DC Power Transmission Systems
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Lecture – 53
DC link control

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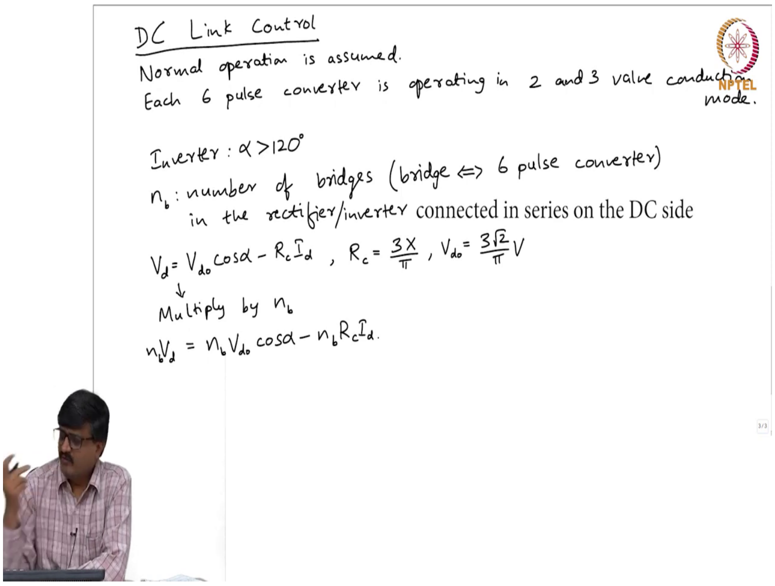

So, let us look at DC link control. So, we will assume normal operation first of all, normal operation is assumed. So, normal operation means each 6 pulse converter is operating in which mode?

Student: (Refer Time: 00:44).

Student: (Refer Time: 00:45) 2 and 3 valve.

2 and 3 valve conduction mode. That means, each 6 pulse converter is operating in 2 and 3 valve conduction mode. And when it comes to one of the sides, that is the inverter side. So, for when it comes to inverter, what is the value of alpha? When I say normal operation.

Student: (Refer Time: 01:30).

What? It should be.

Student: Greater than 120.

Greater than 120, ok. In fact, it is far away from 120. It is much greater than 120. Now I will use some notation n b, n b is number of bridges connected in series on the DC side. What, I mean or in other words, a bridge a bridge is actually a synonym for 6 pulse converter. Bridge means 6 pulse converter. So, it is the number of bridges on the in the rectifier or inverter. In the rectifier or inverter, ok. So the number of bridges should be same because rectifier and inverter are identical circuits, ok. Now what we will try to do is, I will try to get a control strategy which is applicable for any of these links.

Now, for normal operation we got some equations. See if you look at the expression for V d for a 6 pulse converter, we showed that this is equal to V do cos alpha minus R c I d. So let us assume that the DC side is represented by a constant current. And the AC side is represented by a balanced 3 phase voltage in series with an inductance in each phase. So then, V d I d R c V do alpha related by this equation. So, we know what is R c. What is R c? It is.

Student: (Refer Time: 03:20).

3 times x by pi. Is that ok? You recall this, just go to the 6 pulse converter and normal operation, regard this equation where R c is 3 x by pi; x is the inductive reactance of the inductance on the AC side, ok. Now what is V do? V do we got the.

Student: (Refer Time: 04:00).

Expression for V do in terms of the line-to-line voltage of the source in fact. See the AC side is represented by a voltage source in series with an inductance. So in terms of the magnitude of the voltage of the source, we can write V do. So, it is 3 root 2 by pi into.

Student: (Refer Time: 04:20).

V V is the line-to-line RMS value of that source voltage, 3 phase source voltage. Now if I multiply this equation, multiply this equation by n b. Now if I multiply this by n b, this equation, I get n b into V d on the left-hand side, n b into V do cos alpha minus n b R c I d.

