DC Power Transmission Systems
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Lecture – 09
Analysis of 6 pulse LCC neglecting inductance

So, we will start with a simplified circuit where I have a converter with 3 legs.

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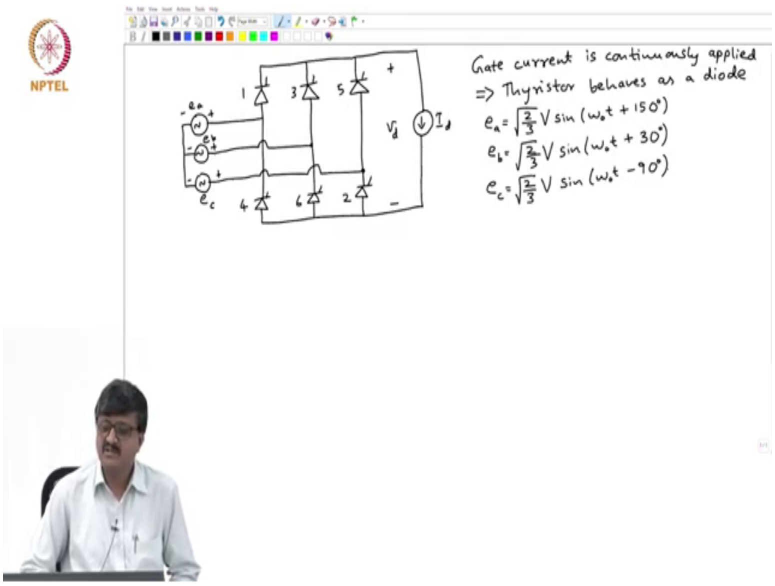

And in each leg there are 2 thyristor valves. So, there are 3 leg shown here and in each leg we say there are 2 thyristor valves. So, they there are two ways of saying, one is one can say that a converter consist of 2 basic commutation groups connected in series or there are 3 legs which is the usual term used in many books, 3 legs connected in parallel.

So, there is 1 leg corresponding to each phase of the ac side. So, we denote the 3 phases by the letters abc. So, I have on the ac side a balanced 3 phase voltage source. So, let me call this voltage e a, this voltage is e b and this is e c. So, the valves are numbered as 1 3 5 4 6 2. On the dc side, the representation is a current source which is constant. So, I have a constant current I d on the dc side the voltage across, the dc side terminals is V d ok.

So, this is the simplest circuit where I actually ignored the inductance on the ac side. So, let us try to analyze this. So, we saw that in the in the last class I can divide the converter into 2 basic commutation groups; upper commutation group and a lower commutation group. 1 3 5 from the upper commutation group, 4 6 2 valves form the lower commutation group. Now, at any instant only one thyristor valve in any commutation group conducts, that is one among 1 3 5 and one among 4 6 2 ok.

Now, for the sake of simplicity what we will do is, we will assume that gate currents are continuously given ok. So, if gate currents are continuously given it is as good as thyristor acting as diodes ok. So, if I say gate current is continuously applied. This is as good as saying that thyristor behaves as a diode. So, behaving as a diode means if it is forward by a state conducts, if it is reverse bias state stops conducting ok.

Now, the question is in any commutation group 1 3 5 or 4 6 2 which is the thyristor valve that conducts? Suppose, I take the commutation group 1 3 5, so how do we decide which one of the 3 valves 1 3 5 conducts at anytime? If you notice the cathodes of all these thyristor valves 1 3 5 are at the same potential. So, the one that conducts is the one with which has the highest potential for the.

Student: Anode.

Anode. Similarly, if you take the lower commutation group 4 6 and 2 the anodes are at the same potential. So, the one that conducts is like one which is having the least cathode potential ok. So, that is the idea ok. So, of course, one has to note that I mean of course, 1 can verify when 1 of the thyristor valves; 1 of the thyristor valves is conducting, the other 2 thyristor valves are reversed bias ok. So, that will verify it ok.

So, we will assume some expression for this e a, e b, e c. So, I said they are balanced sinusoidal; that means, they are having the same ah RMS value or peak value and the phased angle difference between e a and e b or e b and e c or e c and e a is 120 degrees ok. So, let me assume some expression for e a, e b, e c. Now, the only choice I have is assuming the absolute phase angle, I have no choice over the relative phase angle. So, any two voltages will have a phase shift or phase difference of 120 degrees.

