Pulsewidth Modulation for Power Electronic Converters
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Lecture - 26
Analysis and design of PMW techniques from line current ripple perspective

Welcome back to this lecture series on Pulsewidth Modulation for Power Electronic Converters.

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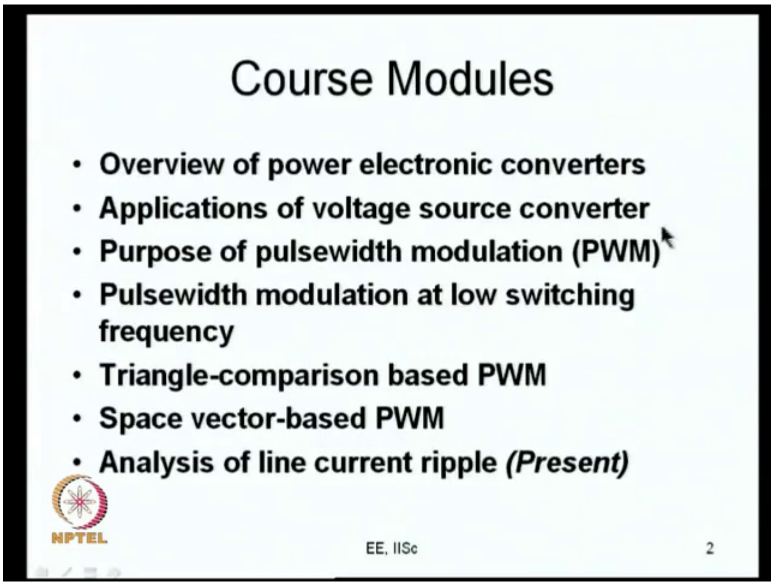

We have been looking at various modules part of this course, we will had an overview of power electronic converters and looked at the applications of voltage source converters, then we looked at such low switching frequency PWM and in the last couple of modules we were looking at the PWM generation, when the switching frequencies fairly higher than the fundamental and the modulation frequency and in the triangle comparison methods we looked at the sign triangle PWM. And third harmonic injection methods and various bus clamping PWM methods, in space vector base PWM also we saw the same similar methods and the advanced bus clamping PWM method, where you know 1 face switches where will another face switches at twice frequency. And now in this module this after this 6 modules and the 7th module we have been looking at the line current ripple, how really are modules focused on how do we generate PWM.

When you generate PWM where controlling the fundamental voltage, you know that fundamental voltage is not just fundamental there are also harmonic components there and they produce harmonic currents and we are being trying see you know. So, all these harmonic currents produced what is called as ripple current. So, we are trying to see we can evaluate the RMS current ripple, that is what we have been doing in this module and then as part of this module.

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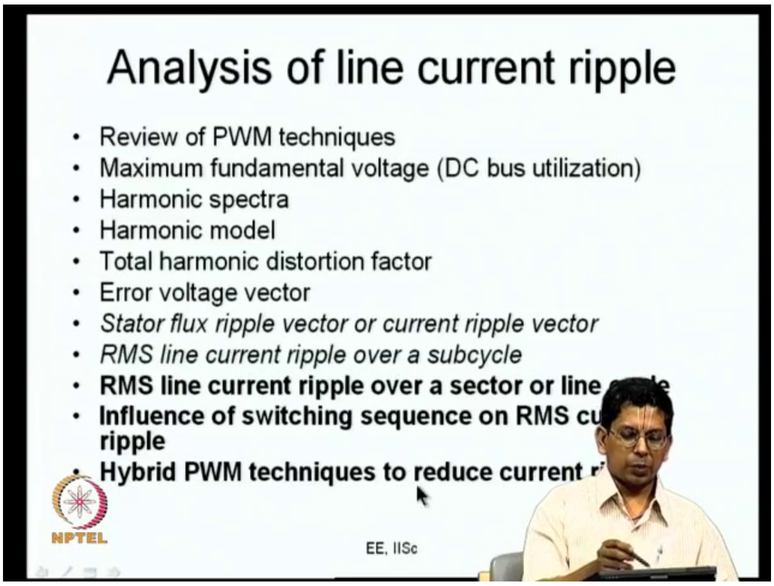

We looked at a few things like reviewing all these various PWM method such as conventional space vector, PWM sign triangle, bus clamping and advanced bus clamping PWM methods and we looked at the DC bus utilization of all these methods. Now given at DC bus voltage how much AC voltage can be obtained here and then we saw that in most of the methods like conventional space vector PWM or bus clamping PWM or advanced bus clamping PWM methods, you can produce about fifteen percent higher AC voltage than sign triangle PWM with the same DC bus voltage, now we also had look at the harmonic spectra and so on.

We generally found that you know all these p w methods resulted in side bands around integral multiples or switching frequencies and the harmonic model of an induction motor is basically it is leakage inductance and we determined the you know looked at and performance matrix and 1 of the performance matrix is basically is a total harmonic distortion factor and we looking at instead of doing all this in the frequency domain we have been looking at in the time domain, we are looking at the error voltage vector that is.

If you look at in the space vector 0.of view, what you need to do is to apply 3 step voltages that is revolving vector. It is a revolving vector of uniform magnitude is needed to be applied. But what you apply is 1 of those 7 vectors produced by an invertors, which is not the same as what you want, there is a difference between what you want and what you apply. And therefore, there is an error and this error voltage vector is integrated to get your stator flux ripple vector. This is what we saw in the last lecture and we are trying to estimate this RMS line current ripple, this integral of this error voltage vector are the stator flux ripple is just proportional to the current ripple and we are trying to evaluate this RMS line current ripple over a particular sub cycle.

So, in this time what we will do is we will quickly review the stator flux ripple and the RMS line current ripple and we look at you know go further and study the influence of various switching sequences on RMS current ripple and how do we come up with hybrid PWM techniques to reduce this current ripple, this hybrid PWM techniques involve multiple switching sequences now.

So, this lecture is specifically analysis and design of PWM techniques from line current ripple perspective. So, we are going to look at the line current ripple produced by various PWM methods, of course the first PWM method we will be considering is conventional space vector PWM which we did last class and we will quickly go through that and then we will go on to the other PWM methods namely the bus clamping and the advanced bus clamping PWM method we will consider.

So, we will do an analysis and we will try to find out how this method compare in terms of how RMS line current ripple can be evaluated in this methods and how they compare and we try and design some hybrid PWM methods, which will reduce the line current ripple which was hybrid PWM or as I mentioned now that implies method which use more than 1 switching sequences now, right.

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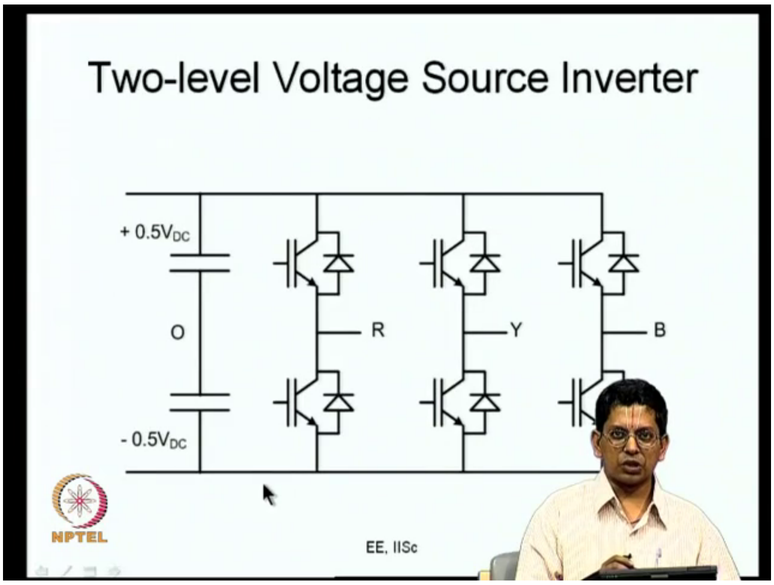

So, this is the voltage source inverter that we have been talking about 2 devices in each 3 legs and so 2 devices in each leg, these are the AC side terminals and these are the 2 DC side terminals.

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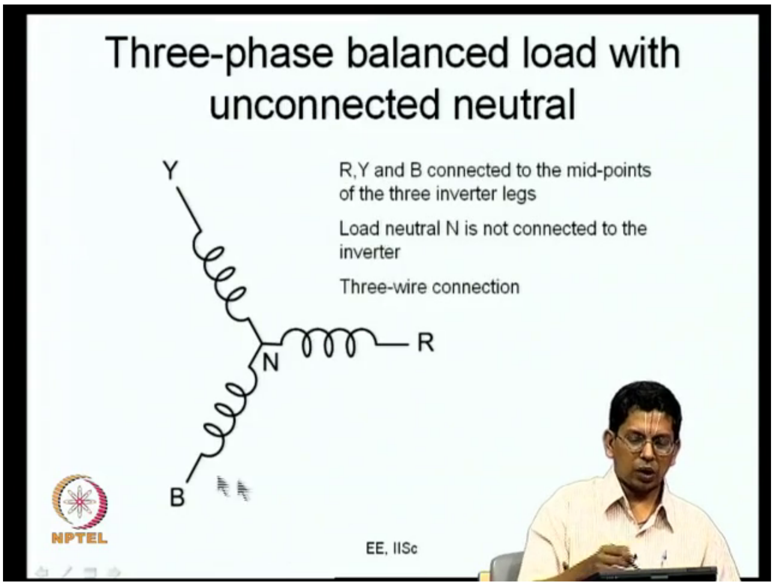

It is connected to a load like this there is 3 face star connected load for the neutral 0.n is not connected anywhere particularly. And so whenever the inverter is in the so called 0 state, all the top devices are on are all the bottom devices are on all these are shorted and therefore, VRN, VYN and VBN are equal 0 and in any of the active states 1 of the faces, say VRN could be plus 2 V DC by 3 while VYN and VBN could be minus V DC by 3 otherwise. So, 1 of the 3 faces could be minus 2 V DC by 3 and the other 2 could be plus V DC by 3.

So, these are the kind of 3 face voltages and inverter applies on this kind of load and when those 3 phase voltages are transformed into voltage vectors.

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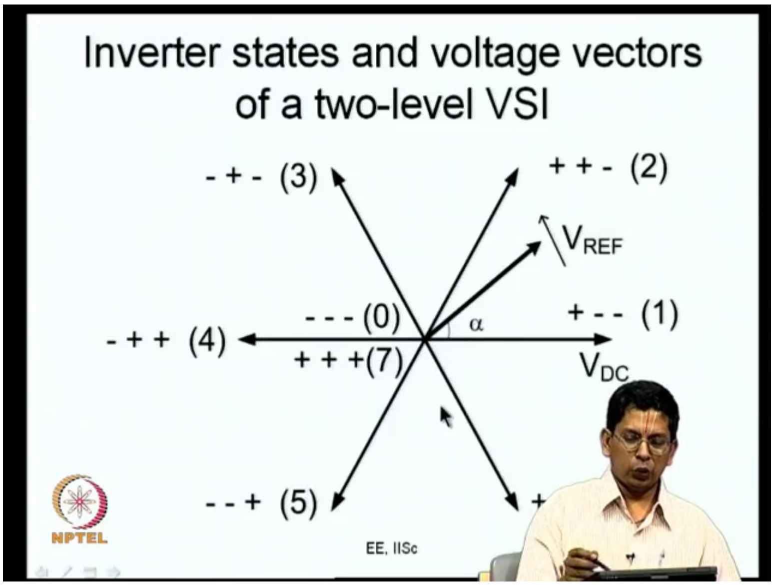

This is what you get now the 6 active vectors active states and they produce active vectors and the 2 0 stage produces null vector now and in the space vector PWM we have a revolving reference vector, we sample it once in every sub cycle duration Ts and try to produce an average voltage vector equal to that sample.

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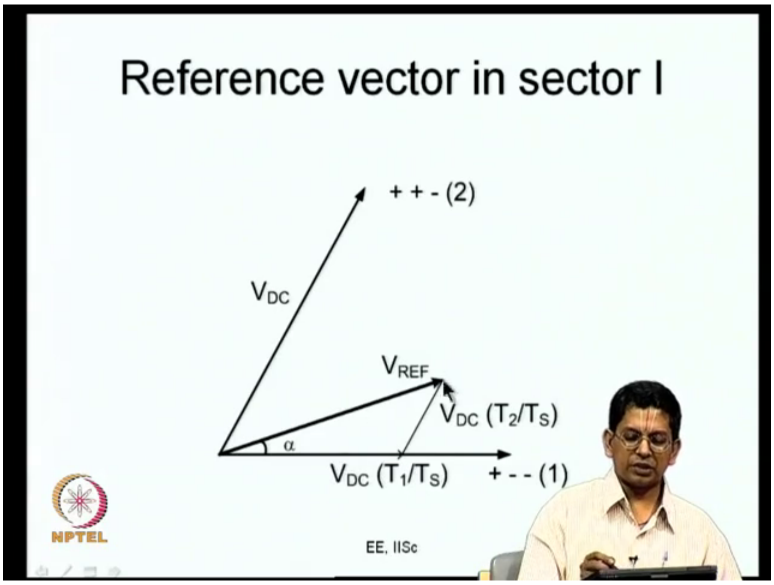

Now let us say this is the sample, this sample falls in the so called sector 1, which is within vector 1 and vector 2. So, you produce this vector by time averaging the null vector 1 and vector 2, you apply vector 1 for T 1 seconds and vector 2 for T 2 seconds and the null vector for the remaining T z seconds to produce this average voltage vector. You do this similarly in different sub cycles.