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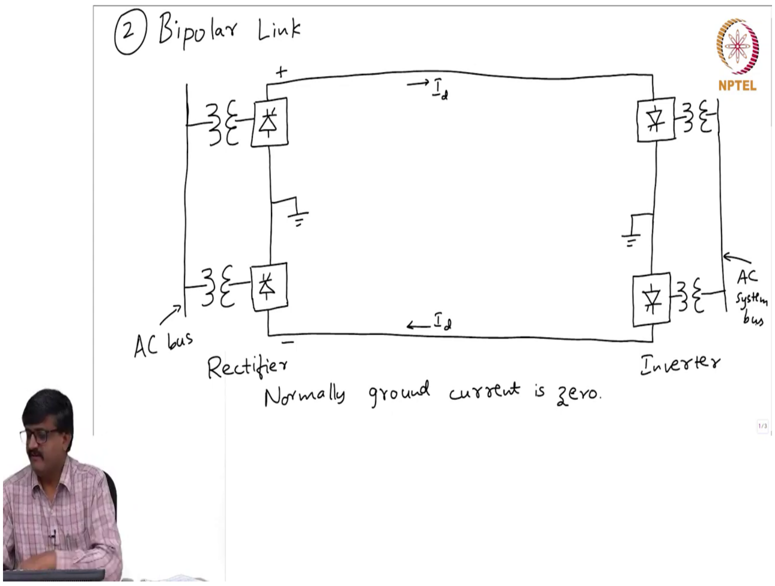

Now, if you look at other go back to any of these links, suppose I go back to say the most common one, bipolar link ok. Now in the circuit, I have an AC bus on the rectifier side, see this is AC this is the AC bus. This is the one of the buses of the AC system. There is another AC bus on the other side. This is the ac system bus. See, one point to notice that this DC link is present in a predominantly AC system, ok.

So, the 2 buses on the extreme left and extreme right are AC system buses. Now what we do as a I mean on the AC side. See, we need a model. So, what is the model that we are using? Say to the left of or to the on the AC side of the converter, what is the model used? If you just go back to 6 pulse what is the model used?

Student: AC voltage (Refer Time: 06:07).

AC voltage source in series with an inductance. Now the AC voltage source is nothing but the bus voltage. And, the inductance is nothing but the transformer leakage inductance. Now, we ignore the transformer leakage inductance when we try to do some analysis for 12 pulse LCC, ok. But that can not be ignored that I mean that neglecting the leakage inductance was for the sake of simplicity to show that some harmonics get eliminated, ok.

So, leakage inductance is actually something which is non-zero and it can not be neglected. So, the leakage inductance serves as the inductance that is appearing in the model of the AC system, that you are appearing on the AC side of the converter. So, I have a 3 phase voltage source with an inductance. Now if you go back to the 12 pulse LCC, I have one wye-wye transformer, there is a leakage inductance and there is a representation of the AC voltage which is nothing but the AC system bus voltage.

Now, when it comes to one more transformer there is wye-delta. Now what I do here is, I will assume that that wye-delta transformer can be also represented by the same inductive reactance corresponding to leakage and another set of voltages, only thing is the 2 voltages are identical except for, except for what?

Student: (Refer Time: 07:30).

Phase shift, that is all. So, one assumption made here is, the leakage inductance the equivalent leakage inductance for both wye-wye and wye-delta transformer are same. That is the assumption, ok.

