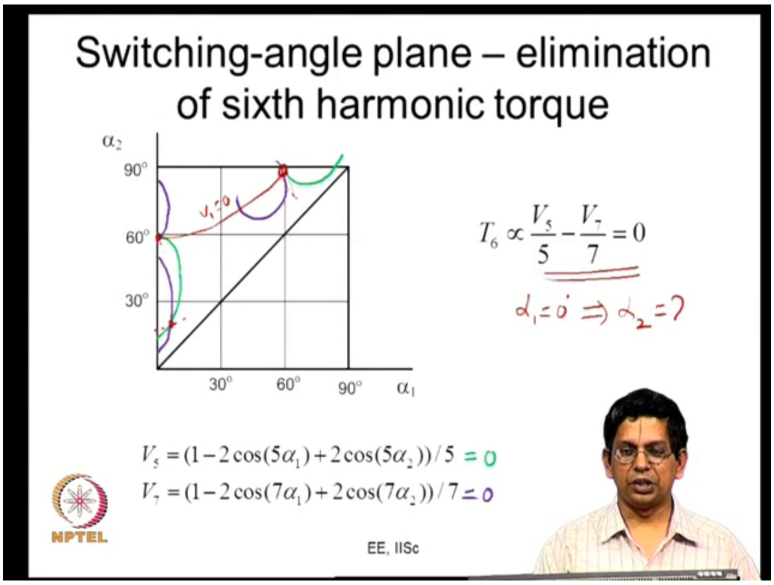

So now what are we trying to do? We are trying to look at the 6th harmonic torque to be eliminated. So, let me quickly reproduce some of this curves here. So, you want; this is your V 5 is equal to 0. Now you have V 7 is equal to 0. This is like this. So, obviously, there is a point here, where both V 5 and V 7 is equal to 0. So, at that point there some modulation index at that modulation index, you are able to eliminate both fifth and 7 harmonic, but you can not do it everywhere. It is only there, but at that point your 6th harmonic is 0, which is the particular case V 5 by 5 where V 5 is 0 and V 7 is also 0.

So, you have this point. Now what you can do is there you can actually look at set of all points where that is 0. So, you would actually find that maybe there are few points, like there are few points like this. You solve for this equation. One way to do this, maybe you say alpha 1 is equal to 0, and then try to find out the different possible values of alpha 2. Or you can consider some other value. So, you can do this. So, you will also fine that the 6th harmonic torque is 0 there, because once again you have V 5, as well as V 7 going 0 there. And the same way, if I redraw that curve, I have this fifth harmonic curve, and I would have another seventh harmonic being 0 like this.

This is again a point at which I will have the 6th harmonic is 0. So, this this are 3 points where I have 6th harmonic to be 0, but these 2 points are actually on your V 1 is equal to 0 line. This are on your V 1 is equal to 0 line. So, you have these points, but you will also get some points in the neighborhood. You will get a few points in the neighborhood, suddenly which satisfies this V 5 by 5 minus V 7 by 7. I would certainly encourage you to solve this and try. So, these are all some points where you get. So, you get some feel for what can be done and how things can be done and so on so forth.

So, this is about how you can eliminate that. It is a very simple exercise, but it is to enhance our own understanding of how things change and how it works, and how you can eliminate harmonic torques.

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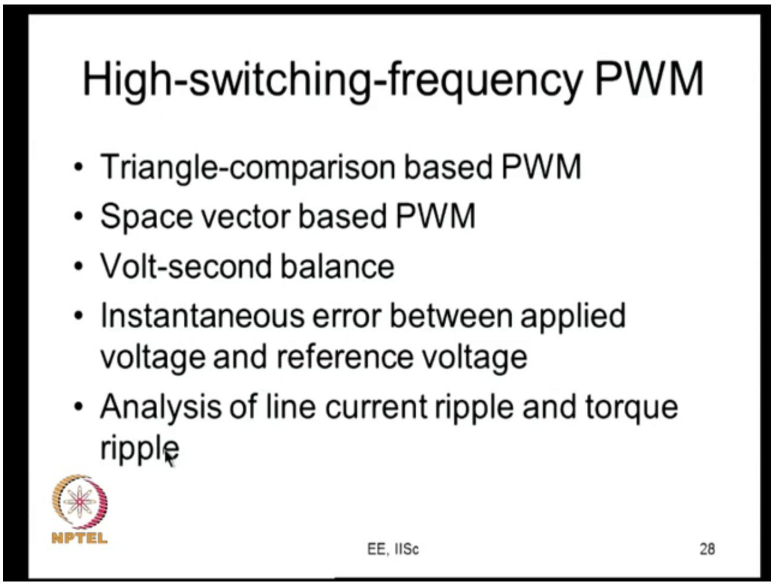

So, you can generalize it. So, this is I have looked at only one switching angle. If you have multiple switching angle, just you can have like as you can eliminate multiple harmonic voltages. It may be possible for you to eliminate multiple harmonic torques also, but all certain if you can eliminate multiple harmonics, you could also eliminate multiple torques. For example, if you have 3 switching angles per quarter, you control your fundamental voltage and eliminate both V 5 and V 7.

So, you are ensuring V 5 is equal to 0 and V 7 is equal to 0 6th is automatically gone. So, similarly, if you have let us say about 9 switching angles, you can control your fundamental voltage. And 4 pairs of harmonics can be eliminated. So many a times when they eliminate harmonic voltages they will eliminate in pairs because that, make sure that a particular torque component does not exists. If you eliminates fundamental, and the first 4 pairs of harmonic like 5 and 7 11 and 13 15 and I mean 17 and 19 and 20 there and

24 23 and 25, you are ensuring that there is no 6th harmonic torque twelfth harmony torque 18th harmonic torque, and 24th harmonic torque.

So, that is normally what is also done. So, you can eliminate the harmonic voltages, once you eliminate a pair of harmonic voltages, it is the particular harmonic current is gone. So now, you we are going to look at the high (Refer Time: 34:42) switching frequency part like it is you know, this is when you go to high switching frequency the pulsating torque is not going to be as bad as it is in the low frequency. But still it is develop it is good to develop a good understanding of this. So, you have this triangle comparison or this space vector based approach, where you have this.

So, what happens in these cases is there is a volt second balance. The triangle comparison method goes on a phase by phase basis for every phase it says, I need so much of average voltage. And that much of average voltage is actually applied by the inverter. So, the applied voltage and the reference voltage are commanded voltage are equal over every sub cycle, or every half carrier cycle. And that is what you call a volt second balance. Here the voltage reference is not provided in terms of three-phase voltages, it is provided as one reference vector.

So, the inverter applies an average voltage vector equal to the reference vector. So, the applied vector is equal to the reference, and once again you call it volt second balance. Therefore, this is how you do that. And this volt second balance is maintain over small intervals of time which are called which is called sub cycle, sub cycle could be like you know if your fundamental cycle is 50 hertz, your sub cycle could be as low as like 100 micro second or 50 micro second depends on your switching frequency, how high you are switching now.

So, like there are some ranges like 15 to 20 times fundamental are, so where you can have significant pulsating torque. And that is where this kind of exercise can actually help you reduce the pulsating torque here. So, let say it is volt second balance, what is the problem? There is an instantaneous error between the applied voltage and the reference voltage. You are matching them in an av on an average sense, but not in instantaneous sense. Therefore, there is a difference between the 2, and that is what causes the ripple current. And the same is the cost for pulsating torque also. We use this for the analysis of ripple current before, and we are going to use the same thing for analyzing the torque ripple now.