So, I will use this expression root 2 by 3 V sin omega o t plus I choose an angle 150 degrees. I could have chosen any angle instead of 150, I mean any arbitrary angle can be chosen, but I m choosing 150 for some reason; it will it is a bit convenient for me as we will see ok. So, V is a constant, omega o is a constant. So, it is a sinusoidal waveform. So, what is this V? So, if I say this is the expression for e a, what is V?

Student: It is the RSM.

Student: Value.

RMS value of line to line voltage. So, please note the 3 voltages e a, e b, e c, the 3 voltage sources single phase voltage sources are connected in thyristor. So, if you look at the line to line voltage it as an RMS value V ok, so that is e a. So, once I have e a, I choose I mean I have no of course I have no choice over e b it has the same RMS or peak value.

And it lags e a by 120 degrees. So, this is sin omega o t plus 30 degrees. And e c lags e b by 120 degrees. So, it is root 2 by 3 V sin omega o t minus 90 degrees ok. So let me try to draw the waveform of e a e b and e c.

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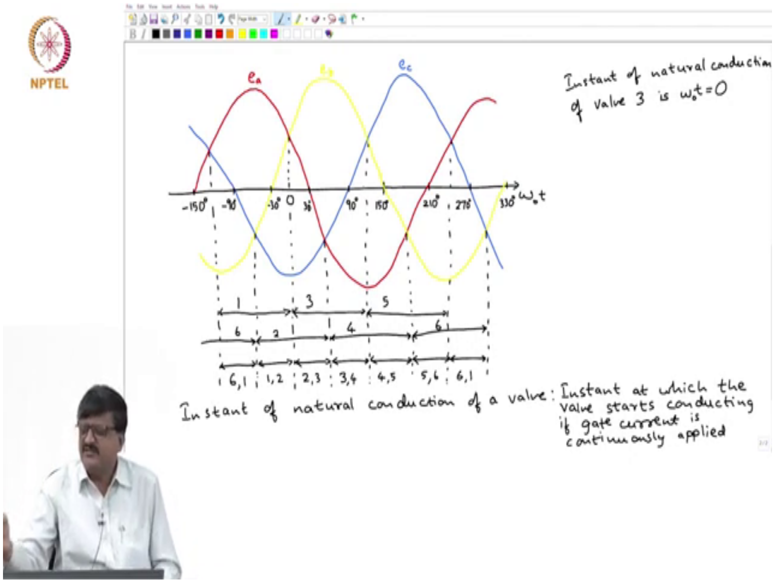

Suppose so this is e b is the yellow line visible ok. Then e c lags e b by 120 degrees ok. So, since it is free hand drawing please not all these wave forms are sinusoidal wave forms, though it may not slightly appear like that and they are balanced; that means, they have equal I mean equal peak values. So, this is e c ok.

So, I will mark some ah angles on the axis. So if I try to take this instant as 0. The instant at which e a and e b are positive and equal in value. So, what will be the instant at which e a is having a 0 crossing from negative to positive. Please note our expression for a is this, it is root 2 by 3 V sin omega o t plus 150 ok. So, this will be minus.

Student: Minus 150.

150. So, what I have shown is every 60 degrees, so this is minus.

90 degrees. This is minus 30, this is plus 30, this is 90, 150, 210, 270 and 330. So, I have shown every 60 degrees, only I mean only thing is I have showed an additional instant 0 also ok.

Now, just now we saw that if I look at the commutation group consisting of valves 1 3 5. At any instant, the valve with the highest anode potential conducts. So, let us try to see or let us try to first mark the instants of the conduction of different valve, so based on the one with the highest anode potential.

So, if I take this instant ok; so if I take this instant and if I take this instant. Now, from this instant to this instant, can I say one of the thyristor valves in the upper commutation group has the highest anode potential? Among 1 3 5; among 1 3 5 which one has the highest anode potential?

Student: 1.

1, so it is 1. Similarly, from here to here from this instant to this instant one of the thyristor valves among 1 3 5 has the highest anode potential that is?

Student: 3.

That is?

Student: 3.