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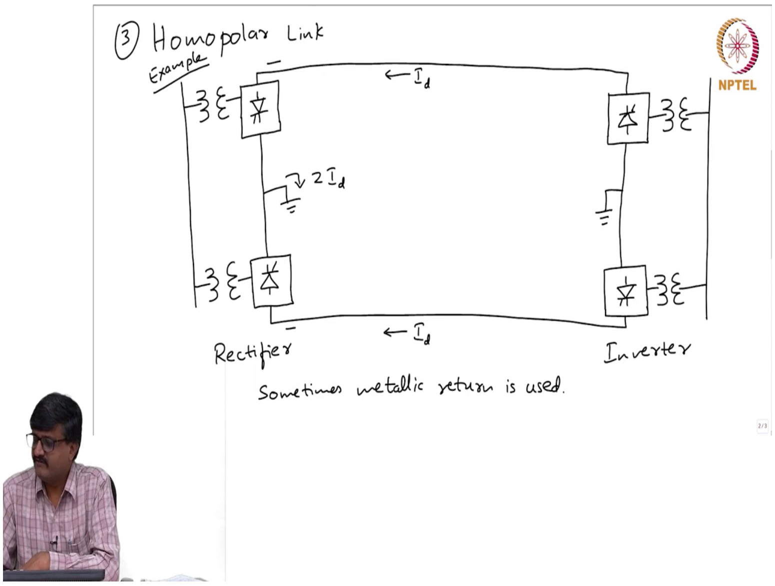

Now, this assumption is I mean I mean something which is necessary and it is not very much deviating from a reality in fact, ok. So, I mean it will help us in trying to do further analysis and its not far from reality, ok.

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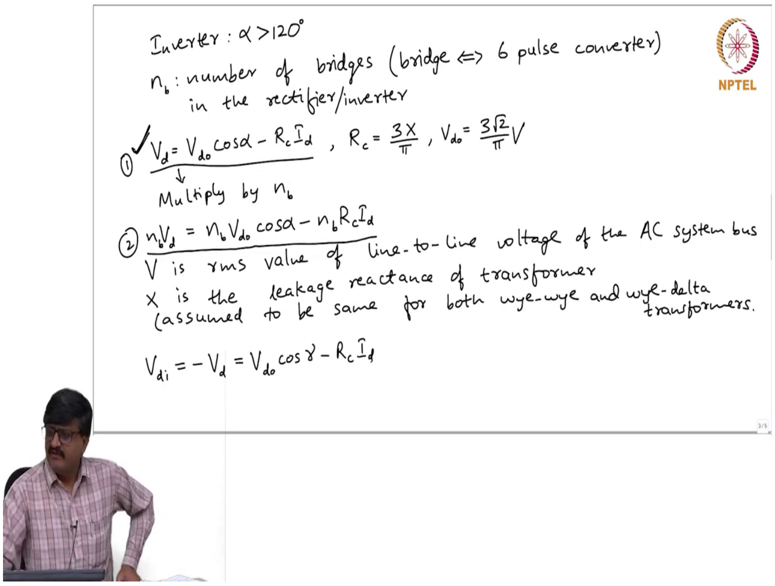

So, the assumption is this V, what I am talking about see this V in the expression for V do, there is a V in the expression for V do, ok. So, V is RMS value of line-to-line voltage. So, if I take either the one of the bridges on the rectifier side or inverter side. So, V is the RMS value, I take 1 at a time. Suppose, I am considering 1 of them. So, V is the RMS value of line-to-line voltage of the AC system bus.

And X is the leakage reactance of the transformer. Now this is something which is assumed to be same for both wye-wye and wye-delta transformer; assumed to be same for both wye-wye and wye-delta transformers. Now if I make this assumption, it means that the equation that I have written here has the same value of R c for all the bridges. Of course, V V do is same.

Please note, they are all connected to the same AC system bus, when it comes to R c which is dependent on leakage reactance. With this assumption, all these have the same value of R c.

Now multiplying by V do, what do I mean? What is the purpose? The left-hand side if I V d is multiplied by n b, the number of bridges

Student: (Refer Time: 10:23).

Now, on the DC side the connection is in.

Student: Series.

Series, is in series. So, that the average voltage that I effectively get on the DC side is some of the voltages of the individual bridges or 6 pulse LCC's. So, n b into V d gives total average voltage on the DC side. So, the that is given by n b V do cos alpha minus n b R c I d. So, what I am trying to say is this particular equation is this equation. This equation is something which is applicable for all the bridges.