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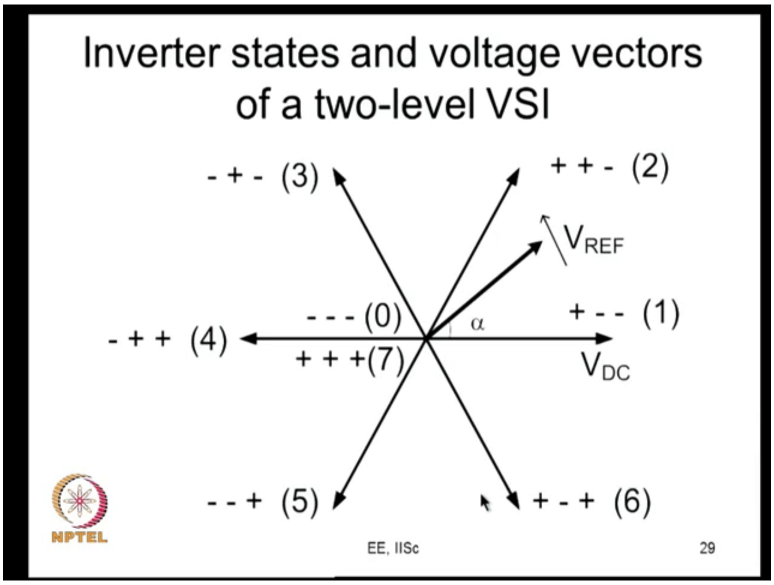

So, let us say this is your vector; this is your space vector plane. And you are fundamental reference going around that. So, you are now looking at sector 1.

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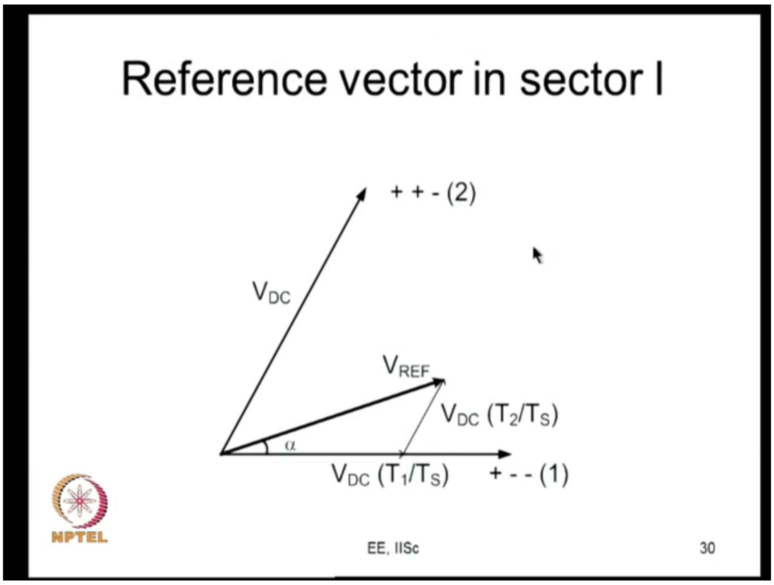

So, if you going to apply that reference vector, what do you do? You apply your active vector for a t 1 seconds, and this active vector 2 for t 2 seconds, and the null vector for the remaining time. So, that you know you have this voltage like this. So, what you what produces here? So, this reference vector is produced now by applying this for t 1 seconds.

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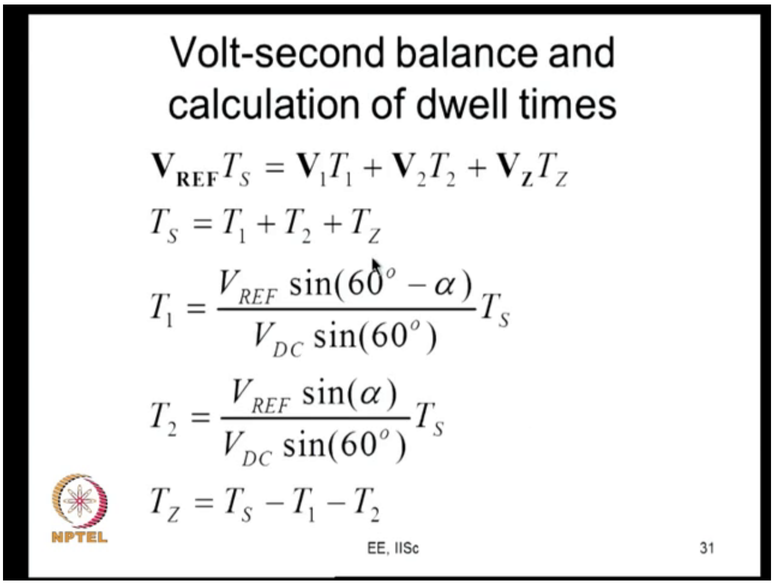

And this for t 2 seconds, and t at the null vector for the remaining once, and how are they calculated? This is what is volt second balance. This is a reference volt second, this is the applied volt second, and they are equal. And the sub cycle time is equal to the active vector time 1, active vector time active vector 2 times and you know the null vector time.

And t 1 is calculated based on your magnitude and angle of the reference vector. T 2 is also calculate based on the magnitude angle, and t z is Ts minus t 1 minus t 2. So, we this we did this in good detail when we did the module on space vector based PWM.

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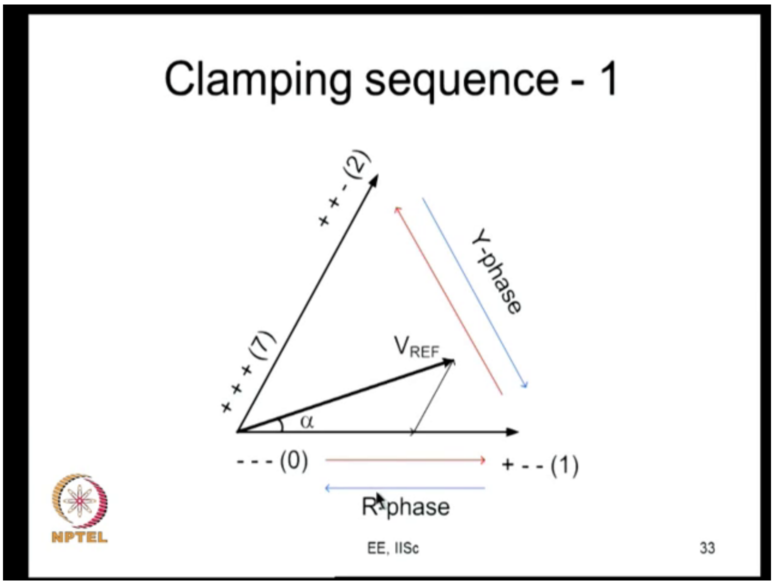

Now, you can produce this in many sequences, what is normally done is your conventional switching sequence, that is you start from here, and you go there, that is you apply this for t z by 2 seconds, you apply active vector for t 1 seconds, you do this for t 2 seconds, and then you once again come here and do it for t z by 2 seconds. But now this is what is called as clamping sequence. You do not have to go to the null vector twice, you can apply this null vector for entire t z seconds here itself, you can stay at minus minus minus for t z seconds, then switch your R phase.

So, that you go to plus minus minus. You stay here for t 1 seconds, then switch your Y phase so that you go to active vector 2 and stay there for t 2 seconds. Your sub cycle is over, next sub cycle what do? You do stay here for t 2 seconds, then switch your Y phase; come to active vector 1, stay here for t 1 seconds. And then you switch your R phase and return back to minus minus minus. So, what happens is here B phase is never switched. And it is clamp, you can see B is negative here B is negative here B is also negative here. B phase clamp to the negative dc bus. And so, we call it is a camping sequence, and this is clamping sequence 1 clamp clamping sequence 1; where a phase gets clamp to the negative bus.