3. And again from this instant to this instant the thyristor valve 5 is at the highest potential ok. So, now, we know which one among the thyristor valves of the upper commutation group conducts. So, if you have noticed we have considered one full cycle 360 degrees. So, we

started from minus though I have not marked it is minus 120; minus 120 and we go up to not again marked here between 210 and 270 there is a 240.

So, minus 120 to 240, so for one full cycle 360 degrees of the ac side. We have noted which thyristor valve of the upper commutation group conducts. Now we have to also find out which one among the lower commutation groups conducts ok. So, I will just extend these lines. So, this is corresponding to 1, this is corresponding to 3 and this duration is corresponding to 5 ok.

Now, to find out which one among the lower commutation group conducts, I take this instant and this instant ok. Suppose I take the duration though I have not marked minus 60 to plus 60; minus 60 to plus 60 so from this point to this point. So, there is one thyristor valves which is the least cathode potential which one is that?

Student: e c.

From here to here.

Student: (Refer Time: 14:42) e c.

Sorry.

Student: Seconds.

Yeah please go to the circuit 4 6 2 which one among these? 2, so it is 2. Again from 60 degrees to 180 degrees, so for this duration. One of the thyristor valves is at the least cathode potential 4 and from 180 degrees to 300 degrees, it is 6. Now, though I have not shown for the duration up to 60 degrees sorry up to minus 60 degrees. So, if I take this duration again this is of 120 degree width, but I am not showing the entire duration. So, if I take for this duration which is up to minus 60 degrees, which thyristor valve is conducting?

Student: 6.

6, ok. Now, again I have covered 1 cycle see if you look at the durations for which either 2 4 or 6 conducts I mean the total duration is 360. Now, what we will do is we will try to consider intervals of length 60 degrees. Suppose I take this or this or this all these are intervals of duration 60 degrees ok.

So, at any instant one thyristor valve in the upper commutation group conducts; one thyristor valve in the lower commutation group conducts. So, in the first 60 degree interval it is 1 and 6 ok. So, instead of writing 1 and 6 I say, 6 and 1 6 comma 1. Then in the second interval of 60 degree duration it is 1 and 2. Then it is 2 and 3, then it is 3 and 4, then it is 4 and 5, then it is 5 and 6. Now, that actually completes one cycle. So, if you go to the next interval it is corresponding to the next cycle again this same sequence follows.

Now, what we have done here is first of all we should note that we have assumed that the thyristors are acting as diodes. So, continuous gate current is applied so, thyristors are acting as diodes. So, we will go to the general case of thyristors are acting for as devices for which they are they are used to ok. See; obviously, if I use thyristors I invest more money than that I do for the diode and obviously, it is used for control purpose ok.

So, there is a provision to delay the instant of giving the gate pulse. So, actually gate current is not continuously applied gate current pulse is given so, that I can delay the instant of turn on. So, that I get some control over some quantity ok.

So, essentially I can get control over say the DC voltage, for a given AC voltage I can get control over the average value of the DC side voltage ok. Now, we define one thing which is called instant of natural conduction. Now. this is a quantity which is defined for any valve any of the 6 valves so, instant of natural conduction of a valve. So, what is this instant of natural conduction of a valve? It means the instant at which the valves start conducting; if the gate current is continuously applied. So, that is the definition.

So, this is instant of or instant at which, instant at which. So, please note this is defined for each and every valve all the 6 valves. So, if I take one particular valve the instant of natural conduction of that valve is nothing, but the instant at which the valves starts conducting; instant at which the valve starts conducting provided I give continuous gate current ok.

So, if gate current is continuously applied; continuously applied. So, that is the definition of instant of natural conduction of a valve ok. Let us see for one of the valves, what is the instant of natural conduction. Suppose I take the instant of natural conduction of say valve 3. So, we I mean the in independent variable is normally the angle omega o t. So, though we say instant we refer to even omega o t as well ok. So, omega o t is equal to.

Student: 0.

0. So, you see that at omega o t equal to 0, 3 starts conducting. So, the instant; at which, 3 starts conducting is omega o t equal to 0. Now, this is the instant at which its starts conducting if gate current is continuously applied ok. So, what we do in practices instead of continuous gate current; gate current pulses are actually applied which are delayed by a certain angle. Say it is as good as applying see there is one more equivalence instead of continuous gate current diode operation is possible even if I just apply gate pulse at.

Student: At the right instant.