So, since its applicable for all the bridges, if I just multiply the equation by n b, I get a resulting equation which is applicable for the rectifier side or inverter side. But 1 point to notice that when it comes to consider both that is, both rectifier as well as inverter, then we need to take into fact I mean, take into account that the AC side system voltages can be different on the rectifier side and inverter side, ok. So, let us see how to analyze this using this. So, our equation will be from now on this one: n b V d is equal to n b V do cos alpha minus n b R c I d.

Student: This equation is common for all bridges (Refer Time: 11:41).

This equation this equation.

Student: So, (Refer Time: 11:43).

See this equation 1 is common for all the bridges, from that I get 2.

Student: Yes, but for the 1, equation 1, alpha will keep changing right, for all the bridges.

Say if you look at the definition of alpha, you can fix alpha as the value for one of the bridges, for the other bridges it is just delayed see.

Student: (Refer Time: 12:03).

If you take 12 pulse.

Student: Yes.

6 alpha for 1 bridge say, wye-wye the one connected to wye-wye.

Student: Ok.

For the one connected to wye-delta, it is just delayed by 30 degrees.

Student: So, but when I am solving.

Student: When I will plug in that delayed value rate here for the second bridge.

Yeah, now when it comes to the second bridge even the source voltage is also shifted.

Student: Ok.

It is not just the pulses are delayed, the voltages that are applied are also shifted by 30 degrees. So, the equation is still applicable.

Student: Effect remains.

Yeah only thing is the all the things are happening is at a later instant, that is all.

Student: Yes.

So, its identical operation, but a delayed a I mean, delayed operation, ok. Now when it comes to bipolar, so, there are 2 12 pulse LCC's, now these 2 12 pulse LCC's operate identically, that means.

Student: The first.

Yeah.

Student: (Refer Time: 12:58).

If I take the 1, a bridge connected to the wye-wye in the first 12 pulse, and another bridge connected to wye-wye in the second 12 pulse.

Student: (Refer Time: 13:07).

They are identical. Only thing is the 1 connected to wye-delta will be delayed in operation that is all ok. So, when it comes to average so, please note when it comes to average, I mean its easy to actually do the analysis. Just multiply it because average if you have 2 voltages in series, and you know that the first voltage has some average value, second voltages has some average value, the resultant average is sum of the averages. That result we are using that is all. So, in instead of 2 voltages, I have n b voltages.

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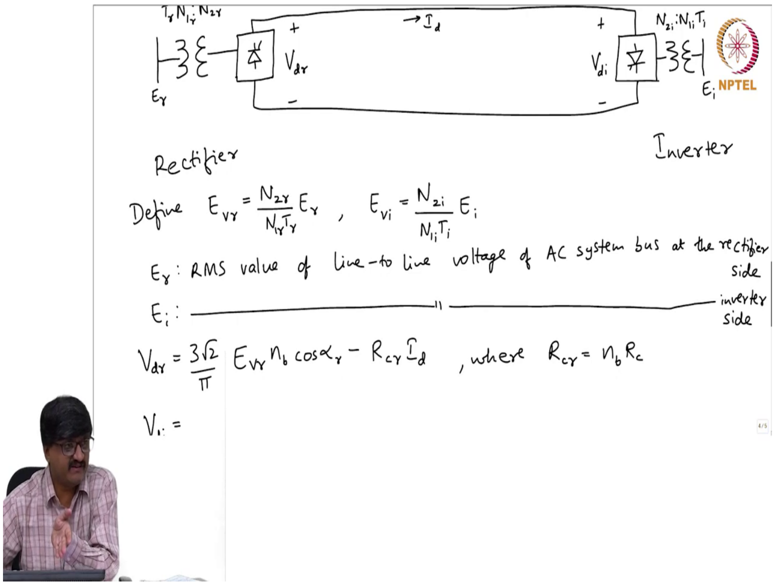

Now, if I want to show a very general arrangement which is common to any of the DC links, I use a different figure. So, I just use this general diagram, again. I again this is another schematic diagram. Suppose I show the rectifier side, so please note now I am slightly changing the meaning of this schematic diagram. This schematic diagram stands for a transformer with box with a rectifier.