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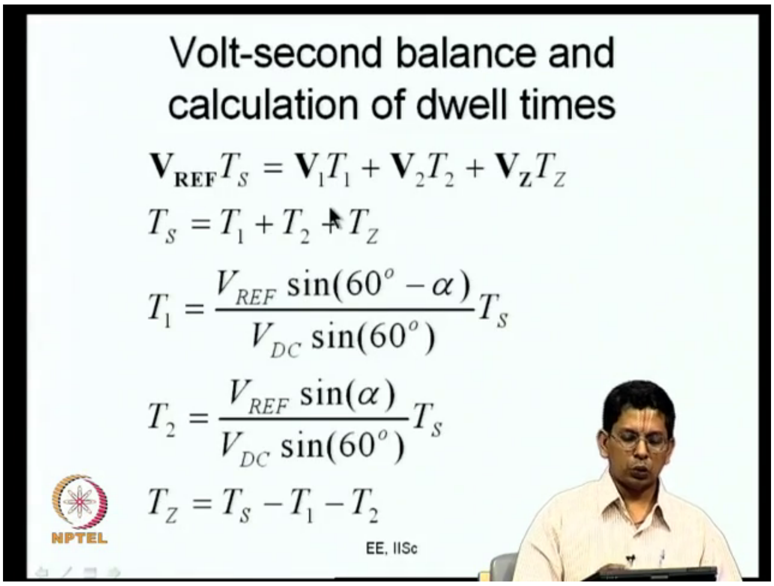

So, to do that average voltage vector this is how you calculate the dual times, we have discuss this in the last quite a few lectures now, right.

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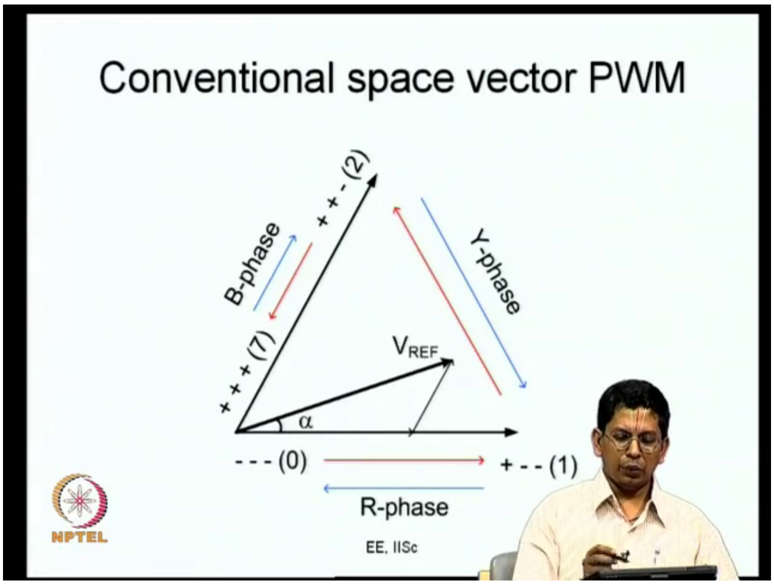

So, we are looking at particularly is conventional space vector PWM, where you start applying 1 0 state and then you switch and go to the first active state and then the second active state and from there you go to the other 0 state, this is you do in 1 sub cycle are half carrier cycle in the other sub cycle are half carrier cycle you come the reverse way.

So, the red lines indicates the sequence in 1 carrier cycle and the blue lines in the other carrier cycle and these 2 alternate, this is what happens at conventional space vector PWM and not just that the time for which this 0 and 7 are applied are equal. So, this applied for some T z B2 seconds this is for T 1, seconds this is for T 2 seconds and this is again T z by 2 seconds right.

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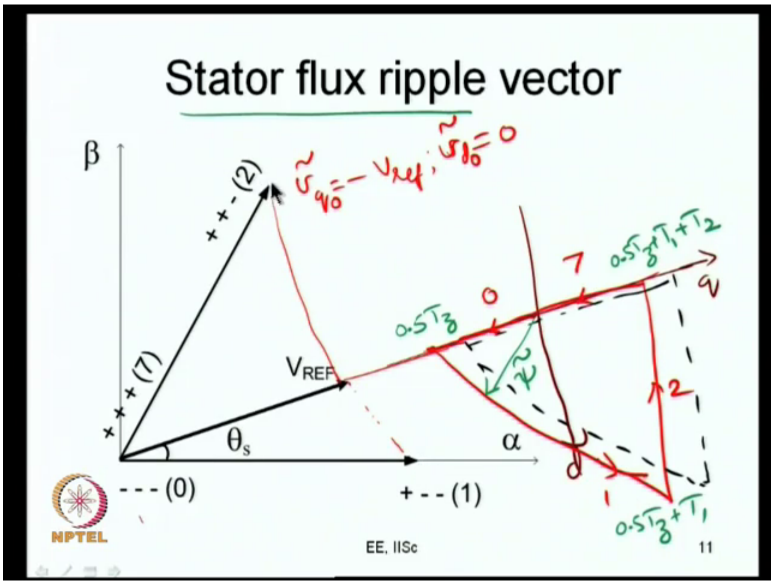

So, when you do this what happens there is always an error vector, what you want is this V reference vector, but what you apply is sometimes null vector sometimes vector 1 sometimes vector 2. When you are applying null vector for example, the error is minus V reference vector is the error now. So, you are applying 0 1 to 7 which we considered last time and when you are applying that your error voltage vector is minus V REF vector and you about integrating that it grows in this direction as indicated here, at this instant at 0.5 T z you switch from the 0 vector to the active vector 1.

And therefore, now your error voltage vector like this and the tip of this stator flux ripple vector now starts moving parallel to this error voltage vector, there is some drawing accuracy here these 2 are actually parallel lines. So, it goes parallely this goes on till 0.5 T z plus T 1, at this instant what we do you switch from active vector 1 to active vector 2. And therefore the error voltage vector now changes and this is the error voltage vector and therefore the tip of the stator flux ripple vector starts moving in this direction and reaches here at the instant 0.5 T z plus T 1 plus T2. And finally it is now time to apply the last 0 state plus.

So, you switch there and your reference vector is once again minus V REF and as a goes on at the end of the sub cycle, the tip of the flux ripple vector comes back to 0 now. So, this has certain RMS value this is the proportional to the current ripple and it has certain RMS value which is what we are trying to find out. So, good way to do that is actually to bracket up into the d access component and the Q access component and then go above doing that here, we just found that you know if you if you divide that T 0 and T 7 little differently not exactly 0.5 and 0.5 let us say this is 0.4 T z and this is 0.6 T z, what you would get is indicated by the other dashed line.

So, what happens is the same triangle the originals kind of shifted here and this actually affects the q axes ripple and the equal division is actually better in terms of the harmonic RMS current ripple point of view, here you see that these both are ripple they are equal in this case this is lower value that is higher. So, that actually means this peak value is higher and the overall RMS q axes ripple in this case is will be higher.

So, this is something we said last time, why sign triangle PWM compare to sign triangle PWM conventional space vector PWM is better, for actually conventional when you divide them by equal division the harmonic performance improves and it is nearly optimal. It is not exactly optimal that is sometime you can divide it in some ratio other than 0.5 to get a better performance, but that is the improvement you get is not very much. So, you can say that equal division of null vector time is kind of close to optimal though it is actually sub optimal.

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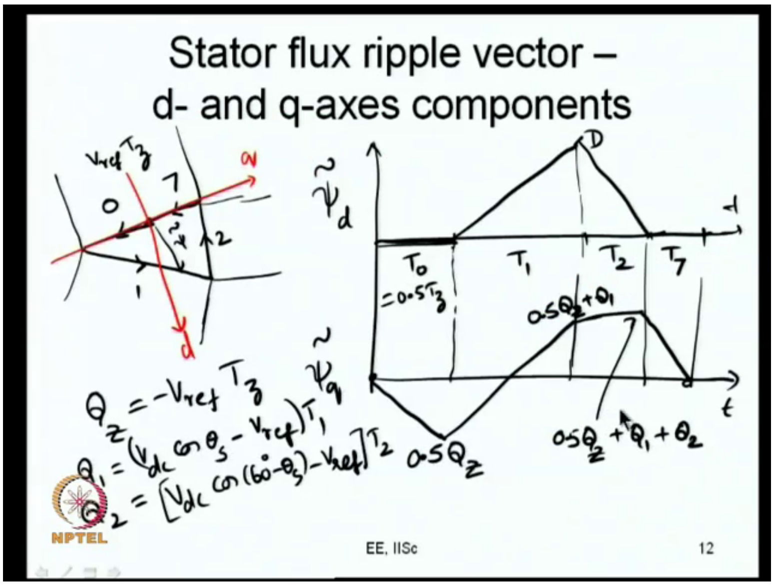

So, this is about dividing the vector between the 2, let us say you divided equally only and then you go about doing that, in this case what happens you have a q axes component you have the d axes components as we did last time now. So, this is the stator flux ripple vector that is reproduced here now and this is the q axes and this is the d axes. So, this is the origins from here it grows in this triangular trajectory now right. So, what happens to the d axes ripple when the 0 state 0 is applied the d axes ripple does not change. Similarly when 0 state 7 is applied it does not change and it is equal to 0 in between when active state 1 and 2 are applied, when 1 is applied the d axes ripple grows like this and when 2 is applied it comes back and the at the end of this duration it comes back to 0 right and what happens to the q axes ripple it is 0 and it goes negative.

So, initially it goes negative to what we call as 0.5 times Q z and where Q z is minus V REF into T z and from there when you apply this active state 1, it goes about increasing it crosses 0 somewhere and it goes to value 0.5 Q z plus Q 1. And then 1 active state 2 is applied it continuous to rise, but not at a very high rate you remember this is for a particular value of V reference vector, the scans of figures will differ for different values V reference vector. We have considered a particular value of V reference vector and for that we are getting this kind of thing is just for purpose of illustration now. So, it increases now at the end of this interval, we apply this 0 state and your Q z goes negative it goes back to 0.

So, you have the d axes ripple in the first and the forth sub intervals it is equal to 0, in the second sub interval it increases in third it falls, whereas the q axes intervals changes in all the 4 sub intervals like this and what do you want to do? You want to find out the RMS value that is you need to get this mean square value and the mean square value of that and add the 2 to get the overall mean square value.

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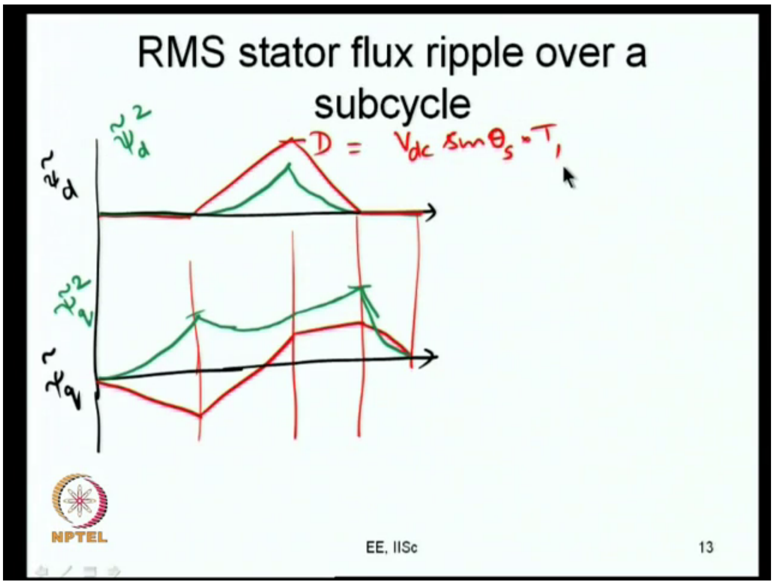

So, how will you get the mean square value for this, if this is the d axes ripple shown in red ink. So, you square it side tilde squared what you get is you get this kind of parabola. So, there are parabolic sections now, the same way the q axes ripple where is the linear function this is straight line and when you square that up it becomes parabolic this is 1 parabola this is section of another parabola, this is 1 section of another parabola. So, you free out the square and integrate that you basically have evaluate the areas into this parabolic sections.