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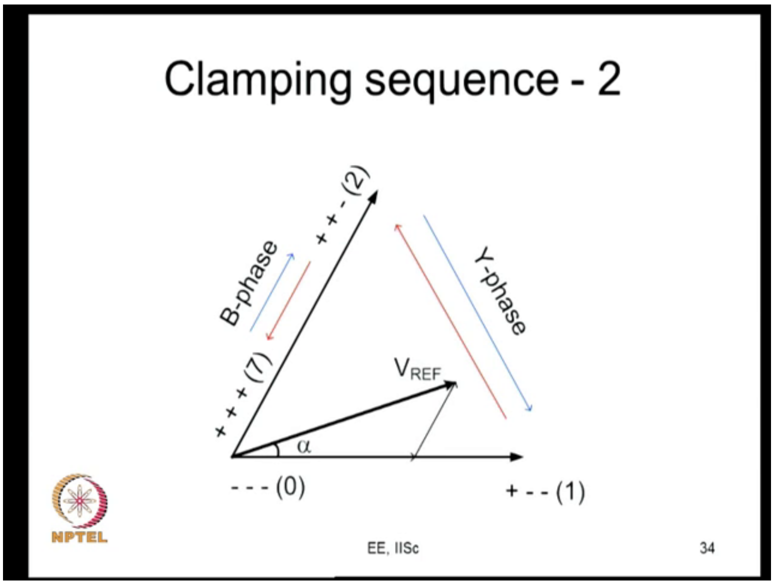

There can be another clamping sequence. For example, you can avoid this 0 stat 0 fully; let us say you start from your active vector 1, apply this for t 1 seconds. Switch your Y phase and move here. Apply this vector for t 2 seconds, then switch your B phase and move here, stay here for t z seconds. Your sub cycle is complete, your produces this reference vector. In the next sub cycle, you will have to produce another reference vector, which will be close to this; on different bicycle angle.

So, what you do? You start from this 0 vector time, stay here for t z seconds, switch your B phase come to t 2. Switch your Y phase and come to 1. And stay for t 1 seconds. So, we can call this is clamping sequence to it is clamping, because you see that minus minus minus is never used, and R phase is always positive here, positive here and also positive here. R phase is clamp to the positive bus. So, (Refer Time: 39:36) is the clamping sequence to distinguish between those 2, we call as clamping sequence 1, and this is clamping sequence 2.

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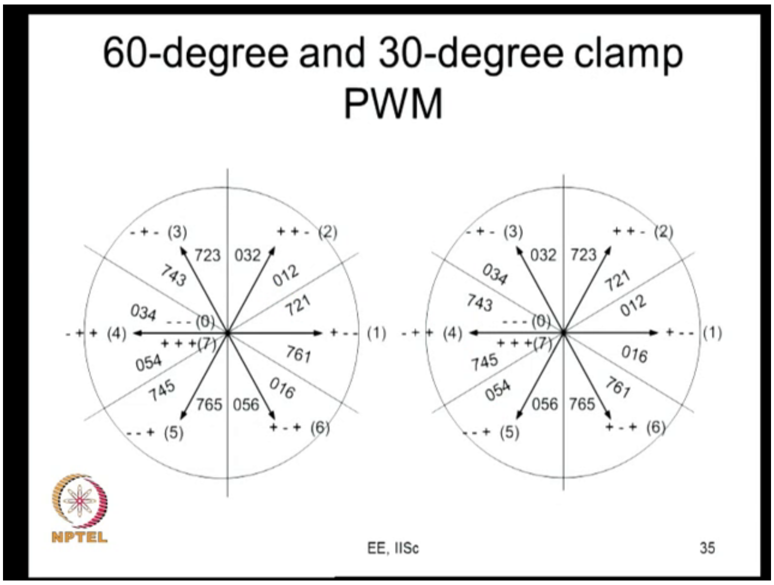

So, what you can actually do is there are these are 2 popular PWM methods. This is one kind of clamping. So, you use this within your sector 1, you use this 7 2 1, in the first half and 0 1 2 in the second half and use similar sequences in the rest of sector. And you will see that your R phase is clamped here to the positive bus, because 7 is plus plus, plus. And minus, minus, minus is never used here; R phase is clamp to the positive bus here. So, R phase will be clamp to the negative bus here.

So, every phase will be clamp to you know one of the dc raise in the middle 60-degree duration of it is line of it is fundamental cycle. Now if you look at here, this is a place where R phases clamp when 7 6 1 is applied. Again, this is a place when 7 1 2 1 is applied R phase is clamp to the positive bus. And R phase has a positive 0 causing here. This is 0 degree, this is 30 this is 60. So, between 30 to 60, R phases clamp to the positive bus. This is 90. This is 120, this is 150, this is 120 to 150. Once again R phase is clamp to the positive bus. So, R phases clamp to the positive bus during the middle 30-degree duration of this quarter cycle, again the middle 30-degree duration of that quarter cycle.

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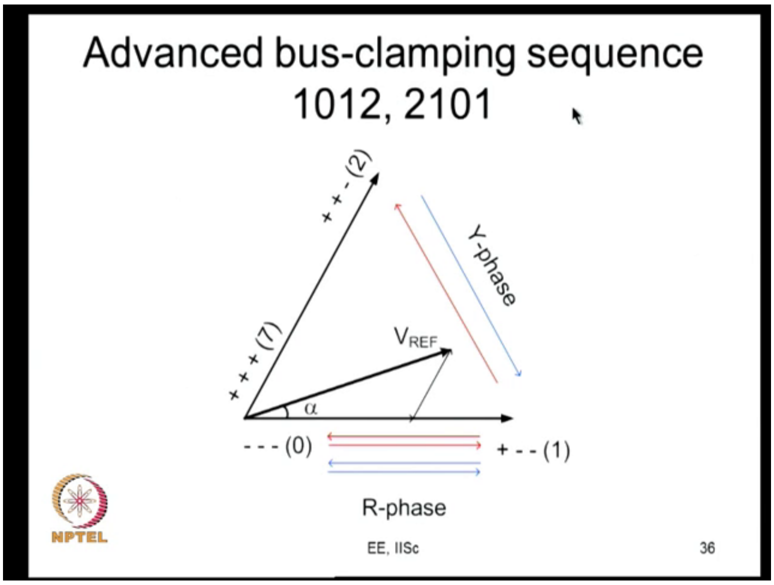

So, we call this as 60-degree clamp PWM method and 30-degree clamp PWM method. Now there are variations, this is where space vector based PWM is little different. You can apply one of the active vector twice. We saw one example earlier, where you can apply 0, and go to one do not stay for t 1 seconds stay only for t 1 by 2. Go here, stay for t 2 seconds, and come back here finally, spent t 1 second; that is 0 1 2 1, we saw this example, when we did this space vector base PWM module and we also when we did the analysis of line current ripple. Now there is another variation we are just looking at here. Let us say we are start from 1, we are here. So, we are not going to be here for the entire t 1 seconds.

But we are here for t 1 by 2 second, half of what is required. Then switch this phase which phase is that R phase. Go here, stay here for t z seconds, then come back come back to active vector 1, stay here for the remaining t 1 by 2 seconds, then switch Y phase go here and stay here for t 2 seconds. So, one sub cycle is complete. And you have applied the null vector for t z second, and this one for t 1 seconds and this 2 for t 2 seconds.