Box with a thyristor actually means 1 side either rectifier or inverter it can be having 2 such things in the case of bipolar, 1 such thing in the case of monopolar or 2 or more in the case of homopolar whatever it is. So suppose, this side is say, rectifier and this is a inverter.

Now, I will give you some names for the voltage here, suppose E r is the line-to-line voltage of the AC system bus on the rectifier side, and E i is the RMS value of line-to-line voltage of the AC system bus on the inverter side. That 2 need not to be identical, they are not same buses. Then of course, the current here is I d. Suppose, I call the voltage between the 2 conductors.

So, in the case of bipolar it is 2 conductors, in the case of monopolar it is conductor and ground. In the case of homopolar, it is conduct any of the conductor and ground, ok. Suppose this voltage is say V d, I add one more subscript r to mean that it is rectifier voltage. And suppose the voltage here is V di.

So, there is a transformer on the rectifier side. Suppose, I take one of the transformers that is one of the wye-wye transformers, we know that the number of turns on 1 side is N 1 and other side it is N 2. Now, to differentiate between the transformer on the rectifier side and inverter side, I add one subscript r; r for rectifier ok.

And in addition to the number of turns which are constants, as I mentioned for the sake of controlling voltage we have tap. So, I have to include tap. Suppose the tap is on the side which is connected to the AC system bus, there is a tap. Again, t is the notation for tap and r is a tap for rectifier ok. So, on the inverter side also N 2i is to N 1i.

Student: T i.

And T i is the tap on the transformer of the inverter. Now I make some notations, define E dr as ok, and before defining E dr, let me define one more quantity E vr. E vr as N 2r by N 1r T r E r. Now what is the purpose of this definition? See, if you look at the transformer on the rectifier side, the voltage that you get on the other side of a transformer. If the one side the voltage is E r, the other side is N 2r by T r N 1r E r. Now, I will not show that as the voltage at this point, because that transformer is not an ideal transformer it is this a ideal transformer plus a leakage reactance, ok.

So, I cannot show this voltage E vr in the figure, please note that. Because I am not shown inductance, the leakage inductance also if I had shown, then I could have shown this. Now the subscript v indicates the valve-side voltage. See, one is the AC system side voltage is E r, E vr is the valve-side voltage v for valve, ok. Then we also define on the inverter side E vi as N 2i by N 1i T I E i.

So one can ok, let me write this. E r is RMS value of line-to-line voltage of AC system bus at the rectifier side. When it comes to E i, it is also the RMS value of line-to-line voltage of the AC system bus at the inverter side. Now, if I take this voltage on the at the DC side terminal of the rectifier, which is, V dr.

Now can I write an expression for V dr in terms of E dr? Or in terms of E vr I think, let me go back to this equation I have n b V d is n b V do cos alpha minus n b R c I d. Now what is n b V d? Its the total.

Student: (Refer Time: 20:35).

Total DC side voltage now.

Student: V dr.

So, it is nothing, but V dr, its nothing but V dr. So, in in place of V do what do I have? What do I have?

Student: (Refer Time: 20:49).

See I take this equation n b V d is equation number 2, n b V d is equal to n b V do cos alpha first term. Let me take one term at a time n b V d is vdr that I have already written, ok. Now if I take the right-hand side, first term is n b V do cos alpha. Of course, let me write cos alpha first that is one of the factors in the first term. Now again, to differentiate between the alpha of the rectifier and inverter I add a subscript r alpha r. Now the remaining factors n b V do. What is n b V do? Using the notations.

Student: (Refer Time: 21:30).

Student: Root 3 E r.

Sorry.

Student: Root 3 E r.