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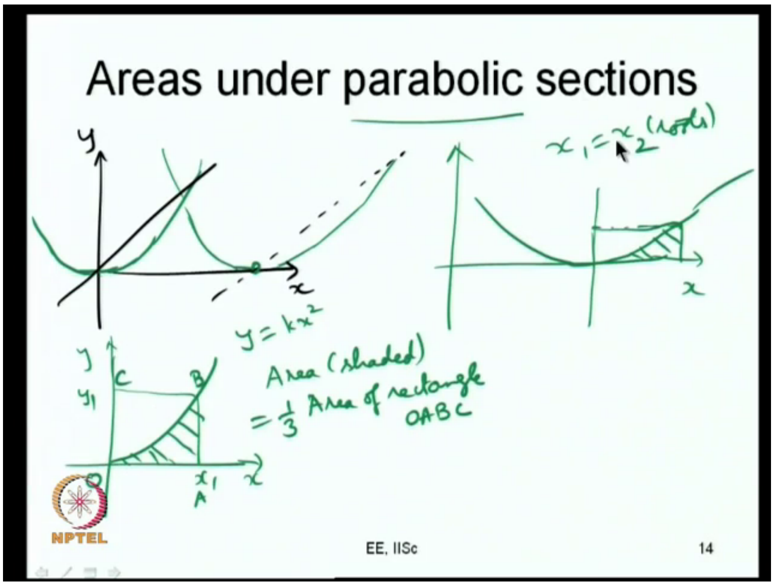

So, how do you calculate the areas into the parabolic sections? If we consider let us say straight line passing through the origin and it square that what you get you get a parabola like this, which is of the form y is equal to k x square, if you have this of the form y is equal to k x square and you consider this area this shaded area, what is that shaded area you have this O A B C you consider this rectangle and it is 1 third area of this rectangle, it is very easy to see that because y equals x square or k x square you integrate that it becomes k x cube by 3. So, this represents k x square and this is x.

So, you know the area is k x cube by 3 or k x 1 cube by 3, if you are considering x is equal to x 1 and 1 third of that area. So, this is this parabolas area is 1 third of that, there is something very elementary idea you do this now and not only when you have a straight line passing through this. Let us say you have a straight line passing through some other like this, when you square that what happens it is become parabola, what kind of parabola? it is a parabola with 2 real roots. So, it is a parabola that just sits on the horizontal axes, it has 2 real roots and they are equal it is on this now. So, you can consider a parabola like this, which has been obtained by squaring a line straight line which passes to this point.

So, now if you are looking at area shaded area, this area is once again equal to 1 third of area under this rectangle excuse me, it is the area under 1 third of this rectangle. So, this is something we should look at last class also and this is there is a quick proof for this.

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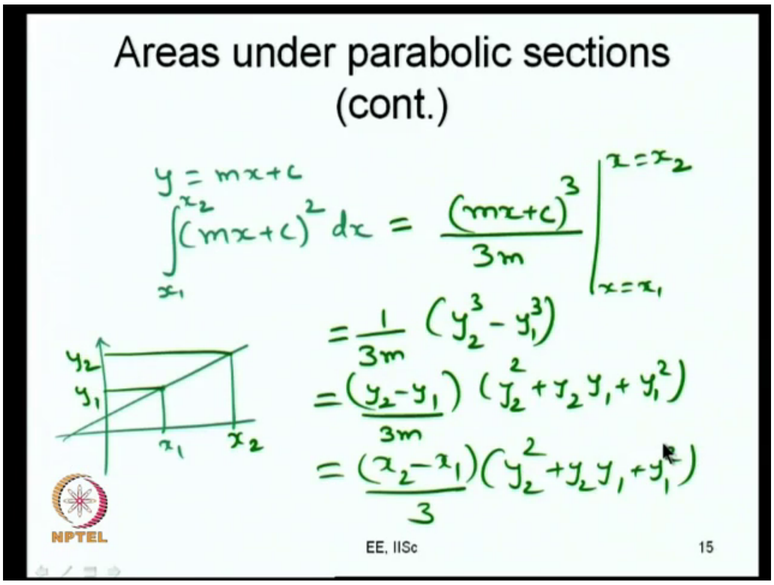

Now if you are considering a line x 1 to x 2 you want to square this linear section between x 1 and x 2 and find out the area under that. So, this is m x plus c, you are squaring that m x plus x whole square you are integrating x 1 to x 2 with respect to d x. So, when you do that you get m x plus C the whole cube divided by 3 m this is what and you are going to evaluate the intervals between x is equal to x 1 and x is equal to x2. So, it is same as saying that is 1 by 3 m times it is m x plus C is nothing, but y therefore it is y 2 cube minus y 1 cube. And therefore you have this relationship y 2 minus y 1 by 3 m multiplied by y 2 square plus y 2 y 1 plus y 1 square. So, you have 1 factor which is y 2 square plus y 2 y 1 plus y 1 square and the other factor is y 2 minus y 1 by m 3 m that becomes x 2 minus x 1 by 3.

So, this gives the area under parabola, if you have a straight line passing through the x 1 y 1 x 2 y 2 and I want to square that and find the area under that then this is what gives that area.

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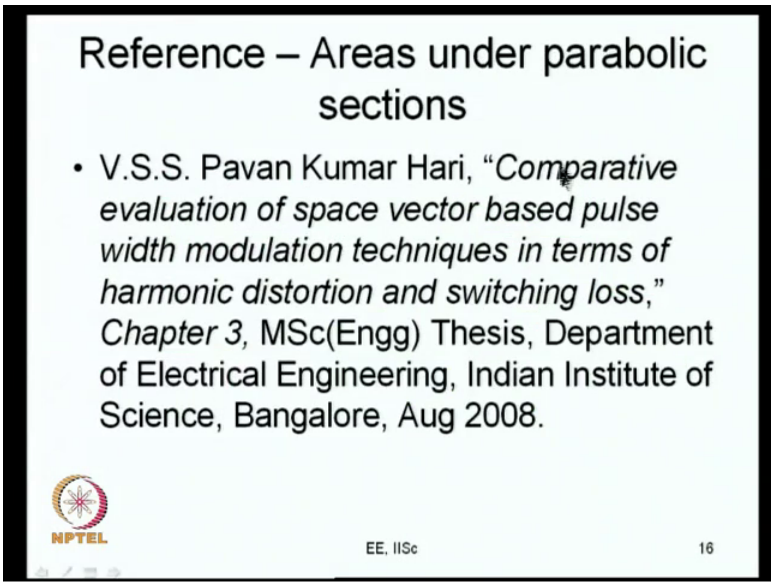

So, this you can see in that particular reference, which I mentioned it even in the last lecture MS C engineering thesis by mister Pavan kumar Hari on comparative evaluation of space vector based pulse with modulation techniques in terms of harmonic distortion switching loss, submitted in the Indian institute of science 2008. So, this is you know you can find more mean the same thing in more detail in case you need a more reference here.

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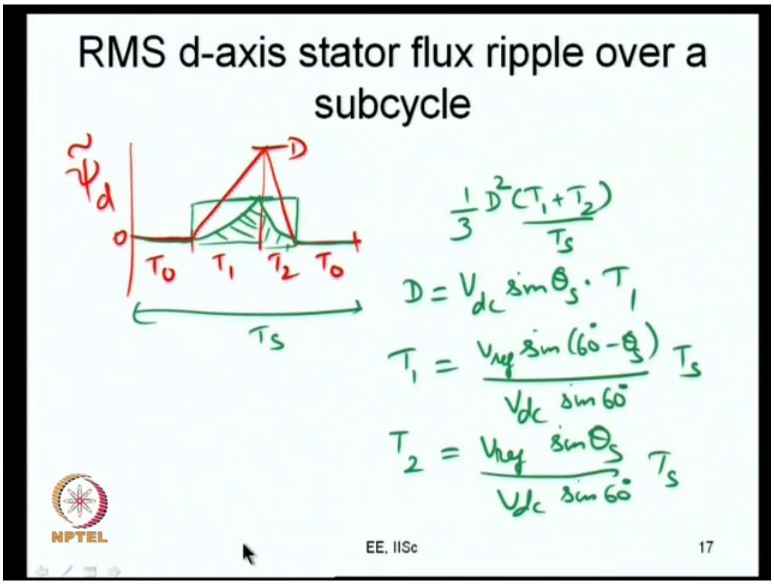

So, now let us say when you want to square this what happens now, let us go about further with the calculation now here it is simple based on whatever we said this area square and this area under this 1 by 3 times d square times T 1 plus T 2 and we want the mean square value and therefore we are dividing it by T s and D here as I said is V DC s into V 1 as we talked about before, let us say we go ahead with this.

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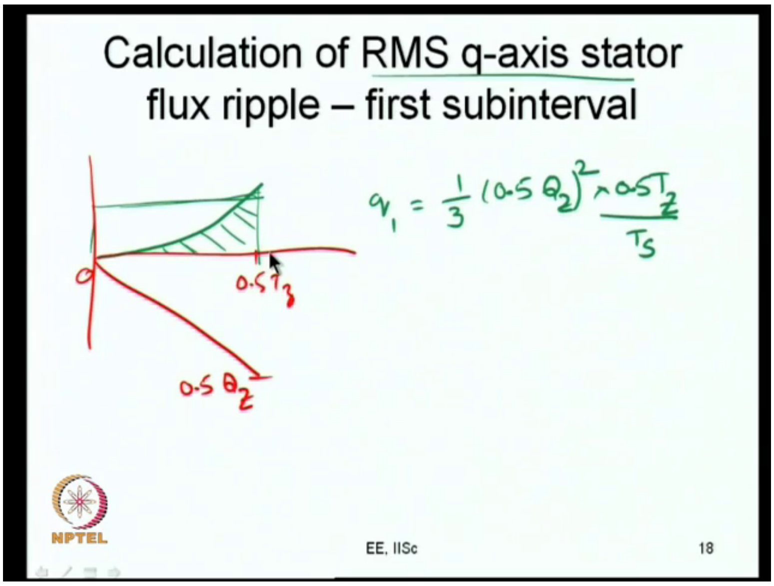

So, this is what this and if you look at the q axes ripple there are 4 subintervals let us look at the first subinterval, what happens the first subinterval we found that it was going negative it is square that it is something like this now. So, this is 0.5 Q z square this is 0.5 Q z the whole square and the shaded area is 1 by 3 times 0.5 Q z the whole square multiplied by 0.5 T z and you divided by T z, just for the purpose of evaluating the mean square value right. So, that is therefore, that is divided by T 1. So, you have got some Q 1 which is basically the area under the shaded curve divided by T s right.

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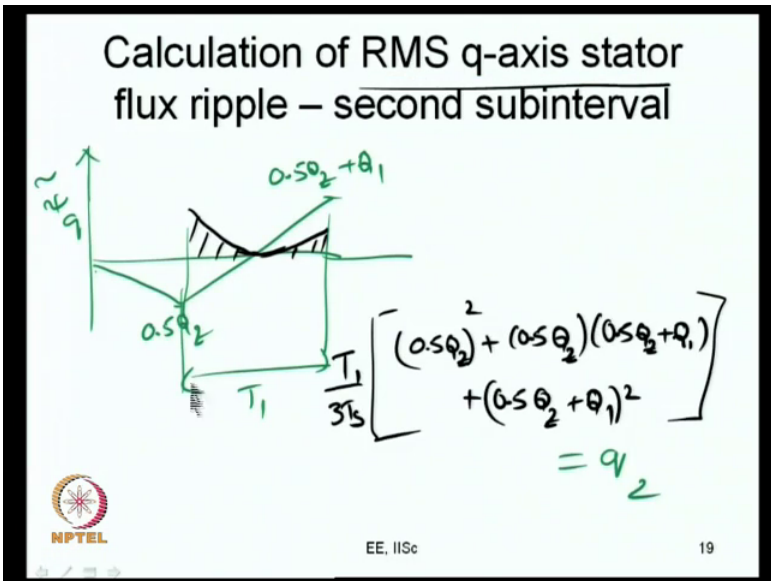

Then you have this second subinterval 0.5 Q z, I mean from where it rises from 0.5 Q z to 0.5 Q z plus Q 1 in this interval, you get this is 0.5 Q z the whole square plus 0.5 Q z multiplied by 0.5 Q z plus Q 1 and 0.5 Q z plus 1 the whole square. So, this whole thing divided by multiplied by T 1 by 3 is the shaded area and you are dividing it by T s that you have to evaluate the mean square value, right.

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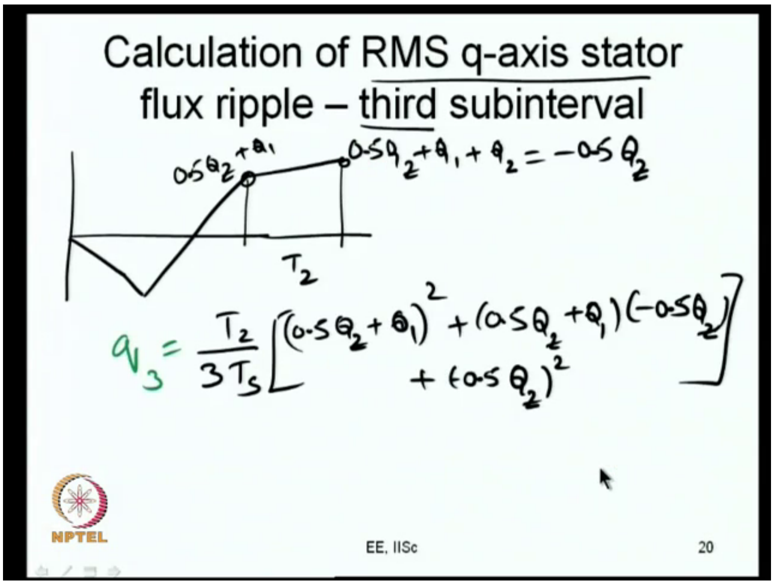

So this let us calling it as Q 2 and look at the third subinterval and during the third subinterval it varies linearly this shown here and during this time you can similarly evaluate Q 3 which is you square it and you find out the area under that and Q 3 is that area that divided by T s. So, you can write down this expression as last time.