So, you are going to produce a desired reference vector no doubt. Except that you are applying the voltage vectors in different sequences now. What you are doing is also you are switching R phase twice, you are switching Y phase once, and you are not switching B phase at all. You may you may worried that what happens to the balance you know there are some phase getting switch more, what you will do is in a different sector we are talking of sector one, or may you know you know in a different sector or maybe in a different part sector one itself. We may double switch another phase, and make clamp R phase.

So, everything will get balance, if you employ the switching sequence in a symmetric fashion, all the problem will be sorted out. So, you can see that is 1 0 1 2. So, this is an example. So, you have gone here, the next sub cycle what do you do? You stay here for t 2 seconds, and switch your Y phase come here. Stay here for t 1 by 2 seconds, go here. Stay here for t z seconds, and come back and stay here for t 1 by 2 seconds your sub cycle is over. So, it is 1 0 1 2 2 1 0 1 1 0 1 2 2 you can go on like that, when your reference vector is moving through sector 1; the same way you can also look at 2 7 2 1.

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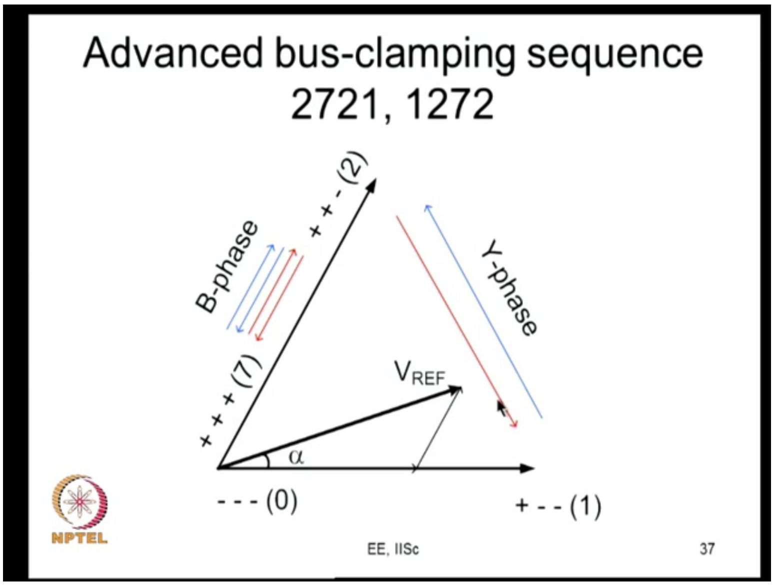

That is what is illustrated here. You stay here for t 2 by 2 seconds, go here stay for t z seconds, go back and spent t 2 base 2 seconds here, and go here and stay here for t 1 seconds.

So, you are going to get the same reference vector, but now the sequences 2 7 2 1. And you can also do 1 2 7 2, the next sub cycle. So, you can use these 2 sequences and alternate sub cycles. So, you have the special sequences with switches twice. You can see that in a half carrier cycle, a phase can switch only ones in triangle comparison based PWM, because it can only intersect once. Whereas, here you can see it is switching twice. So, this is a benefit that we are getting, we are able to divide an active vector time. What we are doing is; this active vector is applied twice which is not possible normally in methods like sine triangle PWM etcetera.

So, an active state will be only applied once. So, the only option is between the 2 0 states, either both will be applied or one will be applied. If both are applied again one maybe applied for 0.8 t z other one may be applied for 0.2 t z or whatever.

So, there the only a degree of freedom is you know division of null vector time between the 2 0 state. Here you have that freedom. So, you are actually using only t 7 sometime, or your using I mean only the 0 state 0 some time. Apart from that you are using this active state solution time, which is actually a freedom that is available with space vector PWM methods.

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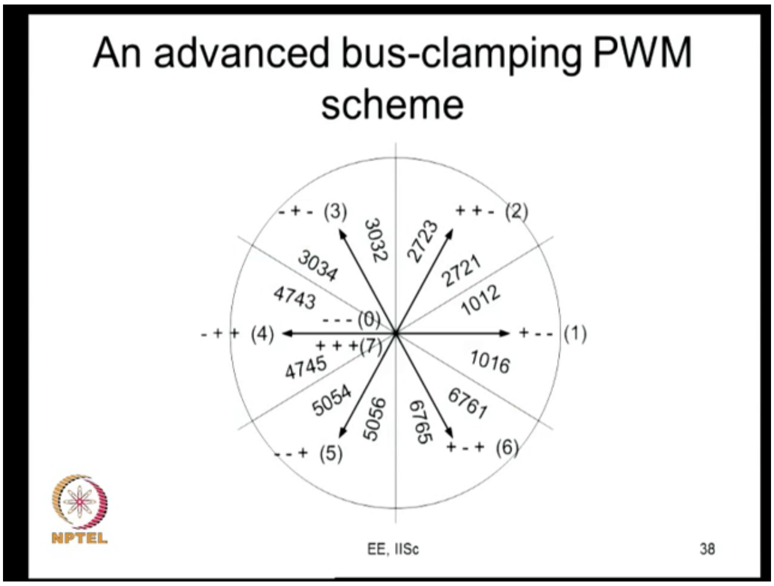

So, you can employ this sequence 1 0 1 2 2 1 0 1 in the first half, 2 7 2 1 1 2 7 etcetera in the second half and similar sequences in the other sectors. So, this is one example of an advanced bus clamping PWM scheme, you can think of various search advanced bus clamping PWM schemes. Quite a few of them have been reported in the literature recently. So, what happens? Now we are now going to analyze the error.

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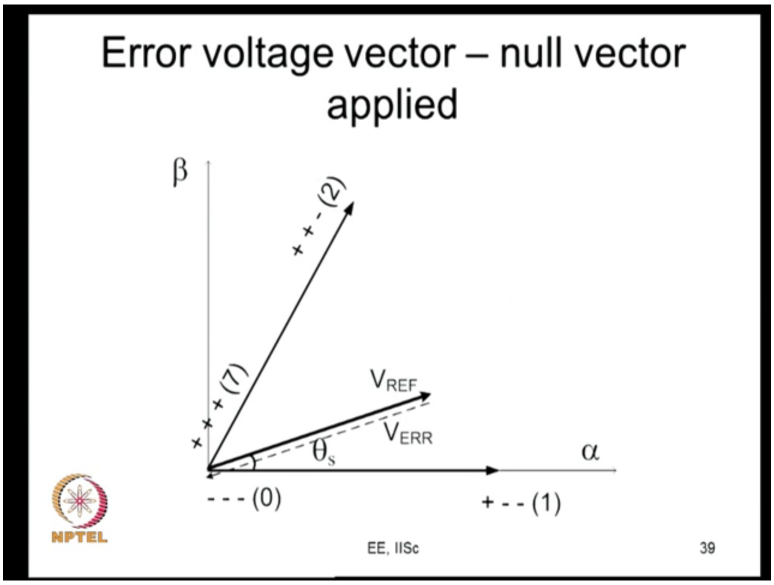

So, this is the error. When you applied reference vector, you what you want is a reference vector, but you have applied a null vector. So, the error is this V error vector.