At the right instance. So, in the case of ah valve 3 if I apply the gate pulse at omega o t equal to 0.

Student: 0.

And the next gate pulse for the same valve.

Student: At for 60 degree (Refer Time: 21:32).

At the for the same valve, I am talking about the same valve.

Student: 180 degree.

Student: 180, 360 degree.

360 degrees. See you apply gate pulse only once in one cycle. So, say there is a diode operation possible even with gate pulse, if I apply a gate pulse to valve 3 at omega o t equal to 0, 360, 720 and all multiples of 360 ok. So, similarly for each valve instead of giving continuous gate current, I can apply gate pulses every 360 degrees at the appropriate instant to get diode operation ok. So, what is actually done is not is neither a continuous gate current, nor gate pulse to achieve diode operation ok.

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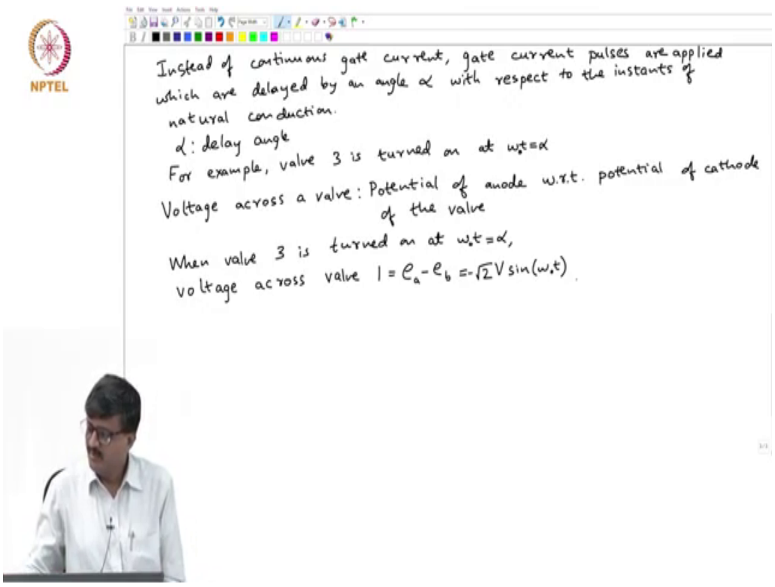

So, we want to how control so, what we do is instead of continuous gate current, what is actually done is, gate current pulses gate current pulses are applied which are delayed by an angle; so which are delayed by an angle. So, we give a notation for this angle alpha. Now, this delay is measured with respect to the instant of natural conduction ok. So, by an angle alpha with respect to the instants of natural conduction.

So, for this converter there are 6 thyristors valves so; that means, there are 6 instants of natural conduction. Now, for each thyristors valve we delay the instant of gate current pulse by the same angle. Please note this alpha is not different for different valves. So, alpha is same for all the valves ok. For all the 6 valves they delay is same so, that is denoted by alpha.

So, there is a name for this I mean alpha is called delay angle ok. So, for example, if I take valve 3; for example, if I take valve 3, valve 3 is turned on; that means, gate per gate current pulse is given at so, if the delay angle is alpha what is the instant of the gate current pulse or the instant of turn on for valve 3. See what was the instant for of natural conduction for valve 3?

Student: 0.

0. So, this will be I mean the instant of turn on in general is omega o t equal to alpha. See if you take valve 4, what is the instant of natural conduction for valve 4?

Student: 60.

60 degrees.

Student: 60 degree.

60 degree. So, the valve 4 is turned on at 60 plus alpha. The instant of natural conduction for valve 4 is 120. So, valve 5 is turned on at 120 plus alpha so on ok. So, for valve 3 it is alpha, just alpha ok. So, what happens to the valve which was conducting earlier, say valve 3 is

turned on at omega o t equal to alpha. What was the valve that was conducting before valve 3 is turned on?

Student: (Refer Time: 25:27) valve.

Which valve was conducting; valve 1. So what happens to that?

Student: Has to turn off.

That will turn off it gets reversed biased. So, it gets reversed biased and it turns off. Now, this is irrespective of whether I give continuous gate current or gate pulse, it is irrespective of that. Say initially I considered continuous gate current I mean to explain the operation that was operation as if everything is work I mean all valves are working as diodes.