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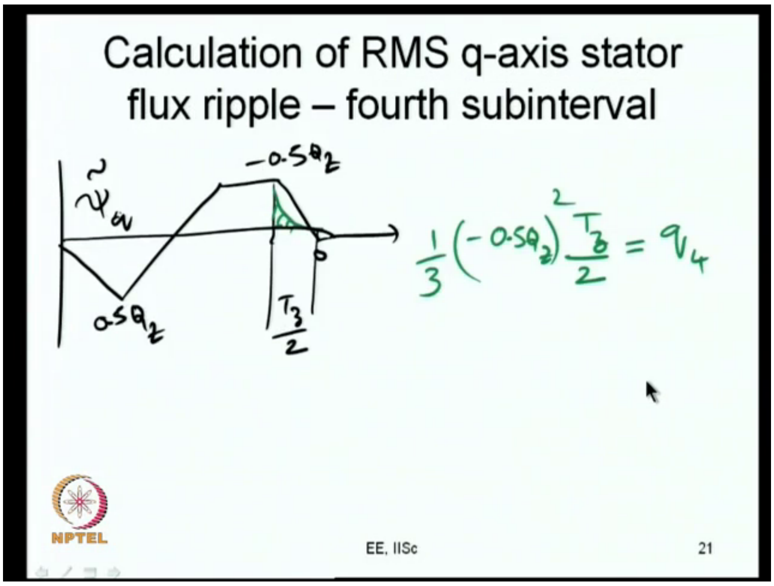

So, then this is the fourth only thing left to the fourth subinterval and this part if you square and you are going to get a parabolic section you can evaluate the area under that and that divided by T s so there should be a T s here. So, that is going to be Q 4 now, so then what do you get is, if you want to calculate the RMS stator flux ripple let me say.

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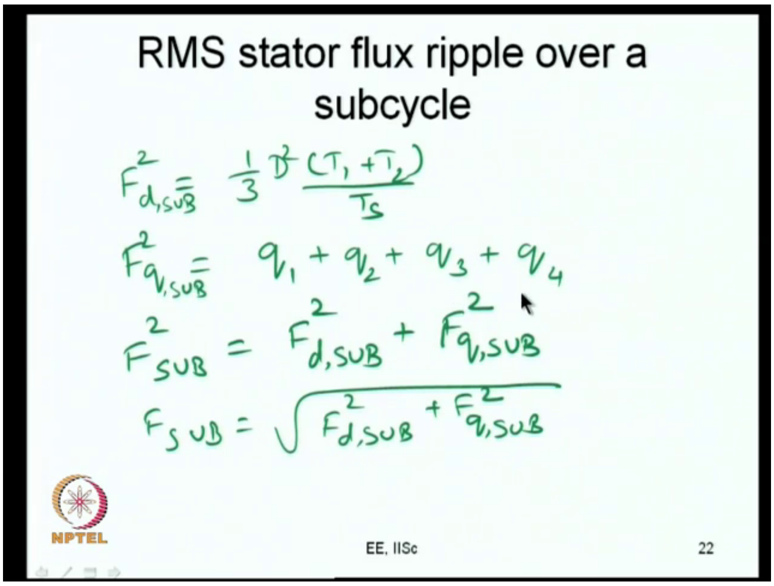

I have my F d square this is the d axes this is what 1 by 3 times d square T 1 plus T 2 divided by T s as I did before and this F this is the mean square value along the d axes and what is F Q square that is, whatever we calculate as q 1 plus q 2 plus q 3 q 4, it is a long expression and you know we found the main 4 different steps q 1 q 2 q 3 q 4 now.

So, let me call this as let me add SUB to this base, what do you mean by SUB I mean a sub cycle. So, this is the RMS value I mean the mean square value d axes ripple on the mean square value q axes ripple, now the mean square ripple over to the sub cycle itself can be given by the sum of the mean square value along the d axes and the mean square value along the q axes this is what you have. So, this completes the procedure evaluating the RMS stator flux ripple over a sub cycle.

So, you consider the error voltage vector and then you get the d axes and the q axes components in square them up and get the area under them and evaluate the mean square value along the d axes mean square value along the q axes sum them up to get the mean square ripple. So, the whole thing under square root would give you this F sub is the RMS value F sub square is the mean square value. So, I have written the mean square value right. So, if you want to say F sub what you need to do here is you just have to say F sub is the whole thing under square root. So, you have this F d sub square plus F q sub square under root is that now. So, this is the procedure for calculating the RMS stator flux ripple.

So, now let little bit more quantitative; so let us look at what is what now all these thing now let us say 1 by 3 times d square T 1 plus T 2 this involves d T 1 and T 2 and then you have q 1 q 2 q 3 q 4 all these things, involve certain things like you know q 1 q 2 q z etc and T 1 T 2 T z etc now. So, let us take a look at what are those values.

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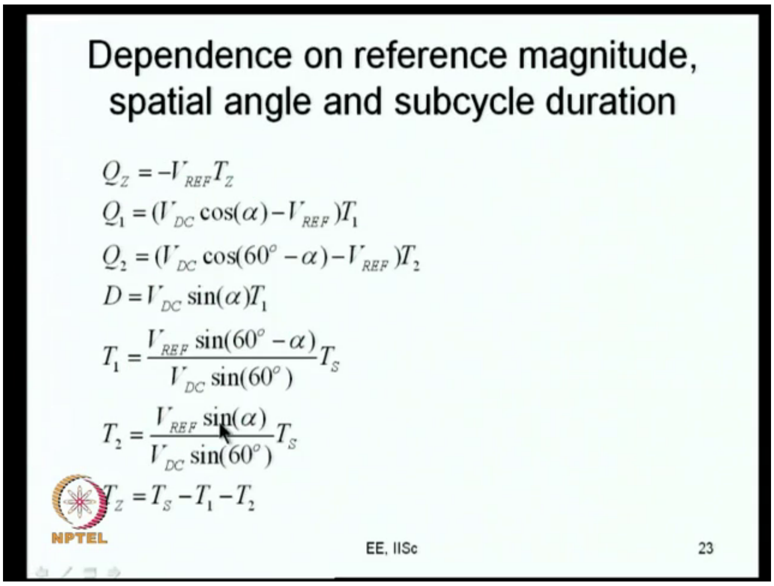

So, let us say you have this T 1 T 2 and T z are the dual times or this is the dual time of active state 1 active state 2 and the null state, if you take active state 1 what is that you can see that it is a function of V reference, that is the magnitude of the reference vector and alpha see I am just use the theta s little before and now I am using alpha. So, please do not mind the in consistency I mean here I basically mean this is the angle of the reference vector now or which I called as theta s in the previous lecture. So, V REF sin 60 minus alpha by V DC sin 60 T s. So, you can see that dual time the time for which active vector 1 is applied is a function of V REF alpha T s.

And similarly the time for which the second vector is applied is also function of V REF alpha and T s and T z is just T s minus T 1 minus T 2 and that is also function of V REF alpha and T s and how put these quantities Q z. what is this Q z minus V REF multiplied by T z, what is minus V REF you have the null vector and when the null vector is applied you have certain error voltage vector this is the q axes component of that error voltage vector and q axes component of that error voltage vector is minus V REF minus V REF is multiplied by T z is what we call as Q z, this is a volt second quantity error volt second quantity right. Q 1 is another volt second quantity corresponding to the active state 1 along the q axes, right.

So, what is that when active state 1 is applied V DC active state 1 active vector 1 has a magnitude V DC and it is q axes component is V DC cos alpha, the reference vector is at an angle alpha the q axes at an angle alpha. And therefore the component of the applied vector along the q axes V DC cos alpha and this is what you want is V ref. So, what is applied is V DC cos alpha what you want is V REF and the difference between the 2 the error between the 2 is V DC cos alpha minus V ref. So, this is error voltage, this is the error q axes voltage; this is the error voltage along the q axes when active vector 1 is applied and this multiplied by T 1 is Q1, Q1 is error volt second quantity corresponding to active state 1 along the Q axes.

Again Q 2 is another error volt second quantity which corresponds to the active state 2, when active state 2 is applied the vector has a magnitude V DC, but the q axes at an angle 60 minus alpha with respect to that. So, V DC cos 60 minus alpha is the applied q axes component, the component of the applied vector are along the q axes is V DC cos 60 minus alpha, this is what is applied and what is required is V REF and the error between the 2 is what is given here V DC cos 60 minus alpha minus V ref. So, this is the error voltage along the q axes when active state 2 is applied and that is applied for the duration equal to T 2 and this is the volt second quantity corresponding to active state 2 right so and d similarly the error volt second quantity along the D axes.

So, let us say when 1 is applied the error volt second is V DC sign alpha. So, V DC sign alpha multiplied by T 1 this is also equal to V DC sign 60 minus alpha multiplied by T 2 right. So, you can see that Q z Q 1 Q 2 d are all functions of V REF alpha and T s. So, these are also so they are they depend on V REF alpha and the dual times, the dual times are again functions of V REF alpha and T s. Therefore, you can say q z q 1 q 2 and d are also functions of V REF and alpha.

And therefore, all these that you have here F d sub squared or F Q sub squared all of them are functions of V reference alpha and T s and therefore the whole thing that you have here this is the RMS stator flux ripple over a sub cycle is actually a function of V REF alpha and T s.

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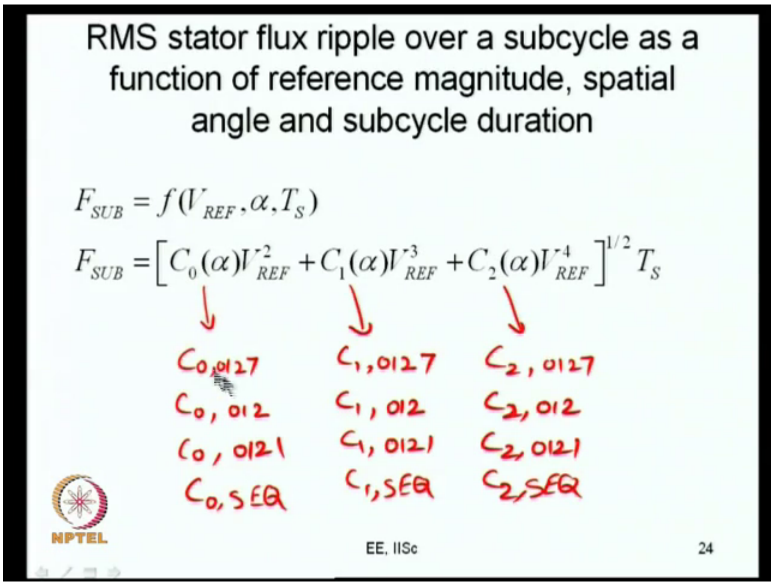

So, what is V REF it is the magnitude of the applied voltage vector, what is F sub it is the RMS stator flux ripple or it may which is equivalent to the RMS current ripple over a sub cycle, that is over a half carrier cycle and this is function of the reference magnitude you have the reference vector, V REF is the magnitude of the reference vector, what is angle alpha is the angle of the reference vector measured from the starting of the sector boundary in this case it is measured from vector V 1 and what is T s T s is the sub cycle duration refer you can say that the RMS current ripple or the RMS stator flux ripple is actually is a function of V REF alpha and T s now.

What exactly is that this is in generic something more specific given here this is the form of that function, F sub you will find is proportional to T s you see is proportional to T s then that is what you say the RMS stator flux ripple are current ripple is proportional to T s make sense right, you reduce the switching frequency; let us say half the switching frequency, what happens your sub cycle duration doubles. And therefore the RMS current ripple doubles or you reduce your switching frequency to half.

Therefore now what happens you are you know you double the switching frequency, if you double the switching frequency the sub cycle duration becomes half and therefore the RMS current ripple is half. Therefore you can see that this sub cycle this the RMS current ripple over a sub cycle proportional to the sub cycle duration if you increase that this increases, if you decrease that this decreases and your switching frequency is nothing but the reciprocal of 2 T s in the case of conventional space vector PWM.

So, you find this here so it is its proportional to T s. So, that is dependence on T s, how is this dependence on V REF and alpha it is actually a polynomial in V REF under square root, it is something like Co V REF square plus C 1 V REF cube plus C 2 V REF power 4 it is like polynomial under a square root and this C o and C 1 and C 2 are all functions of alpha. So, and these are functions of alpha what I should say is they are different for different sequences.

Now that is; what is a different sign I am just going to tell you now. So, in some cases C not could turn out to be a constant whereas, for some switching sequence C not is a function of alpha. So, you can actually calculate that you consider sequences 1 by 1 which will do a little later, that is you know we will consider the different sequences there get an idea of this could be done. So, all these are actually functions of sequences. So, now let me say here this is C0 if I am 21considering conventional it will be something like C0 0127 or it will be C0 012 or C0 01 these are various sequences, similarly C 1 you will have some coefficient C 1 for 0127 this coefficient will be a different function of alpha, if you consider the sequence 012 again it will be different if you consider another sequence 0121.

Similarly C2 of alpha it is also a function of trigonometric function of alpha all these are trigonometric functions of alpha excuse me.