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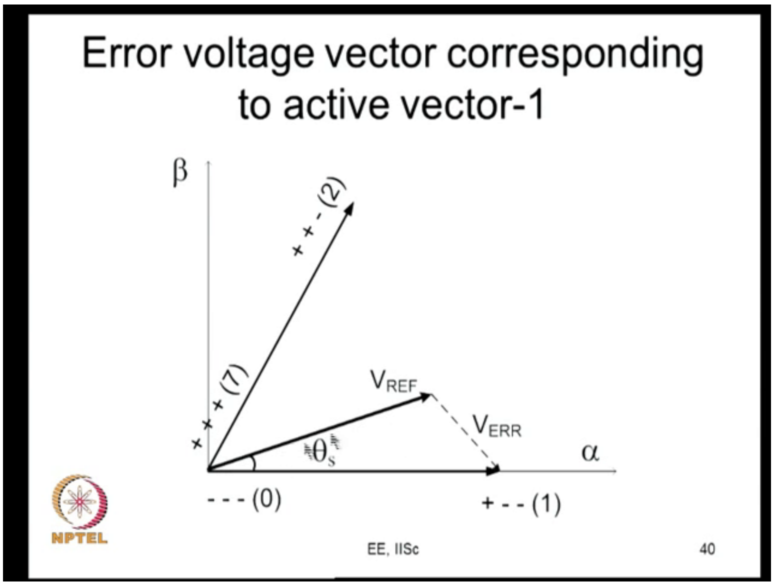

Again, what you want is this vector you have applied V 1 vector. So, this is your error vector.

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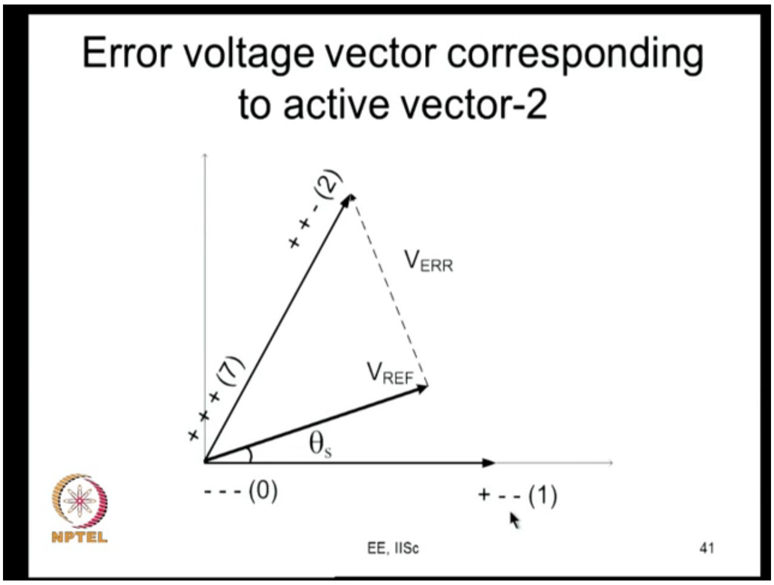

Again, sometime what you want is this reference vector, what you have applied is V 2 vector. So, this is your error vector. So, when you want this reference vector sometimes you have an error like this, you have an error like this, or sometime you have an error like this, and this error is a problem. What does this error represent? This error represents you know all your harmonic voltages in a per phase all the harmonic voltages add them up, you get a ripple voltage.

So, this three-phase ripple voltages, you transform them into the space vector domain that is this error voltage. What is this V ref vector? You have three-phase fundamental voltages, transform them into space vector domain and that is your V ref, is it ok?

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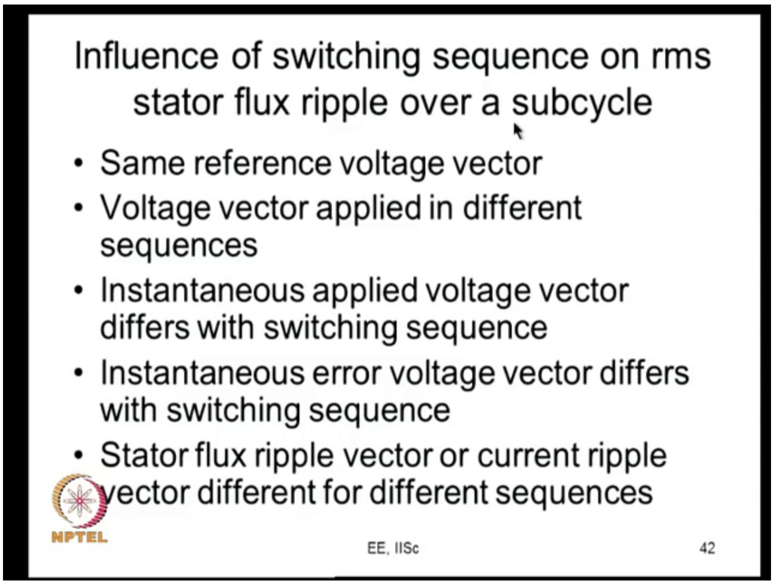

So now what happens? With switching sequence, you may generate the same reference voltage vector, but the voltage vector is applied in different sequence. Therefore, the error that is the applied vector minus reference vector is different. So, they apply instantaneous applied voltage vector differs with switching sequence. Therefore, the instantaneous error voltage vector differs with switching sequence.

And therefore, the stator flex ripple vector or current ripple vector differs now. So, what is the error voltage vector it is after all it is a representative of the various harmonics. So, the harmonic see the motor as it is leakage inductance. So, you can simply integrate this error voltage vector to get a measure of the current ripple, and that is what you called as the stator flex ripple vector; which is actually measure of current ripple.

So, the stator flux ripple vector or the current ripple vector is actually different for different sequences, because the instantaneous error voltage vector is different. That is different because the instantaneous applied voltage vector is different.

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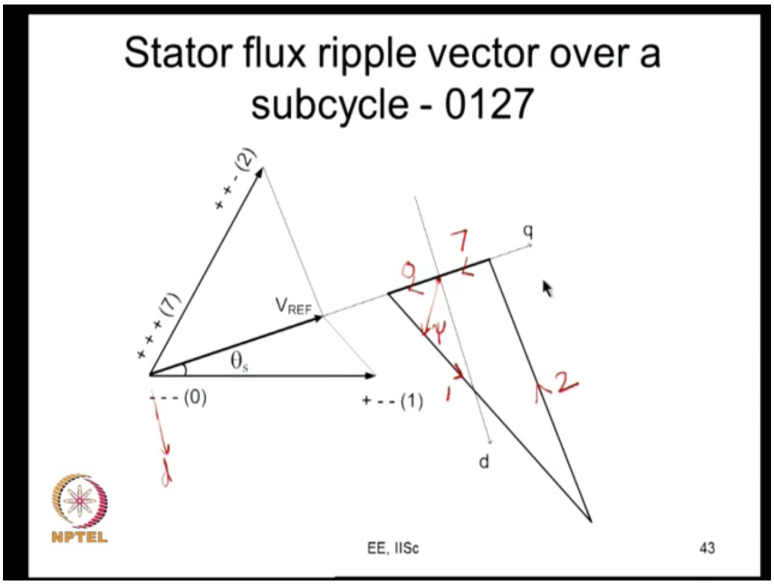

So, this is different when the sequence in which the vectors are applied is different this is how the switching sequence influence. So, this is a quick illustration of what happens here now. So, you have this reference vector, you have this reference vector; now what you have done is; this is a plane we will take this axis as q axis and we will consider this axis as the d axis. So, d axis is where you are fundamental flux vector is; and this is q axis your applied voltage vector. At the start of the sub cycle you are here, then you are integrating the error voltage vector.

So, when you are integrating the error voltage vector, the error voltage vector moves like this. After that the error voltage vector starts moving. Like this is let say what you call as the error or the stator flux vector. When active vector 1 is applied, we have this line. It moves parallel to this line. It moves parallel to this line, this is when active vector 1 is applied and when it is switched from active vector 2, the error voltage vector energy changes. And therefore, the integral of error voltage vector of status flux ripple vector also changes, and it moves along this line, it tip moves along this line. And finally, it comes here and switches here, and this is where 7. So, it starts from 0 magnitude, it is magnitude goes on increasing in this direction, then it is tip moves along this direction, it reaches here. Again, the tip moves back.