So, irrespective of continuous gate current or gate pulses as soon as valve 3 is turned on and it starts conducting valve 1 will turn off. And of course, one can verify that it is reversed biased, is it not reverse biased what will be the voltage across valve one as soon as valve 3 is turned on.

Student: E b minus e a.

E b minus e a. So, what happens to e b minus e a.

Student: Actually, I know cathode will be a minus e b, but a minus.

Yeah.

Student: E b will be negative.

Say we define one quantity here for convenience voltage across a valve; voltage across a valve; whether it is valve 1 2 3 4 5 or 6. By definition it is the potential of anode so every time I will not say the potential of anode with respect to cathode. So, I will just say voltage across valve 1, potential of anode with respect to cathode of the valve. So, I was asking what happens to the voltage across valve 1, when valve 3 is turned on.

Student: (Refer Time: 27:23).

Let us find out the expression for voltage.

Student: C a minus c a.

So, when valve 3 is turned on at omega o t equal to alpha, turned on at omega o t equal to alpha, then the voltage across valve 1 voltage across valve 1 is equal to. So, let us go back to the figure the circuit diagram.

So, 3 is turned on; so 3 is turned on means the valve 3 acts as a short circuit. See, we are assuming ideal thyristors. So, the voltage across the thyristors or thyristors valve is 0, when it is on or when it is conducting ok. So, this is a short valve 3 is a short. So, what is the voltage across valve 1?

Student: P a minus; p a minus.

It is anode potential minus cathode potential. So, it is e a minus.

Student: e b.

e b. So, it is e a minus e b which can be obtained from the circuit diagram, e a minus e b. Now, we have expressions for e a and e b. Now, using the expressions for e a and e b can I say what is e a minus e b. E a is having a phase angle 150, e b is having a phase angle of.

Student: Root 3 V.

30.

Student: Root 2 2 V.

Root 2 first of all this is a line voltage please note e a minus e b is line voltage. So, the peak valve is root 2 V.

Student: Sin omega.

Sin omega o t.

Student: 180.

180. So, can I say that it is minus root 2 V sin omega o t.

Student: minus (Refer Time: 29:21).

Ok. Now, for the time being let us assume that, alpha is taking such a value that voltage across valve 1 is actually negative as soon as it stops conducting ok. So, then what should be the range of alpha?

Say alpha can be 0, see alpha is equal to 0 corresponds to diode operation. Now, if alpha is increased ok. Now, beyond a certain value what happens to voltage across valve 1? See please note this voltage across valve 1 is negative only for omega o t less than; less then?

Student: (Refer Time: 30:14).

Look at the expression minus root 2 V sin omega o t; it is negative only from 0 to.

Student: 0 to pi by 2.

Pi by 2. Is it pi by 2?

Student: 1.

0 to?

Student: 0 to pi.

0 to pi ok. So, for the time being we will assume that alpha is close to 0 ok. We will consider the general case shortly. So, if alpha is say close to 0 ok, so then as soon as valve 3 is turned on voltage across valve 1 is negative as soon as it stops conducting ok. Now actually that is a mandatory requirement because if the voltage across valve 1 is not equal to a negative value for a certain minimum duration then it will again start conducting without gate pulse.

Student: It is because the current is not (Refer Time: 31:06).

So, that is a property of a thyristor I will not get into the device physics here. So, I mean I do not know whether you are familiar with that. A thyristor will actually start conducting again, see one the thyristors once it stops conducting because current goes to 0 ok.

So, if it currents goes to 0, it starts conducting sorry current goes to 0 it stops conducting. Then as soon as it stops conducting the voltage across the thyristors should be negative, that is anode to cathode voltage should be negative. If it becomes positive it is forward biased and without gate current it will start conducting, if it is not negative for a certain minimum duration ok.

So, that is one property of thyristors which we have to consider in this course of course, in the analysis of any converter though we are assuming ideal thyristors. See please note in other ways it is ideal, but as far as this aspect is concerned we have to take that practical operation of thyristors here. So, there is a certain minimum duration say we do not want the thyristors to conduct as soon as it is forward biased; we want the thyristors to conduct when we want, that is when we give the gate current pulse.

So, if it conducts just because it is forward biased than the control is lost ok. So, whenever a thyristors valve stops conducting then there is a minimum duration for which the voltage across the thyristors valve should be negative. If that is not maintained if it again becomes positive, the thyristors starts conducting again without gate pulse ok.