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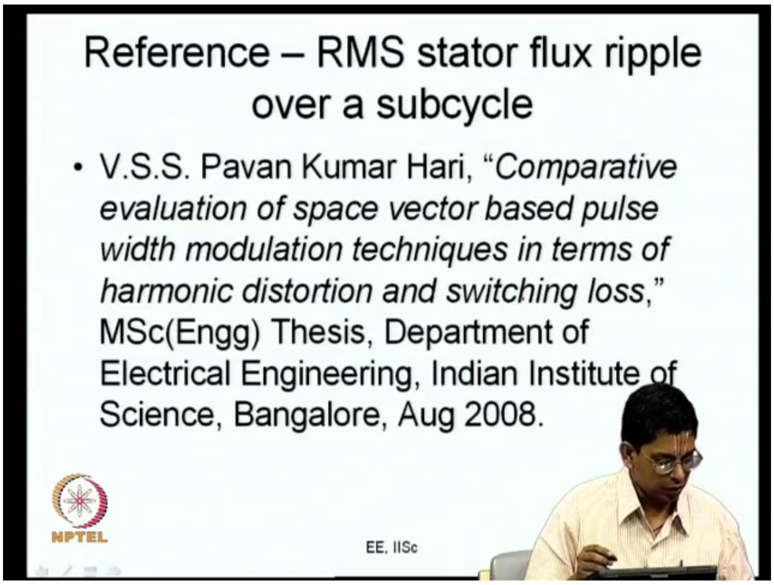

So, this is again you can consider them different for different sequences they are C 2, you can say 012 there is C 2 for 0121 all these are different now. So, in general you can call this as Co sequence and you can call this as C1 sequence and this is C2 sequence as these coefficient differ, from 1 switching sequence to the other that is we have consider the conventional switching sequence still now. What we have consider is 0127, so for that you will get some C o C 1 and C 2 which are trigonometric functions of alpha, instead of 0127 if you consider 012 you will get some different C0 some are C1, for example at different function of trigonometric function of alpha this will be a again a trigonometric function of alpha from what is that right.

So, let us look at those various things if you need you know actually this reference is useful, if you want to do the derivations and all that you can find the details here the same MSc engineering thesis which I by Pavan kumar Hari which I mentioned a very back right.

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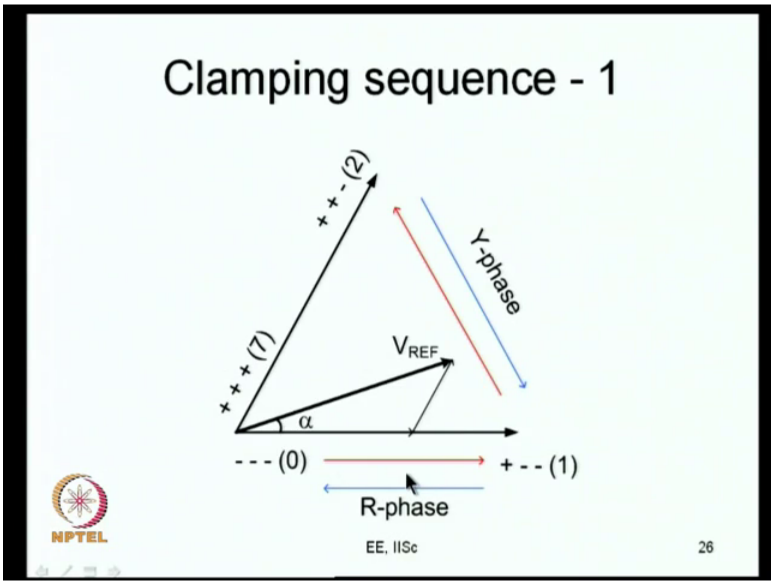

So, let us take a quick recap at this switching sequences, which we did few lectures back. So, because we are going to look at the various sequences on their effect on the RMS ripple. So, let us say you consider this sequence 012; that is you do not apply this 0 state 7, for the entire null vector time T z you apply only 1 0 state and that is minus minus minus are 0. So, you stay here for T z seconds and go here; stay here for T 1 seconds and switch Y-phase and go here stay here for T 2 seconds, that is the end of seconds then you come back switch Y-phase come here again here come here.

So, the red indicate the switching sequence one half carrier cycle are sub cycle, the blue indicates this switching sequence and the other carrier cycle. These two alternate in your sector 1. So, they alter this is one clamping sequence where only 0 state 0 is used.

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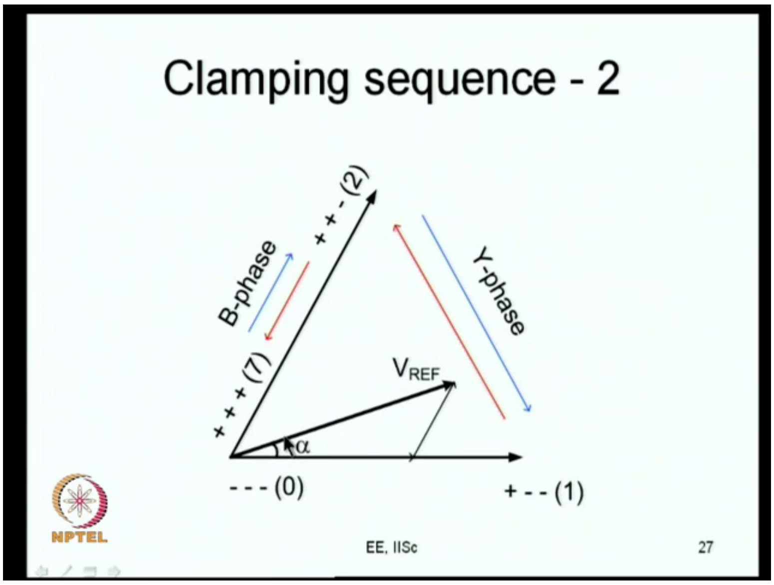

Another clamping sequence is where this 0 state minus minus is not at all used, but plus plus plus is used this is for the entire duration T z. So, this is T z and then you switch B phase, and it go here and stay here for T 2 seconds and then you switch Y-phase and go here for T 1 seconds; so T z T 2 and T 1.

Again you go back in the reverse directions stay here for T 1 seconds, switch Y-phase go here stay here for T 2 seconds, switch B-phase and go here stay here for T z seconds. So, this is a state where you know there is another clamping; in the previous case plus plus plus is never used you see minus minus minus plus, minus minus and plus plus minus B-phase is negative, B-phase is negative, B-phase is negative. So, B-phase always clamps to the negative bus in the next case it is plus plus plus, plus plus minus and plus minus minus. So, the R-phase is always positive. So, here the R-phase clamp to the positive DC bus. So, these are called clamping sequence.

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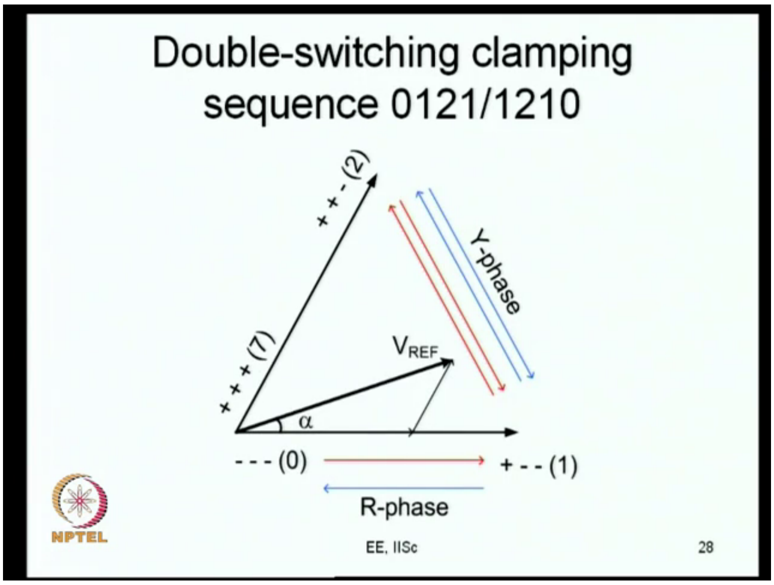

Similarly, we also discuss double switching clamping sequences, which are used in the advanced clamping PWM. So, you can say 0 you can apply this 0 for the entire T z and from here go for T 1 by 2 seconds. Go to vector 2 apply for T 2 seconds and come back and apply for T 1 by 2 second. So, it is 0121; similarly in the reverse what you do 1210. So, this is what you can do this is one variety of double switching clamping sequence.

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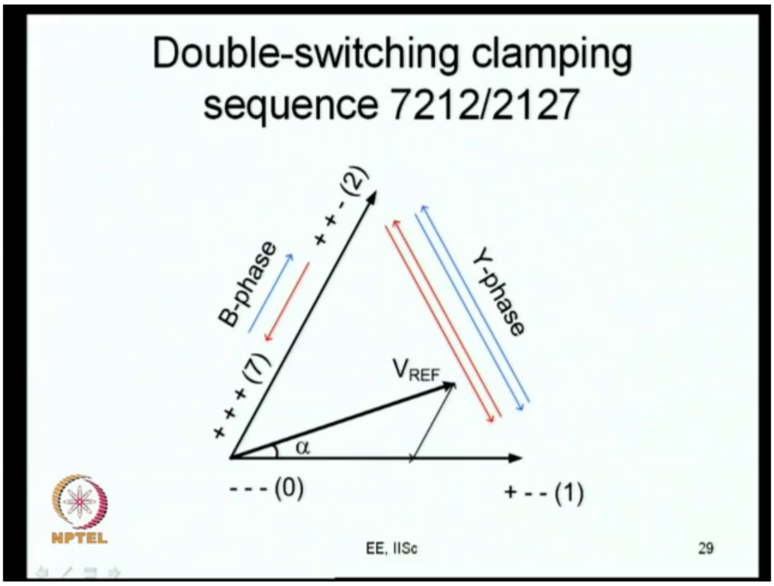

Another variety of double switching clamping sequence are it is complimentary 1 is where you use the other 0 state. You go 7212 you apply 7 for duration T z 2 for duration

T 2 by 2 and 1 for duration T 1 and again 2 for duration T 2 by 2. So, 7212 the reverse would be 2127. So, once again you can do this.

So, there are also switching sequences 1012 and 2721 which I am not talking about now I have discuss this before now.

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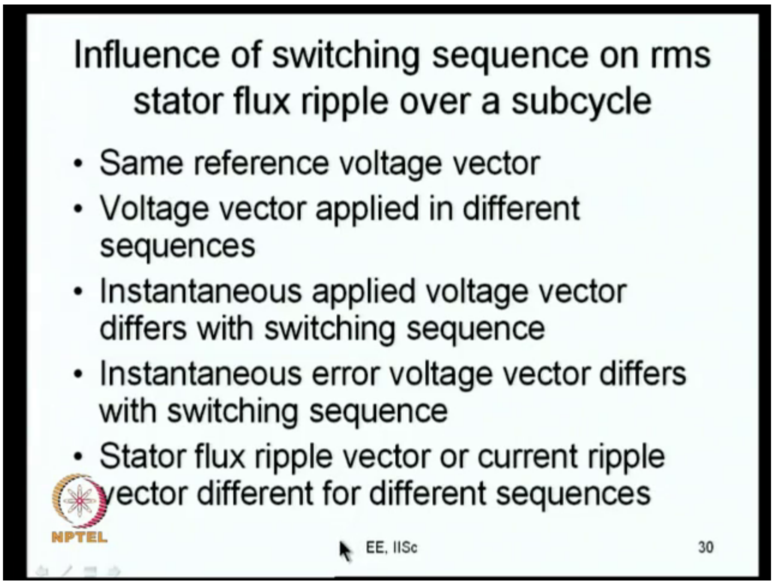

So, now let us say why should the switching sequence influence the RMS stator flux ripple RMS current ripple over a sub cycle now. What we are considering? We are considering a particular sub cycle and we are considering a same reference voltage vector that reference voltage vector say something like V REF is equal to 0.75 and alpha is equal to 10 degrees 15 degree is considered. So, the same reference vector you are using different switching sequences.

So, what you do is basically the voltage vectors are applied in different sequences. So, sometimes it may be 0127 or 0121. Therefore, the invertor voltage vector is applied in different sequences that are the instantaneous applied voltage vector differs with switching sequence. So, when the instantaneous applied voltage vector differs, the reference vector is the same therefore, the error is applied minus reference.

Since the applied is changing, the instantaneous error voltage vector also differs with switching sequence. If you use 0127 you will get some error voltage vector as a function of time. If you use 0121 or let us say 7212 you will get another error voltage vector as a in a different function of time. So, the instantaneous error voltage vector changes differ with the switching sequence use. And therefore, it is integral; integral of this stator flux ripple vector that also differs for different switching sequences. And therefore, you get the RMS current ripple over a sub cycle changes; and when the RMS current ripple over sub cycle changes naturally the RMS current ripple over the entire fundamental cycle should change.