And finally, here it goes back to 0. That is because volt second balance is being maintained, where the error voltage vector average over sub cycle is actually I mean it 0.

It is starts from error the integral of the error voltage vector start from 0, end in 0. So, this is what happens when you have apply 0 1 2 7, right? So, the only difference that we are going to look at here is; see what causes this ripple there is something on the q axis there is something along the d axis. So, you can actually resolve this error along the q axis error along the d axis, and you can compute the RMS along the d axis RMS along the q axis. And then you get the overall R m s, this is what we did when we analyze that current triple.

Now we want the torque ripple, what is this torque ripple? Like you know pulsating torque; so you are actually looking at the harmonics you know interacting with the fundamental flux. Your fundamental flux is along the d axis. So, you looking at the pulsating fields which are perpendicular to that these are basically cause by this harmonic currents, and it is your q axis ripple; that is actually going to give you torque ripple. So, any ripple along the d axis is not going to because your steady flux along this direction. So, this is not going to interact, if you consider the ripple along d axis there is no cross product. So, you need some cross product whereas, so, you fundamental flux being or steady flux being along d axis, any ripple along q axis would actually cause you the pulsating torque.

So, when the differences is you have to consider only this, that is you start from 0; the q axis ripple goes to a maximum, and after this what happens the q axis ripple is coming down, here it is 0. Here it is going to negative, here it is going to some negative maximum, or it is a positive maximum, here it is negative maximum and then here cross 0, and goes to positive maximum. And then again slightly slowly reduces goes down here. And from here it reduces fast, and goes back to 0.

So, this way of you know the psi q if you take, that is a measure of your torque ripple, when you can compute the RMS value of a torque ripple.

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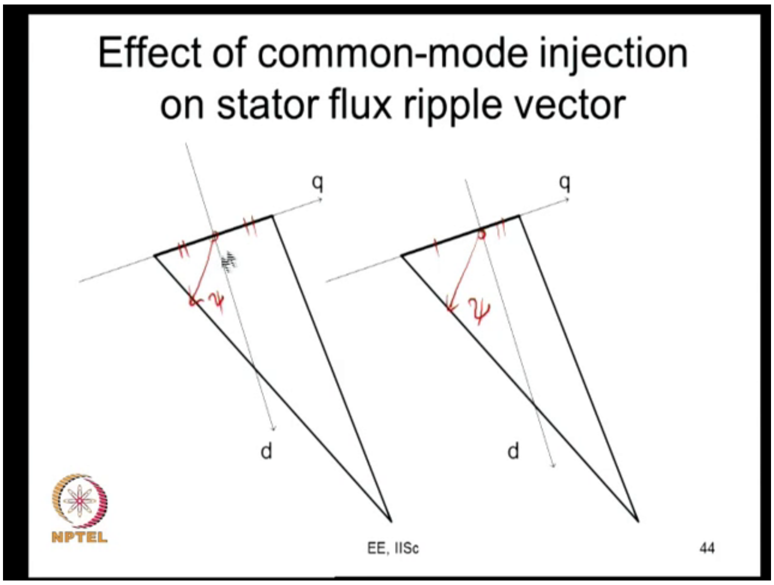

Now, if you change your sequence to something else. For example, from your conventional sequence you go to some other sequence, you see that the origin has been shifted here. That is, you may look at this is your psi vector whereas, here this is your psi vector. These 2 triangles are almost the same, except that you look at this point, it has been shifted. Why that it is been shifted? Here it is equal, here it is not. So, this is the effect of common mode addition. So, here you are added common mode such that the active vector times I mean the null vector times are divided equally. So, this is a measure of your null vector time, this is again a measure of null vector time. Here this is like t 0 and this is t 7, here t 0 is longer than t 7. So, you have this now.

So, what happen? You can see your q axis flux ripple, it is some negative maximum it is some positive maximum. Whereas, here you can see your negative maximum is much higher than what you have here. So, in this case you will have lower q axis ripple, in this case you have higher amount of q axis ripple. And therefore, this is going to leave due to more amount pulsating torque. Therefore, if you divide the null vector time equally, your pulsating torque is low, if you divide at unequally in general your pulsating torque is higher. So, dividing it equally is not actually optimal it is suboptimal it is very close to what is optimal. Many a times when you are using continuous PWM, it is best that you divide that equally.

If you divide that what happens the q axis current ripple reduces. Therefore, the torque ripple reduces of course, over all current ripple also reduces now. So, this is one comparison. So, conventional space vector PWM is better than sine triangle PWM. And third harmonic injection except one forth, third harmonic injection one forth is similar to conventional space vector. So, it is better than those PWM methods now.

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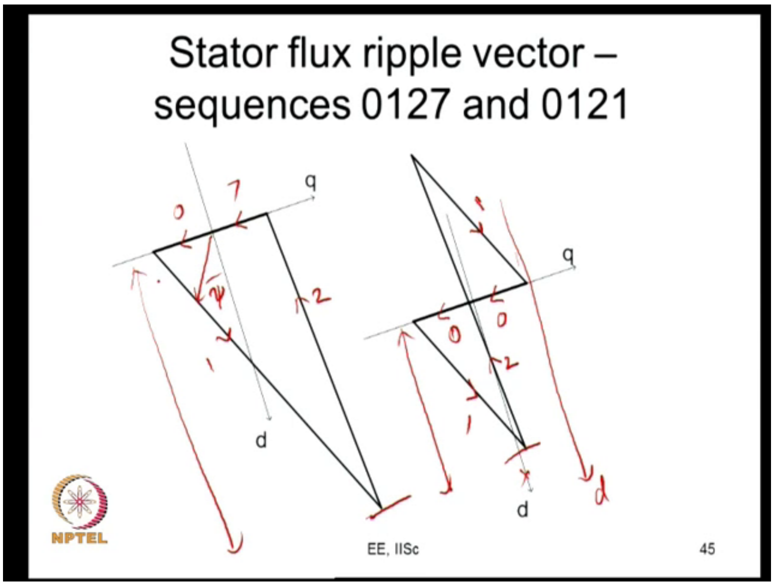

So, if you use 0 1 2 1 for example, what is happening is; you have this is when 0 is applied, this is when one is applied, this is when 2 is applied, this is when 7 is applied. So, this is your flux ripple vector or current ripple vector trajectory. Now if you are going to do it as 0 you know 1 2 1, I am sorry; the d axis must be here, ignore this. So, when it is 0, it goes like this, and when you apply 1. It goes like this when you apply 2 the tip goes like this when you apply 1, it goes like this. So, we had also done this when we are analyzing the current ripple, there are quite a few papers which discuss these things in good detail now. So, here what you can see is; you look at your peck d axis ripple. You see a peck d axis ripple. Here you see a peak d axis ripple. Your peak d axis ripple is much lower here. Whereas, your peak d axis ripple is much higher here. So, you are able to reduce d axis ripple, this means a considerable reduction in your current ripple though not necessarily torque ripple.