Root 3 is it just.

Student: We will use root 3 E r V d (Refer Time: 21:40).

E r E r or E vr?

Student: E vr.

E vr.

Student: E vr (Refer Time: 21:46).

See that.

Student: E vr.

Transformation you have to take the transformation also into account. See in if you look at the AC side representation, when we did earlier, we what we get as so, voltage source on the AC side is the transformed voltage. So, the transformation also has to be taken into account. So, it is the transform voltage is not E r, it is E vr.

Student: But we take voltage which is behind the inductance right.

Yeah that is that is a E vr.

Student: E vr is after the (Refer Time: 22:19).

Ok.

Student: Transformation (Refer Time: 22:21).

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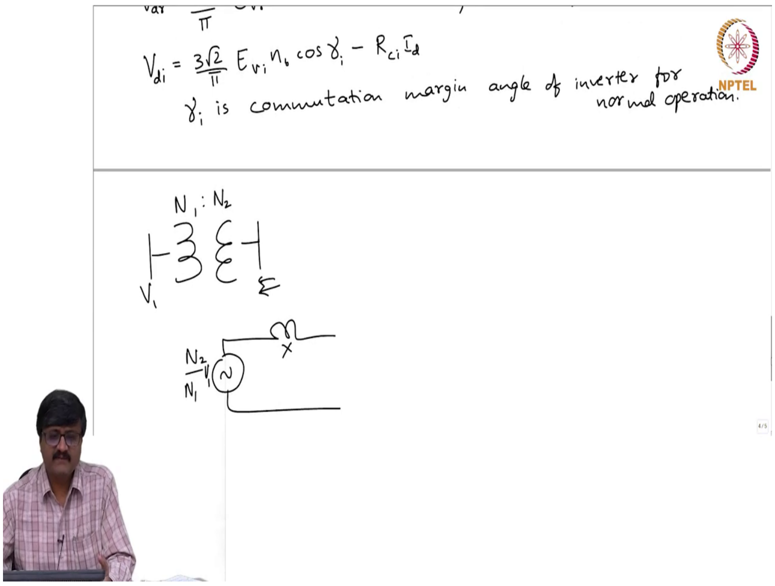

See, if I have, let suppose I have a transformer, ok. Suppose, this is a I mean N 2 by N 1 or whatever ok, N 1 by N 2. So, this is the representation. Suppose, this is V 1 ok, now this representation when you look from this side is a voltage source in series with the reactants like this.

Student: Yes.

Which is N 2 by N 1 V 1 under a reactance. See, we are looking at the transformer from this side from this side.

Student: Ok.

So, when you see from the converter side it is the transformed voltage that you see.

Student: Ok.

Please note, we are trying to see from the converter side. So, the. So, what we need to do is write it in terms of E vr not E r ok. what is the expression?

Student: 3 (Refer Time: 23:36).

In terms of.

Student: root 3 (Refer Time: 23:38).

3 root 2 by pi.

Student: Into root 3 E vr.

Into root 3 why root 3?

Student: Because line- to-line.

No, no, no all this are line-to-line voltages only.

Student: All these are line (Refer Time: 23:49) E vr.

E vr into.

Student: n b.

Into.

Student: n b.

N b into nb, ok. So, that is a first term on the right-hand side. Now what is there on the right-hand side as a second term? Minus n b R c I d. If you look at equation 2, there is n b R c I d. So, I will write this as minus R cr I d where, I just introduced a notation R cr which stands for n b into R c that is all. Instead of writing n b R c, I am writing R cr,. Now, this is as far as the rectifier is concerned.

Now, if I want inverter V di. So, if you look at this circuit, the inverter side DC voltage is V di. Now please note V di is not equal to V dr because the transmission line can have a resistance and hence a drop across this resistance, ok. Now before coming to this special case, I mean if you go back to the analysis of 6 pulse converter, we had defined 1 quantity called V di.