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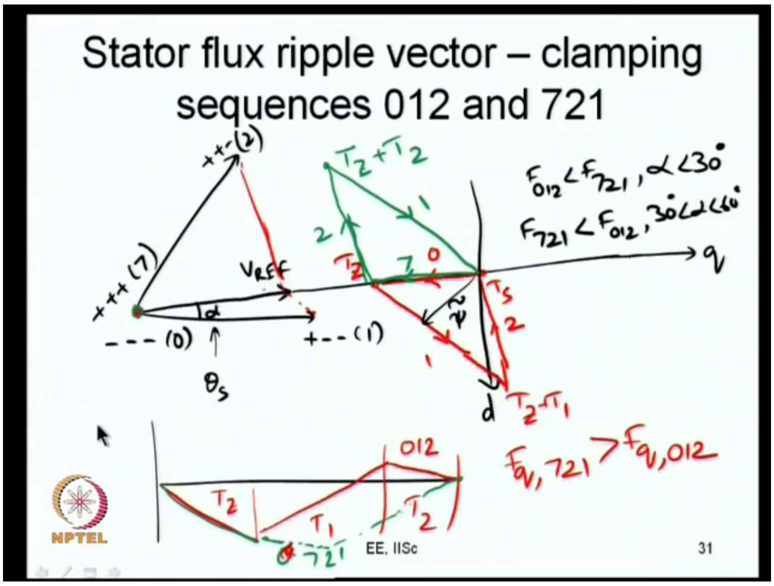

So, let us just bring that out now. So, here we are going to look at this stator flux ripple vector for clamping sequences 012 and 721; like we did before we had this sequence now let us say we did this for sequences 0127. So, the same thing let us now do for plus minus minus this is 1 and this is plus plus minus this is we call as 2, minus minus minus is 0 and plus plus plus this is 7. So, these are the invertor states in sector 1 now, what we do is let us say we are looking at a reference vector like this. This is the reference vector that we want to produce it has a magnitude V REF and it has a sign angle alpha this angle alpha I also called theta s sometime before, it is angle alpha theta s whatever it may be.

So, I am going to now we earlier looked at how the ripple, I mean varies for conventional sequence. So now, I am going to consider sequence 012 and 721 now let me take sequence 012. So, this is the T axes and I am considering d axes to be here now all right when I apply 012. So, what happens? I get 0 is applied like this. So, it changes like this;

when I apply this vector 0 the error is minus V reference vector this is the error minus V reference vector. And therefore, it grows here and I come to this and here to the instance T z I come here; and after that you know after 0 I am applying 1 and then I would apply 2. So, when I am applying 1 the 1 is applied for fairly long duration, I am sorry it is I am applying 1 for a fairly longer duration.

So, let me just re do this. So, when I apply it 2 when I apply active vector 1 it is may be like this, and when I apply active vector 2 it is parallel to this line which I would say is like here. So, one may active vector 1 will may take up to this 0 and this is my active vector 2 this is what the stator flux ripple vector. So, this is the sight tilde vector the stator flux ripple vector; it is 0 to start with 0 to start with excuse me. So, and it goes on increasing along the q axes when the null vector is applied and after that it tip moves parallel to the error here, and after that it tips moves parallel to this error corresponding to this error voltage vector 2 and it goes back to this origin.

So, let me also write down the other instance of time here, this is T z this is T z plus T 1 here it is back to T s. So, this is the nature of variation we can see it is different from what it was with the conventional space vector PWM. So, anyway let us just contrast with something else, let us contrast with 721 when you are applying 721 what is going to happen, it is the same movement that you will see when active vector 7 is applied. It is because it is also 0 vector, it is applied for duration T z now. Then you are going to apply this active vector 2.

So, this moves parallel to the active vector 2 this moves parallel to this now this is active vector 2; then what happens this is the instant T z plus T 2 after that what happens? We are going apply the active vector 1. And therefore, this vector will move parallel to this and come back to the origin this is one. So, you can see that there is a difference now. So, this is 0121 here also you apply the 0 state and then 1 and 2 here you apply this 0 vector you first apply the active vector 2 and then active vector 1 that is the essential difference now do you see a difference now.

So, if you say 0121 first one difference that is along the d axes that you can see if it is 012, next if you consider 210 it will go along the other way. So, it will go in the alternate direction as per the d axes ripple is concern; what I am saying is if you consider 012 the d axes ripple is positive in this sub cycle. If you consider the next sub cycle when it will be 210 the d axes ripple will be negative and so on. So, that is not a very important thing now, but if you see the 0 vectors applied, after 0 vector the active vector 1 is applied and active vector 2 is applied.

Here this after this 0 vector active vector 2 is applied then only active vector 1 is applied now. So, what is the difference you can see? Now in both the cases you can see the q axes ripple is varying excuse me is vary 0 it goes to some value in both the cases then what happens?

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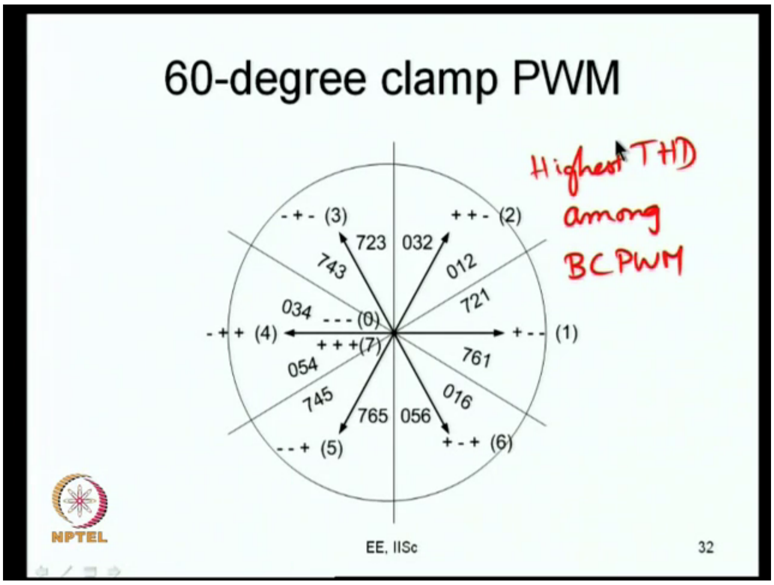

In the case of 012 the q axes ripple starts falling quickly it comes at a much faster rate what happens in the 7 to 1 case? The q axes ripple is more or less is the same value rather it actually goes on increasing a little. So, while here the q axes ripple is very low, and from there it fall into 0 on the other hand when you with 721 you find that the q axes ripple is very high and it gradually falls on lower did you get that.

So, let me just plot that out. So, let me just take this once again and plot that into 2 different q axes ripples alone how to that? In the first case let us say let me use a red ink as I did before. So, the q axes ripple is like this, then next T 1 what happens it goes here and it goes slightly positive and then T z. So, or T 2 it comes like this. So, this is interval T z this is I am sorry this is interval T 1, this is interval T 2 this is not there, alright.

If I take the other one here T z is the same then here what happens is, instead of is going down it is like this, it increases in the negative direction, and finally it goes back to origin. So, this is the case of I am sorry 721 and this is the case of 012. So, you can see that in case of 721 the q axes ripple is more. F q corresponding to 721 is greater than F q corresponding to 012. So, the d axes ripple both of them have same peak value.

So, you can see that both of them have same peak value along the d axes. And since they have the same they have the same RMS values also that differences of the q axes ripple the q axes ripple pertaining to 721 is greater than the q axes ripple pertaining to 012 when is that you can see the whenever V REF is closer to active vector 1; whenever this is alpha equal 30 degree whenever it is within that you will always get that to be higher than that.

So, I can actually summarize it like what I mean I can say this way that is F 012 is less than F 721 for alpha less than 30 degrees then alpha is the angle of the reference vector. And I can say that F 721 is less than F 012 for 30 to 60 alpha coming between 30 to 60 degrees now. So, this is a difference between the 2 clamping sequences and therefore, you get these corresponding differences between various PWM methods.

Now, you have 60 degree clamping PWM method, you consider the sector 1 it is 721. So, what happens is null vector and after the null vector the dominant vector active vector 1 and active vector 2 is not so dominant. So, the null vector is followed by here and then here. So, in this case the current ripple is a little higher the same way the current ripple is also little higher here. This is so 60 degree clamp gives highest THD this gives the highest THD among all the bus clamping PWM methods, because it has the worse of the 2 employed why? It has worse of the 2721 is worse of the 2 in the first half 012 is the worse of the two. So, it gives the highest THD among the bus clamping PWM.

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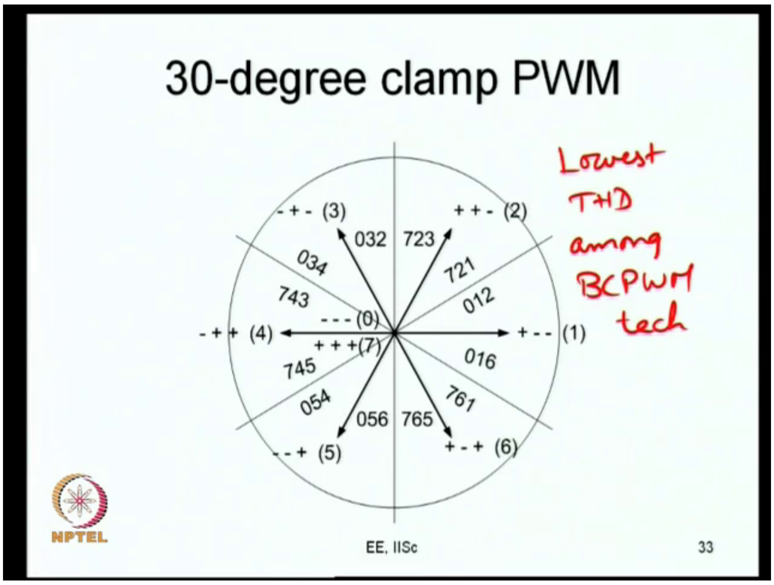

On the other hand you go to 30 degree clamp it use 012 is the better of the 2 in the first 30 degree 721 is again the better of the 2 in the next 30 degree. And therefore, this is the lowest THD among B C PWM techniques. So, such that you can see this is the error voltage analysis, this analysis based on the stator flux ripple of this integral of error voltage vector gives you some idea as to what exactly we can expect now. You can actually do all this quantitatively though I am just because of constrains here I am only integrating the procedure as to how exactly we can do this now.

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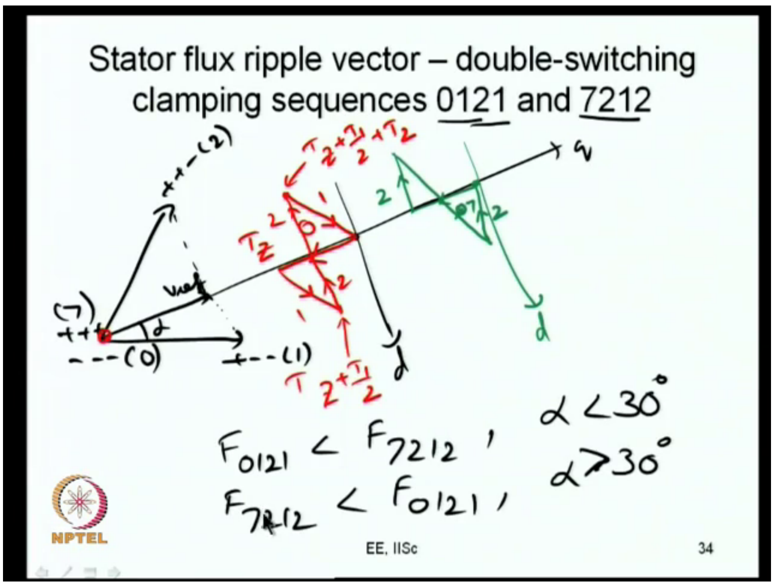

The same way if you want to do some analysis for let us say this current ripple vector corresponding to sequence 012 and 0121 and 7212; let us see we want to do this now. Same way you can start of consider a similar reference vector let us say this is minus minus minus this is plus minus minus that is active state 1, this plus plus minus active state 2, here is plus plus plus are 7 here you have minus minus minus r is 0. So, you are considering let us say reference vector like here this is the reference vector V reference and this is the angle alpha now.

So, these are the errors. So, what you can do is you can consider let us say the d axes and the q axes this is the q axes and let us say this is the d axes. So, this is the origin now. So, let me consider sequence 0121. So, when I do 0121 what happens? First during the initial T z interval null vector 0 is applied. Therefore, the error is minus and therefore I will get is like this now then it is 1 what will happen? My movement will be like this and then when it is 2 I will move parallel to this and 1 will bring me back to this now.

So, what will exactly happen is. So, this is when I have 1 and this is when I have 2 and finally, this is back to 1 this might be a little confusing. So, I will explain this again to you. So, when I am applying the first what I am applying 0 state 0. So, when I am doing that the error vector is minus V REF along the q axes and therefore, this grows like this that is why there is an arrow mark and this is for 0 it grows like this now, this is the time instant T z now. After that what happens, we are applying the active state 1 during the time the error volt second is like this and it actually moves parallel to this error voltage vector.

So, it moves like this and here this reaches at instant, this instant is T z plus T 1 by 2 and this instant is T z plus T 1 by 2 plus T 2 and here it is back to T s. So, what you really get is double triangular trajectory you get at double triangular trajectory here, here it goes back up and back here. So, you get it like this now, this is 0121 now. So, you can see that this kind of sequence has a good advantage in terms of the d axes ripple the d axes ripple is lower in this case compare to the conventional which we will look at little later now.