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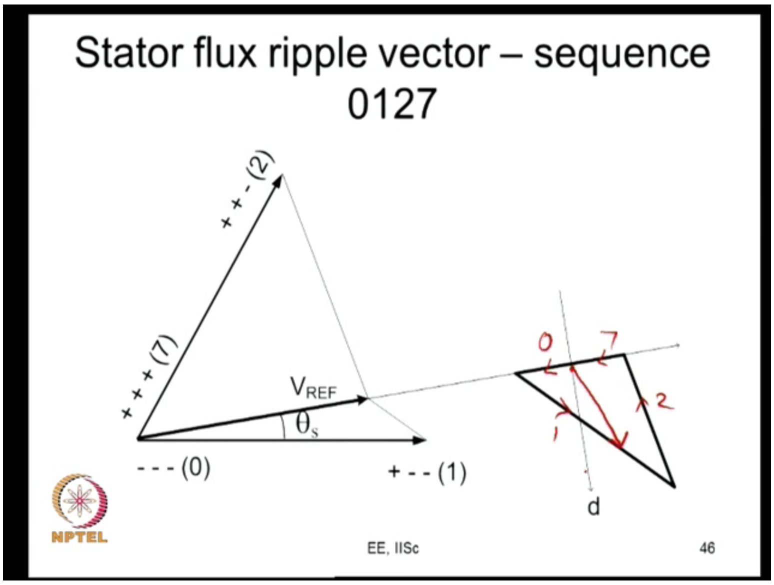

You have another example of let us say 0 1 2 7, now I am considered a different value of a reference vector, this is 0 1 2 and 7.

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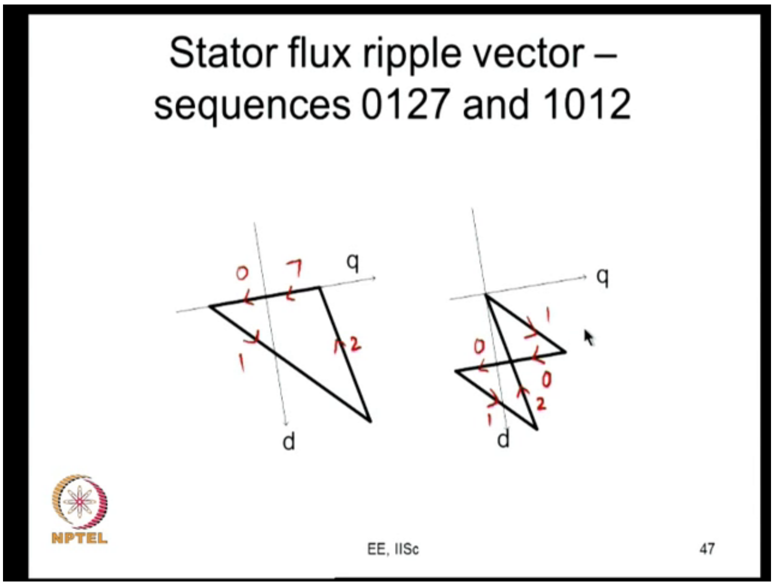

So, the flux vector actually at a moves along this path. So, if you compare this with something else, like 0 the same picture I reproduced here 0 1 2 7, I am comparing this with 1 0 1 2. This is let say 1, this is 0 0, it continues this is 1, this is 2. So, when I applied in a different sequence as I show here, you see that this is like a triangular 1 you see that it is w triangular.

Now sometimes it is possible, that this is my peak q axis. Here it is my peak q axis ripple. It is possible that my peak q axis ripple is lower than that R. The RMS q axis ripple here could be lower than this if you chose it correctly. For certain values of V ref this could be better. You have to find out what those values are.

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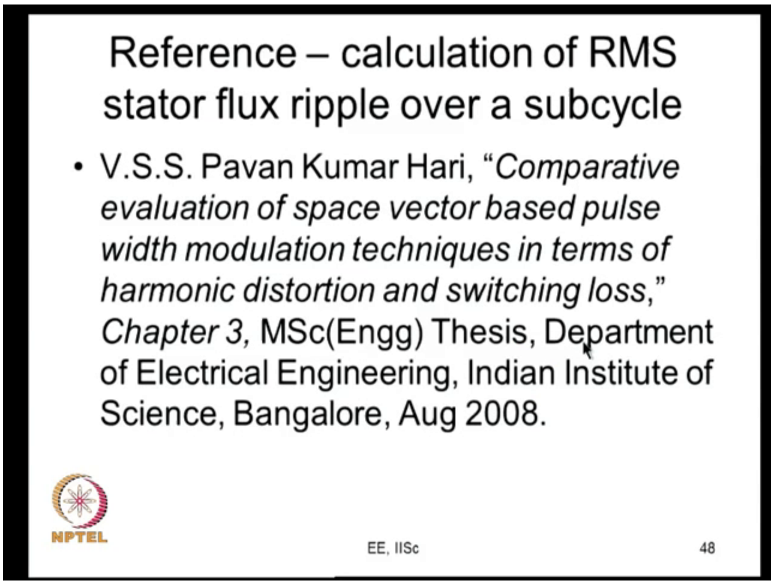

So, that is what has been done in the literature to come up with improved PWM methods now; so to actually calculate the RMS stator flux ripple along the d axis and q axis. So, this is useful reference. What you need to do is; you have to resolve this along q axis and then d axis, you will get piecewise linear functions you have to calculate square and calculate the area under them. So, this is actually been I have also mentioned this reference earlier to you when doing the line current ripple module.

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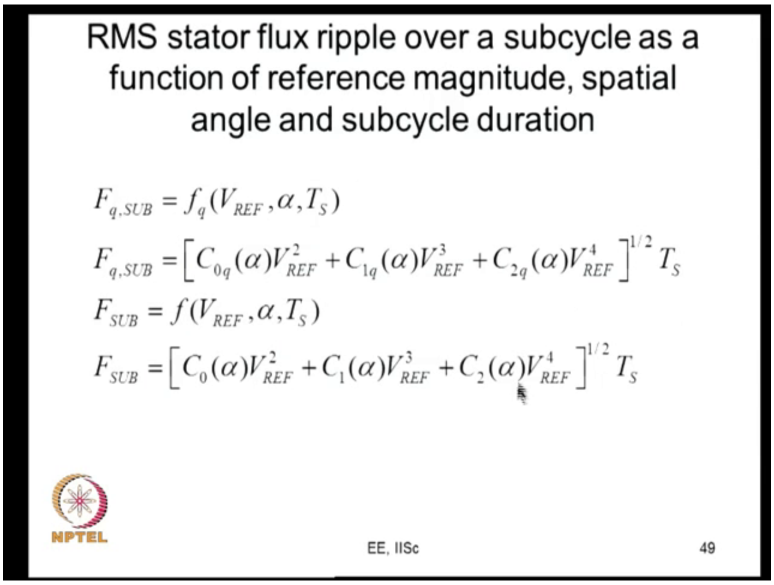

So, you will actually get this as one function. This is the q axis ripple, you will get it as some function V ref alpha Ts. And you will get the total stator flux ripple also some function of V ref alpha and Ts. And the nature of the function is actually shown.

So, what you can do is; this is available. This will be a different function. These coefficients will be different for different sequences. It will be something for conventional, it will be something for 0 1 2 1 something else for 1 0 1 2 etcetera. It is possible for you to compute all these and compare them.