If you recall just go back to the recall what we did for 6 pulse LCC, we defined a quantity called V di which is nothing but.

Student: Minus.

Minus V d.

Student: Minus V d.

And we also derived a relationship between V d I d R c and gamma. So, if you can recall this is equal to V do cos gamma minus R c I d you recall. Now, when it comes to inverter V d is negative, V di is positive. Now what I have shown here is not the usual V d, V di in this figure. In this figure is not the usual V d, it is negative of V d when it comes to inverter. So, V di is negative of the usual DC voltage that we considered for the 6 pulse LCC.

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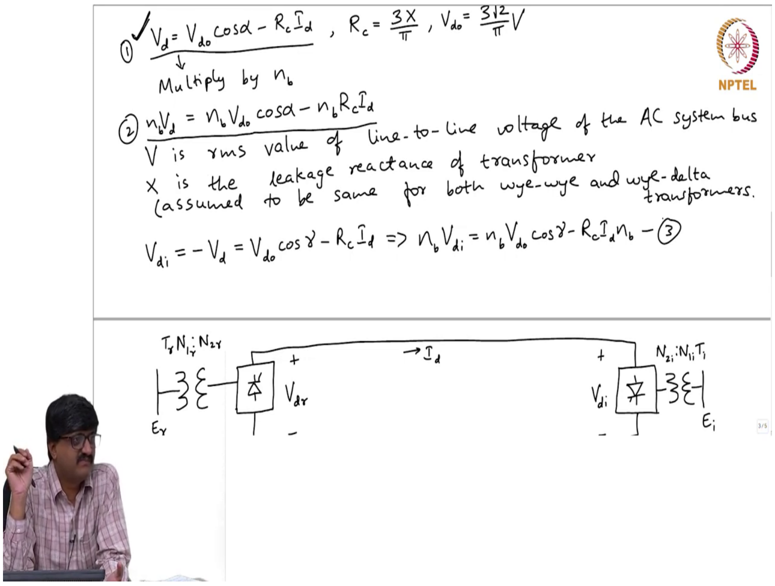

Now, if I do similar manipulations. Again, multiply this by n b. So, from this I get n b V di is equal to n b V do cos gamma minus R c I d into n b. Now equation 2 and 3 are slightly different. 2 is in terms of alpha, 3 is in terms of gamma ok. So, we will see why gamma is used for inverter, alpha is used for rectifier shortly. But before that, can we write an I mean from this equation 3, can we come back to this figure and get a similar equation as we did for rectifier? So, what is V di? Similar to the just the previous equation, it is 3 root 2 by pi into.

Student: (Refer Time: 27:36).

Sorry.

Student: It should be minus 3 (Refer Time: 27:45).

Yeah, go back to this equation number 3. Is there any minus there? I want to write it in terms of gamma, in terms of gamma. So, we will see why we write it in terms of gamma is something which will be obvious shortly. So, if we write it in terms of gamma it is 3 root 2 by pi E.

Student: (Refer Time: 28:07).

Vi n b cos gamma. Now again, to differentiate between the gamma of rectifier and gamma of inverter, I use a notation gamma I minus should I differentiate between say, R cr is the resistance corresponding to rectifier. Now I use a notation R ci for inverter is that? Are the 2 inductances are reactances different?

Student: (Refer Time: 28:43).

Student: Same.

Same.

Student: Depends on transformer.

Depends on.

Student: Transformer.

Transformers are identical.

Student: (Refer Time: 28:51).

Then same yeah, now they are same provided the taps are same. Please note the taps in general are not same. See, the inductance effective inductance that comes into picture depends on tap. Yeah, I mean these are tap changing transformers the depending on the position of the tap, we have the value of the inductance, ok. This is something which you would have studied in a power system course or in an advanced power system course not in an undergraduate course, ok.

So, then I mean, I will not try to cover that in the in this course ok. So, the point to note is the leakage inductance is dependent on tap that is the point. So, here I have written in terms of gamma, why? Any, what is the significance of gamma for inverter?