The same way if you consider 7212 for example; so 7212 what will happen is let me just choose a different color here. So, let me say this is the d axes s it starts let say this is the origin. So, 7 would be the same way, and 2 it goes practically like this I am sorry. So, 2 would move on the upper direction, it is parallel to the error voltage vector pertaining to that. So, for 2 it is movement is like this, this is 0 sorry 7 this is 2 and when you apply 1 you come back here and when you apply 2 you go back here.

So, this is 7212 let me retrace the path here this is 7 2 this is 1 this is 2 7, 2 1 2 here also you see that there is a that d axes ripple is smaller actually the peak d axes ripples are equal in both the cases in terms of the q axes ripple also the peak q axes ripple in these cases are equal here and there, but way that q axes falls from here the q axes ripple falls a little faster, here the q axes ripple does not really fall that fast. So, you will find that the RMS q axes ripple in this case is the little higher than the RMS q axes ripple here.

Therefore, I can actually write this similar fashion to before you know, I can say that F 0121 is actually less than F 7212 whenever alpha is less than 30 degrees. And F 7212 is less than F 0121 whenever alpha is greater than 30 degree that is between 30 and 60 degree, similar to what you found is 0121 721 except the difference here is not very high that is the difference between F 012 and F 7212 is not so high.

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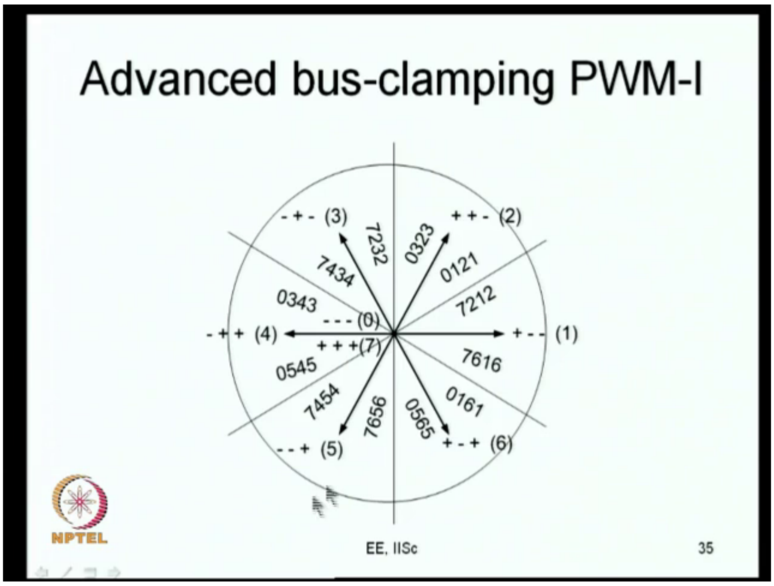

Therefore, what you find is, here also you will have this is the worst scenario among the bus clamping PWM method, which you 7212 and 0121; 7212 is worse of the 2 that is used in the first half 0121 is the worse of the 2 in the second half.

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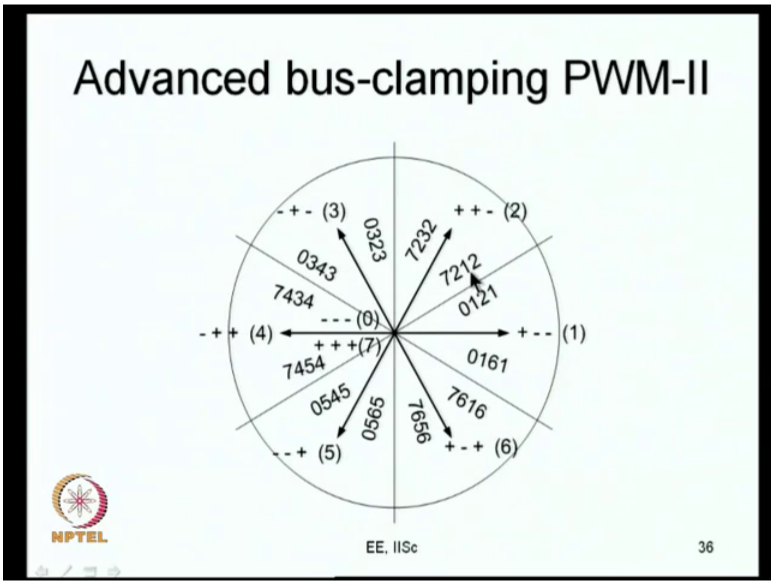

So whereas, this is the better of the 2 this is also the better of the 2 in that. So, this what we call as advanced bus clamping PWM 2 is lightly better than what is that.

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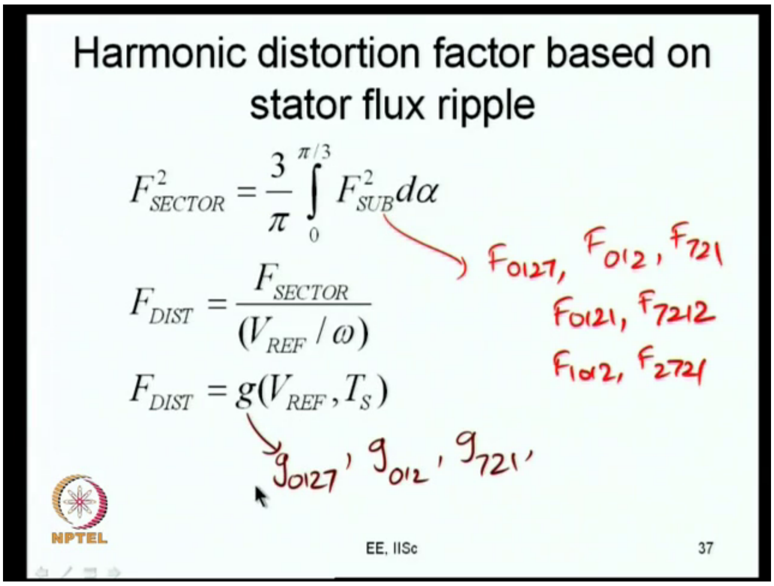

I am saying slightly because it is really slight if you work it out you will find the improvement is not so high. The distortion both the method is are very close to one another, but this is a little better the distortion is little lower than that. So, once you calculate the harmonic distortion like this, based on the stator flux error voltage vector we integrate and it calculate the stator flux ripple vector and from this 0. What you can do is you can right the expression corresponding to the q axes ripple and d axes ripple and you can square and integrate and write down the expression for the RMS stator flux ripple as we did for the conventional. Only for conventional sequence we worked out the entire sequence and try to domain we did in some greater detail, the same way you can write down and you can come up with an expression for the RMS stator flux ripple over a sub cycle for any sequence now.

Once you have that for any sequence. So, this F SUB is F SUB square is the mean square value over a sub cycle for any given sequence, this will change this will be F 0127 you can say many things are there here. So, you can. So, if you are considering 0127, you may have some F 0127 this is some function of V REF alpha and T s otherwise you may have F 012, you may have F 721 you may have F 0121 or F 7212 depending on what sequence, you use or it can also be F 1012 or F 2721.

So, all for all this functions what you have is they are all essentially functions of V REF alpha and T s, but they are different functions particularly the coefficients C 0 and C 1 and C 2 that a tact of they are different for all these now. So, but never the less you have them as a function of V REF alpha and T 0 going to integrated with respect to alpha over a sector that is 0 to phi by 3 and this is 3 by phi. So, this is the mean square value over a sub cycle, this is the mean square value over the sector mean square value over the sector is same as the mean square value over the line cycle because in every sector it is symmetric. So, this is the mean square value over that, and this is F is available for you as a function of V REF alpha and T s and you are going to integrate with respect to alpha.

So, once you have done that this is what you get this your RMS current ripple this is the RMS stator flux ripple this RMS stator flux ripple is proportional to your RMS current ripple it is a measure of the RMS current ripple. And as you have in THD in current THD what do we do? We have the RMS current ripple, we normalize it with respect to the fundamental current. The same way what we can do is we can normalize this RMS stator flux ripple with respect to the fundamental flux on the fundamental flux basically it is the fundamental voltage divided by omega. So, that is what I am trying to that omega is fundamental angle of frequency. So, you can do this and this you can call as F dist or what is called as Harmonic distortion factor.

This Harmonic distortion factor is actually a dimension less, I mean it is independent of (Refer Time: 49:24) dimension list number it is independence of the machine parameters just like your weighted THD of the voltage way form; the weighted t. So, you can also see this similarity between this and the current THD. So, this is like the RMS current ripple and the fundamental current. Instead of RMS current ripple what you have is the RMS stator flux ripple and instead of the fundamental current ripple what you have is the you know fundamental flux that is what you have now.

And this actually numerically it will be every close to what you get is the weighted THD of the voltage way form. You have the voltage way form and you can get a measure of the current ripple by weighting all the fundamental all the harmonic components you can take V n by n V n is (Refer Time: 50:00) V n by you can do and sigma V n by n square under root that divided by V 1. So, you have the weighted THD of the voltage you should derive, and this number is actually end of close to that now. And if you really do this if you have integrated this alpha has gone out of that; and what you going to get is a it is going to a function of V REF and alpha V REF and T as alone and you can actually get your F dist as a function of V REF and T s.

And this function will be different functions. So, I would probably say they are you know for example, for conventional this may be some function, which I can call as g 0127 for the other sequence it may be g 012 for it may be g 721 and so on and. So, for different sequences, you will get it is as different functions of them and if you are using you know again different not the same sequence between 0 to phi by 3 let us say, using some sequence to 0 to phi by 6 ad some other sequence from phi by 6 2 phi by 3 you can also do that integration suitably and you can come up with the harmonic distortion factor.

So, you can finally come up with the nice close form expression, which will be something like you know k 1 V REF square plus k 2 V REF Q plus k 4 V REF 4 power under root multiplied by V REF into T s and something like there is the kind of expression that you can get now.

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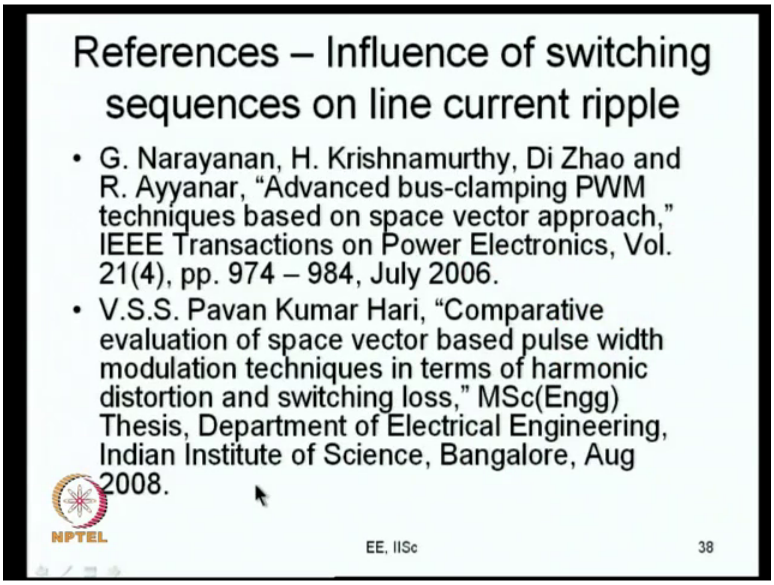

So, you can get the all details this is very difficult to do all the derivations in a video lectures such as this you can find several details of this now. So, for example, for the influence of switching sequences on current ripple, which we found these are good papers which you can refer to this advanced bus clamping PWM techniques based on space vector approach by Narayanan Krishnamurthy Di Zhao and Ayyanar, this is in power electronics. This talks about the effect of these clamping sequences 012 721 and also 0121 and 721 this talks about the sequences.

And this thesis MS c engineering thesis by Pavan Kumar Hari which I mentioned a while back this is again a good reference for the understanding the influence of switching sequences. Here you will find for all the switching sequences like 012, 721, 0121, 7212, 1012, and 2721 for all the sequences, which we are considering you will find them here now.

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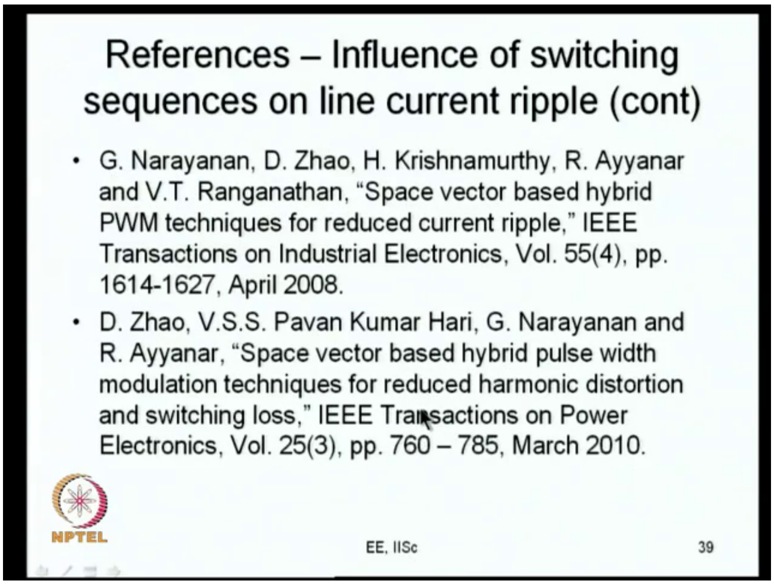

And again you can find the influence of switching sequences, you can study from these papers also which is space vector based hybrid PWM techniques for reduce current ripple. This is published in the transactions on industrial electronics in April 2008 and then there is also another paper Zhao Pavan Kumar and Attal. So, this is space vector based hybrid pulsewidth modulation techniques for reduced harmonic distortion and switching loss.