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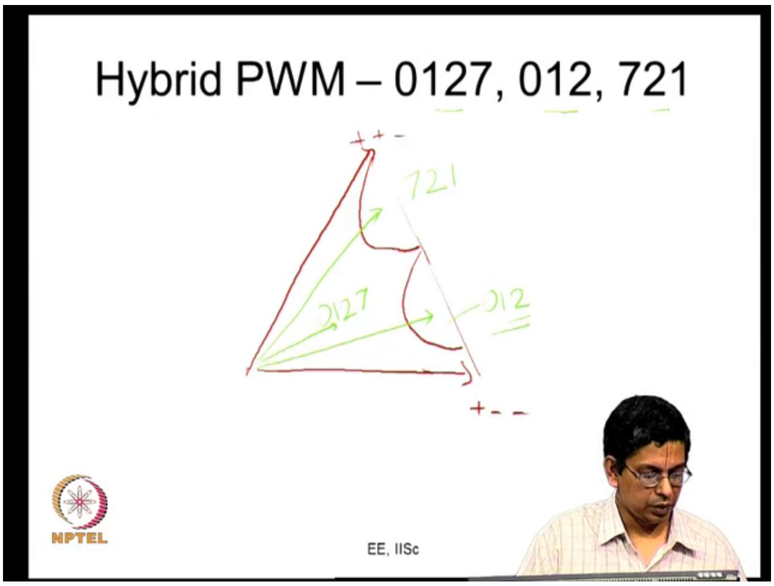

And once you compare them, it is easy for you to generate, you know many PWM methods. For example, you take your sector 1, this is your active vector 1, this is your active vector 2. Now what you will see is; you will have a range of vectors, that is you may have a vector whose tip is like this.

If there is a vector whose tip is like this, then you can apply 0 1 2. 0 1 2 will give you lower q axis ripple, then 0 1 2 1, 0 1 2 7. Similarly, you may have another one, you may have another region like this, if you have, if your reference vector tip falls within this region; then 7 2 1 could be better, means it could give you a lower flux q axis ripple then 0 1 2 7. And in this region 0 1 2 7 can be better. So, depending on where your reference vector false, you can either chose 0 1 2 7 or 0 1 2 or 7 2 1. The same thing you can do in all the other sectors. So, this can actually reduce the torque ripple for you.

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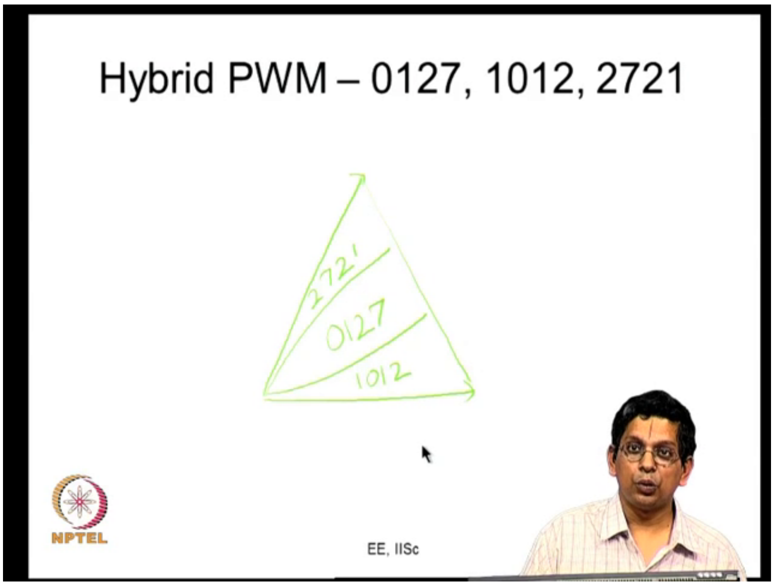

Similarly, let us say if your 0 1 2 7 etcetera, you know any sequences can combined. What you will find is if you do an analysis you go by the current ripple, you will find that there is a particular area where 1 0 1 2 gives lower current ripple than the others, again you will find some area where 2 7 2 1 gives lower current ripple than the others, and 0 1 2 7 use a lower current ripple than the others.

Now you can use a combination of these 2 sequences. Whenever the reference vector falls here, you use this sequence, whenever it falls here use the sequence, when falls here you do this now. This will give you a slightly lower current ripple and a significantly lower torque ripple. It reduces the q axis these 2 sequence, reduce the q axis ripple compare to 0 1 2 7 in this regions now.

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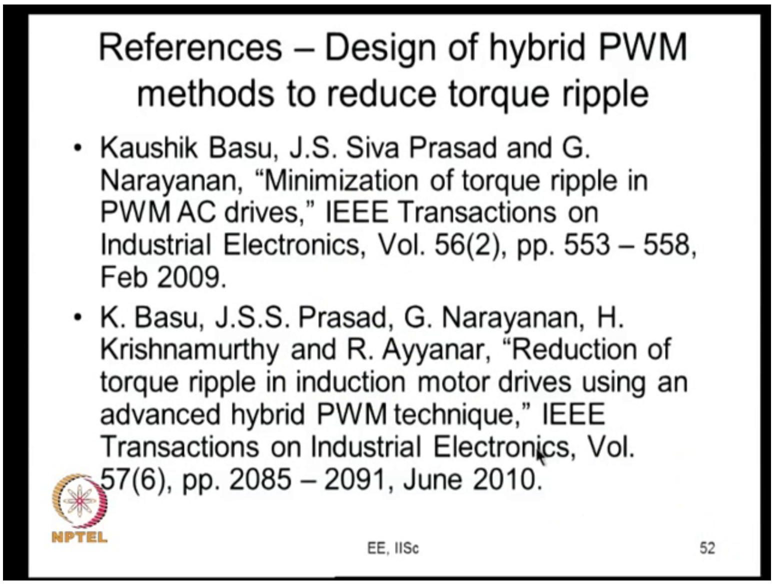

So, this is how you design hybrid PWM methods, these are all discussed in good detail in this 2 paper. The first one is the earlier method. Which is a combination of the conventional and the clamping sequences, and the second one is the other the second method that indicated. So, you can see these 2 methods and good detail in these 2 papers.

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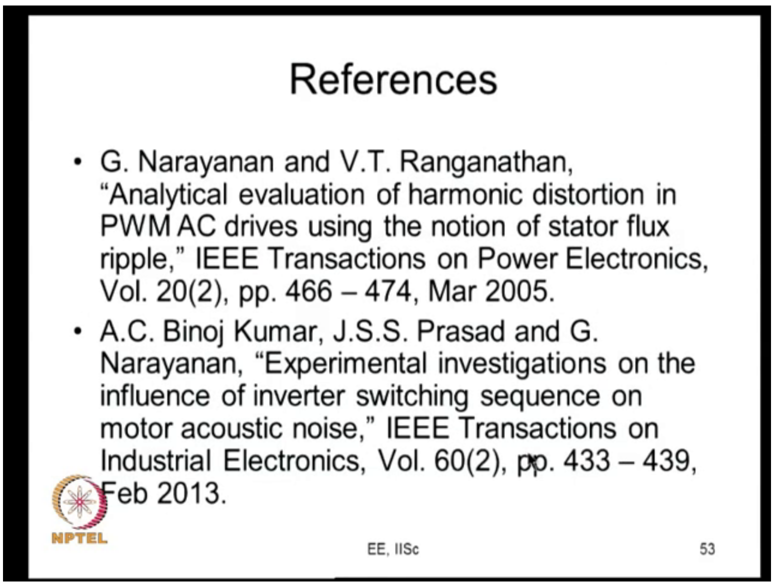

So, these are some other references. Where you know the d axis and the q axis, what are their significances? These kinds of things are explained here. There is also know earlier paper by professor fukuda, which talks about these things.

So, this is one paper where we talked d axis and the q axis ripple, and their significances. And this is another one interesting paper, where this PWM method where use 1 0 1 2 and 2 7 2 1; it reduces the motor acoustic noise, it is not an pulsating torque. But it shows that this kind of a sequence has the benefit of reducing the acoustic noise.

So, you can go through this reference of further knowledge in this. And I thank you very much for your attention, and I hope you were benefited by this lecture, and hope you would continue to have interest in the subsequent lectures.

Thank you very much.