So, this is something we will come back again ok. So, we will come back to that analysis again. Now, what we will do is we will try to look at the different intervals that we have seen in the previous page see there are 6 intervals in one cycle each interval is off duration 60 degrees ok. So, we will try to form a table and do further analysis.

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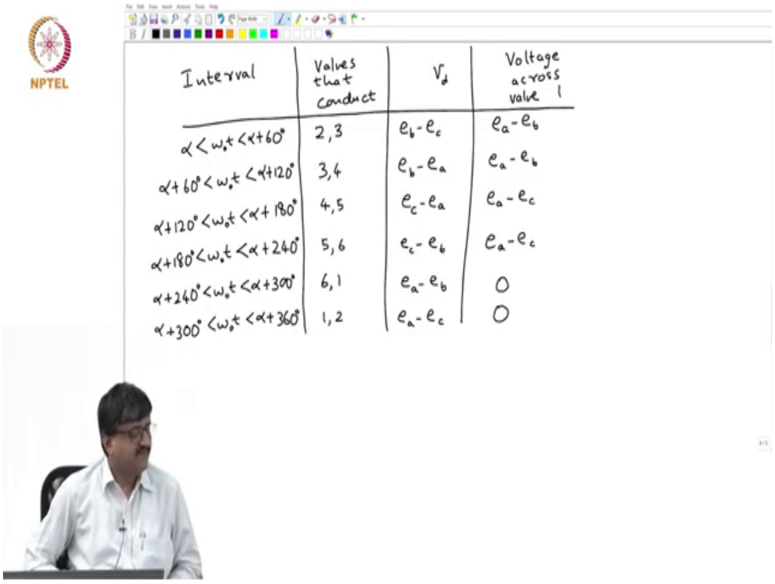

So, I will list all the 6 intervals and in each interval we will see what are the valves. There are 2 valves; 1 valve from the upper commutation group, 1 valve from the lower commutation group that conducts; so valves that conduct. And we are interested in what is happening to the DC side voltage ok. So, we look at the expression for the DC side voltage V d. See V d is see if you go back to the circuit V d is the voltage across the DC side terminals ok.

So, we look at the expression for V d. And we will also look at voltage across one of the valves, there are six valves. Now, one can show that there is symmetry, if you look at the voltage across one of the valves; say valve 1. The voltage across valve 2 will be similar to valve 1. In fact identical to valve 1, except for a phase shift.

So, voltage across all the valves are identical, except for phase shifts ok. So, I will I can just see what is happening to voltage across one of the valves. So, voltage across say valve 1; so I will try to form a table. So there are 6 rows in this table.

So, the 6 rows corresponds to the 6 intervals ok. So, what is the first interval?

Student: (Refer Time: 34:33).

Ok, I am not going by this figure see this figure has 6 intervals, but this first was corresponding to diode operation. See please note here this is something which is corresponding to continuous gate current ok. So, if I assume a general case where there is a delay, if there is a delay in giving a gate current pulse with respect to instead of natural conduction. What is the first interval? See suppose I take valve 3, valve 3 is turned on at alpha ok. Now it continues to be on up to what instant.

Student: Alpha plus (Refer Time: 35:14).

Alpha plus?

Student: 120.

12. So, each thyristors valve conducts for 120 ok. But I mean before the next thyristor in the same commutation group starts conducting there is one more thyristors valve in the other commutation group which starts conducting that is 4. See 3 is in the upper commutation group, 4 in the lower commutation group. So, 4 is turned on at, see you can refer to this figure, where I have considered a continuous gate current.

Student: 60 to 70.

So, at 60 plus alpha. So, here the only thing is the gate pulses are as good is as good as giving gate pulse at 0 for valve 3, at 60 for valve 4 and so on. Now, in general it is alpha for valve 3, alpha plus 60 for valve 4, alpha plus 120 for valve 5 and so on ok. So, I can say that I can consider the cycle which is of duration 360 degree to be divided into 6 equal parts ah. So, each of this is called an interval. So, the first interval is between alpha and alpha plus 60 degrees ok.