Here the objectives to reduce the current ripple here the objectives to reduce both the distortion and switching loss, but some methods you know you can also get a good understanding of this from this here also.

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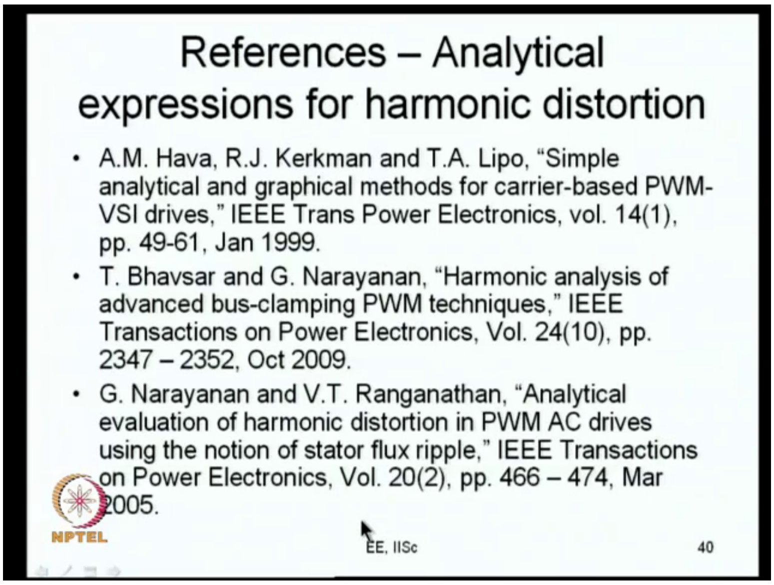

So, if you look at the analytical expression, you can find the analytical expression in a few different papers now. This paper by Hava Attal gives you some analytical expression for a for example, sign triangle PWM conventional space vector PWM and bus clamping PWM methods. And the advanced bus you know here you will find for bus clamping as well as advanced bus clamping method, that is an Bhavsar Tushar Bhavsar and Narayanan. This paper you will find that this is again on transactions on power electronics.

So, you have at another paper here this is analytical evaluation of harmonic distortion in PWM AC drives using the notion of stator flux ripple; here you will find for PWM method, but these are synchronism PWM methods. So, they are low switching frequency PWM methods for such method analytical expressions are given in this paper right.

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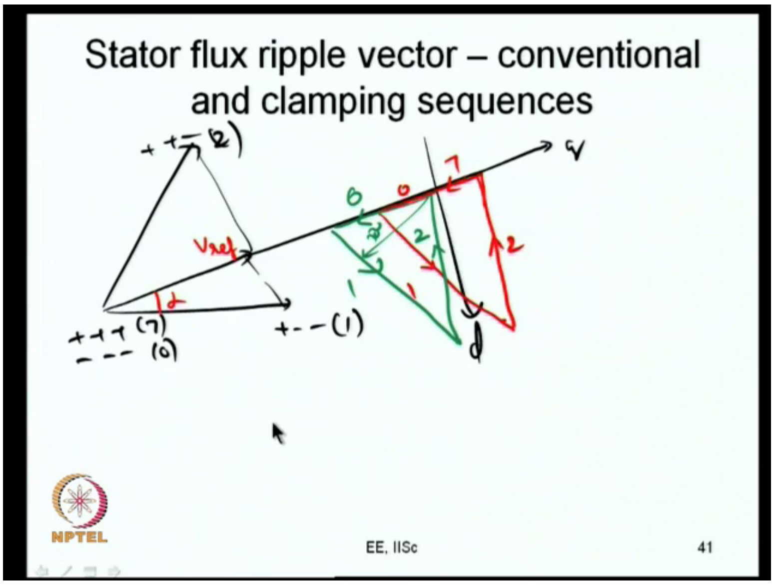

So, if you have to do this, you can come up with the comparative thing of conventional and clamping sequence now. So, we looked at the individual once if you have a comparison what we can do is, let us say this is the reference vector you are talking of. So, these are plus minus minus plus plus minus you have minus minus minus plus plus plus 0127. So, these are the respective error voltage vectors, now let us say this is the d axes I mean this is the q axes and this is the d axes. So, do 0127. What I am going to get is 0, and this is 1, and 2 sorry. So, I will have 012 and 7, this is actually should be symmetric once again excuse me.

So, this would be the conventional 1 let us say for this particular reference vector with V REF is the magnitude and let us say angle alpha. So, this side is parallel to the null vector, this is parallel to the error voltage vector 1 this is parallel to the error voltage vector 2 0127 to do like this now. Instead if you do 012 what happens you apply the 0 vector for the entire period the same 0 and you will get it like this 1 and 2. So, this is 0 this is 1 and this is 2. So, this is your flux ripple vector. So, you can see that your flux ripple vector increases now particularly the q axes component is increased. In the earlier case the peak value of q axes is only half now the q axes values doubled. So, when you compare conventional and clamping sequences what you will find is, the clamping sequences will be kind of double the q axes voltage.

So, that is why the error is very very high, I mean the q axes the harmonic distortion will increase. Whereas the d axes ripple volt change now, but still it can happen now. But you what the different is find is in the conventional you have 3 switching whereas, in the clamping sequences there are only 2 switching. So, it is possible that you can reduce this sub cycle duration for the green thing by two thirds for the same average switching frequency. So, then it this will get shrunk this triangle green triangle will get shrank by two thirds of values.

And if you do that then what you will find is at higher modulation indices green will be better than red; the green is actually worse than red, but if reduce the sub cycle durations to two thirds you get the green could become better than red at high modulation indices. So, this is comparison of conventional clamping sequences bus clamping PWM methods at high modulation indices, can you know reduce the THD over conventional PWM at high modulation indices.

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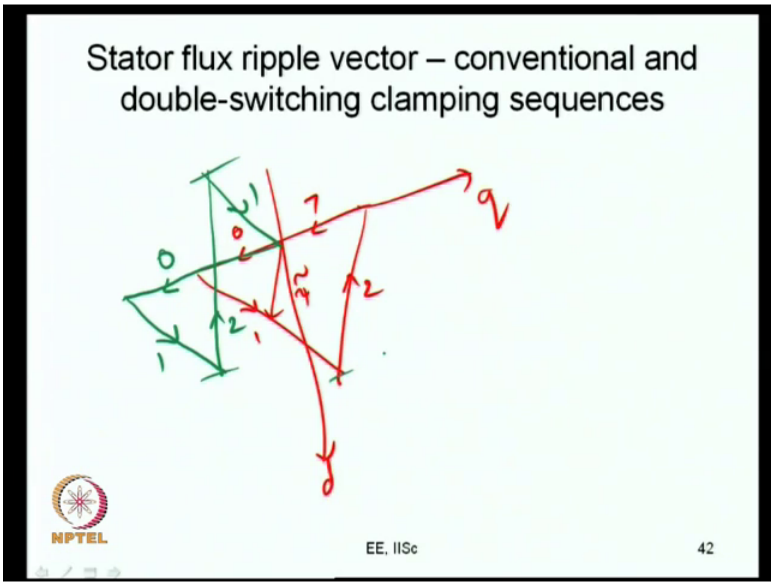

So, similar comparison you can also do for bus clamping methods. So, what you can do is if you take 0127 now this is let us say is your I am doing it like this is 0 this is 1 this is 2 this is 7 if you want to. So, this is the. So, please understand this is the d axes and this is the q axes.

So, instead if you are do 0121. So, 0 will double q axes will increase, but 1 I am applying for half the time and 2 goes above and 1 brings it back. This is 0 this is 1 this is 2 this is one. So, the d axes ripple the peak d axes ripple is half of what you get with here and therefore, this will reduce the RMS d axes ripple and this is advantages under certain conditions.

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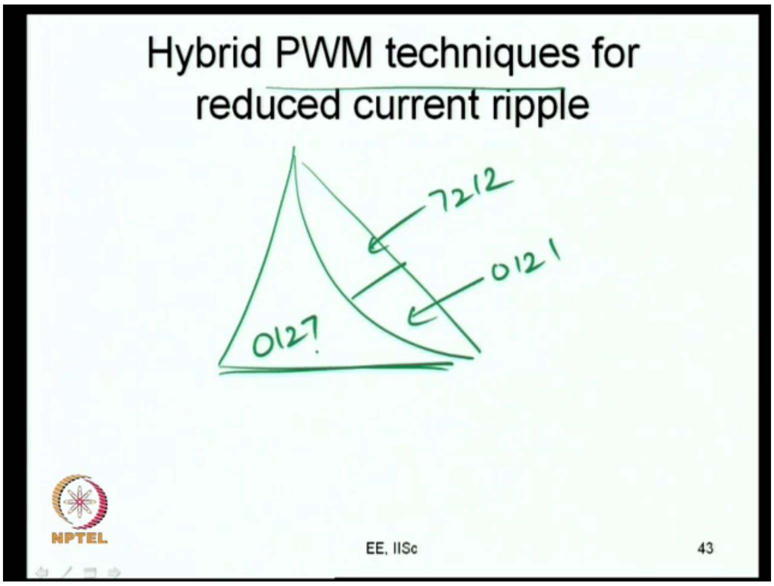

So, all these can actually be worked out to bring certain hybrid PWM techniques. So, you can actually consider something like sequences 0121 here, 7212 here and 0127 here these are hybrid PWM methods you can discuss lot of the hybrid PWM methods you will find them in papers.

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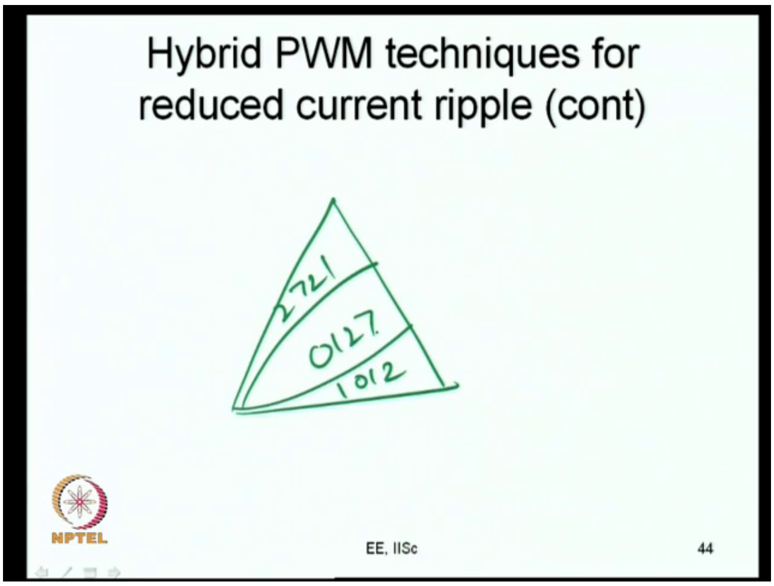

So, you will also find them as 1012 here and 2721 here and 0127 here this is also another hybrid PWM method.

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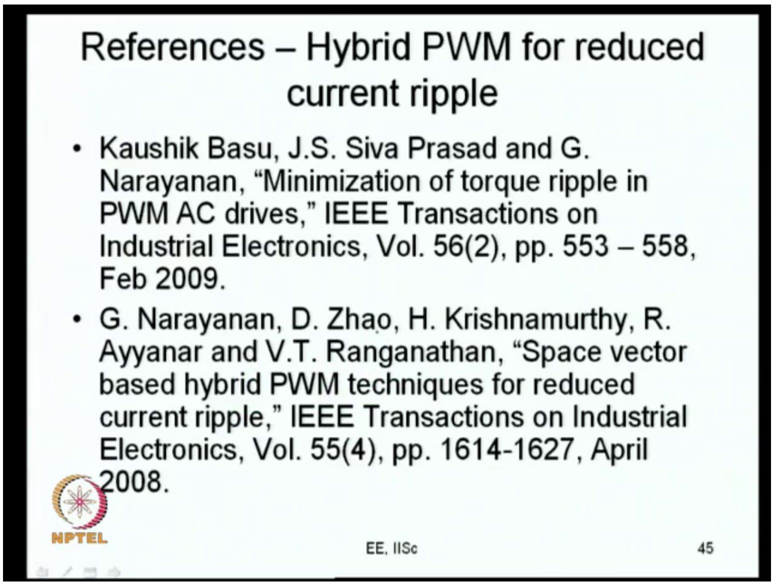

I will discuss more of these when I deal with the reduction and pulse setting talk, here I am just giving some references for you to follow about that if you need and when you discuss the torque pulsation at that time we will get into the hybrid PWM method and do this at greater details. So, these are 2 methods for just meant papers to you to look at now.

So, thank you very much to this and next module we will take up pulse torque and in the pulse setting torque. We will again do the evaluation of pulse setting torque and how to design such hybrid PWM methods there we will discuss about both of them for reduction in current and also in torque.

Thank you very much.