Student: That commutation margin angle.

Yeah. See commutation margin angle is a very important thing when it comes to inverter. And for normal operation when our alpha is greater than 120 degrees for inverter, gamma I is commutation margin angle of inverter for normal operation. So, normal operation means alpha greater than 120 degrees.

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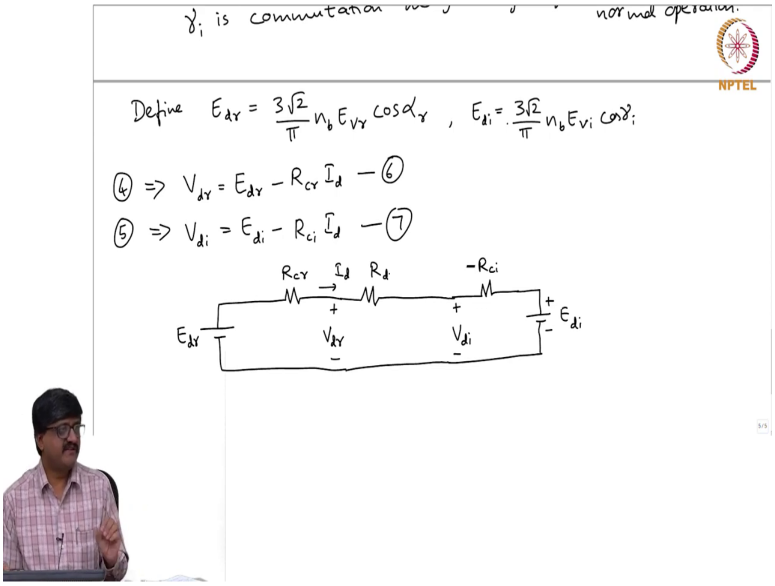

Now, I will use a few more notations, define E dr I already defined E r E vr. Now I am defining E dr as 3 root 2 by pi n b E vr into cos alpha r. And I also define E di as 3 root 2 by pi n b E vi cos gamma i.

So, if I just look at the 2 equations, let me call this as equation number 4 and equation number 5. So, if you look at equations 4 and 5, 4 can be written as V dr is equal to the first term on the right-hand side is just now you have a definition E dr. So, V dr is E dr minus R cr I d and equation 5 becomes with the new definition that I have for E di, it is V di equal to E di minus R ci I d.

Now it appears as if I can draw some equivalent circuit corresponding to these 2 equations. So, if I call these equations as 6 and 7. So, if I take equation 6 I can have a circuit equivalent for this equation 6. So, the circuit equivalent is like this, a voltage source in series with a resistance. So, the resistance is R cr, the voltage source is E dr and the current that is flowing is I d. And what I have as voltage at these 2 terminals is V dr.

Then similarly, on the inverter side I have an equation 7, I can draw an equivalent circuit for this equation 7.

The voltage source is E di minus R ci. The resistance and our current is same, I d. The voltage at these 2 terminals is V di. Now between these 2 terminals are these 2 ports where the voltage is V dr and V di. What is there? What is there?

Student: (Refer Time: 34:02).

So, no what is there? In see if you go back to the circuit, V dr is the voltage of the DC side.

Student: Transmission line.

No, it is a transmission line, ok. So in general, there can be a link. If there is no transmission line if it is just a back-to-back converter. See, if there is no transmission line, if the converter both the converter rectify inverter or the same location, we call it as back-to-back converters. There is no transmission line, ok. So whether there is transmission line or not, we can represent the equipment between these 2 by a resistance. If there is no transmission line and this resistance is 0 that is all.

So, I will use a notation for these transits for this resistance R d, ok. So, this is the equivalent circuit. So, this is the equivalent circuit corresponding to equation 6 and 7 after taking into account that if there is a transmission line between the rectifier inverter it is a represented by just a resistance.

So, I will stop here.