Then the second interval is between alpha plus 60 degree, see what I have written here is in the first case omega o t is greater than alpha and less than alpha plus 60. Then the third interval is alpha plus 120 to alpha plus 180 degrees, then alpha plus 180 degrees to alpha plus 240 degrees, alpha plus 240 degrees to alpha plus 300 degrees. And the last interval is alpha plus 300 degrees to alpha plus 360 degrees ok.

So we have just listed all the 6 intervals in one full cycle. See this one cycle is for the AC side or AC side period is 360 degrees please note that ok. So, if I take the first interval alpha to alpha plus 60 ,what are the valves that conduct? Valve 3 is turned on at.

Student: (Refer Time: 37:53).

Alpha. So, there is one more valve in the lower commutation groups that is conducting that is.

Student: (Refer Time: 37:58) 2.

2. So, valves that conduct in the first interval are 2 and 3. Then the next interval 3 4, 4 5, 5 6, 6 1, 1 2, then if you take the next interval of course, the cycle repeats. Now, can I write the expression for V d in terms of say e a e b e c looking at the circuit diagram. See in the first interval 2 and 3 are conducting.

So, if you look at the circuit diagram. From the circuit diagram if 2 and 3 are conducting can I get an expression for V d. Say it is as good as saying 2 is a short circuit; valve 2 is acting as a short circuit, valve 3 is acting as a short circuit, other valves are open acting as open circuits. So, the positive terminal of the DC side is connected to the positive terminal of e b through this valve 3 which is acting as a short circuit.

See what I am trying to say is in the first interval 2 and 3 are conducting so they are acting a short circuit. So, the positive terminal of the DC side is connected to the positive terminal of e b, the voltage source e b through valve. The negative terminal of the DC side is connected to the negative terminal sorry positive terminal of e c through valve 2 which is again acting as short circuit. So, what is V d?

Student: E c (Refer Time: 39:26).

E b minus?

Student: E c.

E c ok. So, it is e b minus e c. so let us write that, so e b minus e c. So, looking at the circle diagram we can say what is the expression for V d because based on what are the thyristors valves that conduct I mean they are acting as short circuit. So, you can easily get the expression for V d in terms of e a, e b and e c. So, when 3 and 4 conduct e b minus.

Student: E a.

E a. So, the valves that conduct are actually acting as short circuits that is all. When 4 and 5 conduct?

Student: E c minus.

E c minus.

Student: E a.

E a. When 5 and 6 conduct, e c minus.

Student: E b.

E b fine. Then when 6 and 1 conduct.

Student: E a minus e b.

Ea minus e b. When 1 and 2 conduct.

Student: E a minus e c.

E a minus e c fine, this can be easily obtained from the circuit diagram ok. Then let us look at the voltage across one of the valve say valve one. Now, how to get the voltage across valve 1, again go back to the circle diagram. So, 2 and 3 are conducting in the first interval. So, what is the voltage across valve 1?

Student: (Refer Time: 40:59).

Now, it does not matter whether 2 conducts the point is 3 is conducting. So, once I know 3 is conducting, 3 is acting as a short circuit and the cathode of valve 1 is connected to the positive terminal of the voltage source e b and the anode of valve 1 is connected to the positive terminal of e a. So, from that I can say what is the voltage across valve 1.

Student: E a minus e b.

So, it is e a minus e b yeah. So, I will stick to the definition of voltage across the valve it is always the voltage of the anode with respect to the cathode fine. Similarly can we say what is the voltage across valve 1 when 3 and 4 conduct, again go back to the circuit diagram. Now, it does not matter whether 4 conducts or not 3 is conducting. So, it has the same as what happened in the previous interval. So, 3 whenever 3 is conducting it means it is e a minus e b.

Student: E b.

Now, in the next interval 4 and 5 conducts. So, please note again it does not matter whether 4 conducts or not 5 is conducting what matters is 5 is conducting. So, since 5 is conducting, 5 is acting as a short circuit. So, voltage across valve 1 is e a minus.

Student: E c.

E c. Again in the next interval it does not matter whether 6 conducts or not. Say whether 4 conducts or 6 conducts, it does not matter. The point is 5 is conducting so the expression is e a minus e c and the last two cases are very easy.

So, in the next 2 intervals; one is conducting. So, one is conducting means by your assumption of ideal thyristors valve this voltage is 0. So, we will try to analyze further by using this table and a few other explanations that was done in this class. So, I will continue with this in the next class.