Power System Analysis
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Lecture - 4
Inductance Calculation

Welcome to lesson 4 on Power System Analysis. Before we start this lesson 4, first I would like to take up the questions that we asked in lessons 3.

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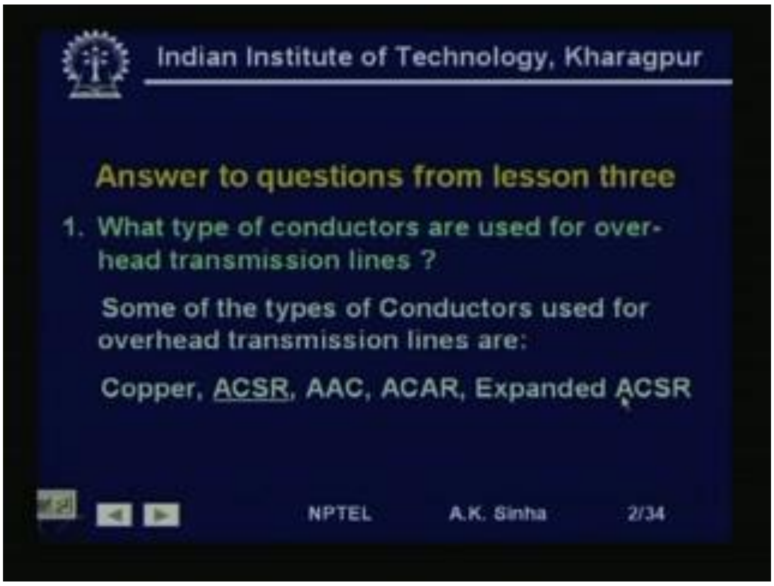

First question was, what are the types of conductors used for over head transmission line? Well, some of the types of conductors used for over head transmission lines are copper conductors, which is very rarely use nowadays. ACSR, that is Aluminum Conductors Steel Reinforced conductors. Then, all aluminum conductors are ACAR conductors or expanded ACSR conductors, which are used.

As I have already said in lesson 3. Sometimes, we want to increase the effective radius of the conductor. And for that, we used expanded ACSR conductor in ESB transmission lines.

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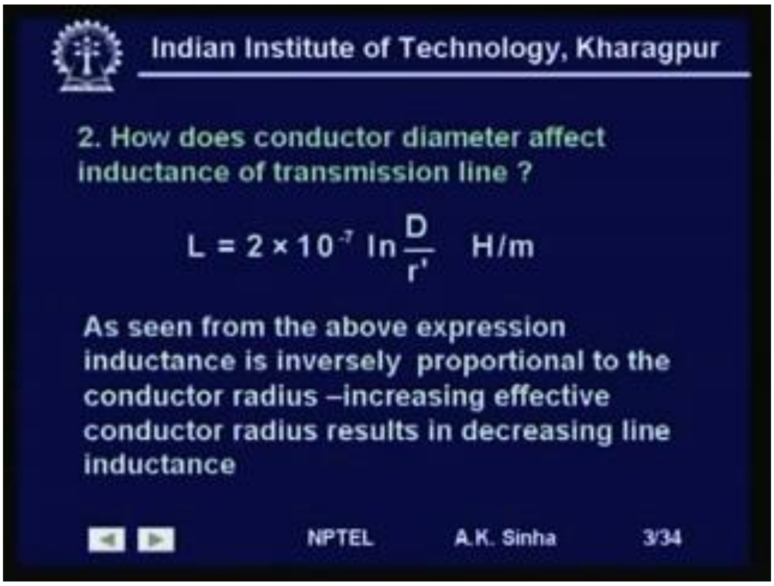

Next question was, how does conductor diameter affect inductance of a transmission line? Well, if you remember the equation for inductance, which was L, is equal to 2 into 10 to power minus 7 log n D by r dash Henry's per meter. Now, from this expression it is very clear. That inductance is inversely proportional to r dash or the effective radius of the conductor. So, increasing effective conductor radius will result in decreasing line inductance. And that is why, as I said earlier, sometime, we use expanded ACSR conductors for transmission lines, specially in extra high voltage transmission lines.

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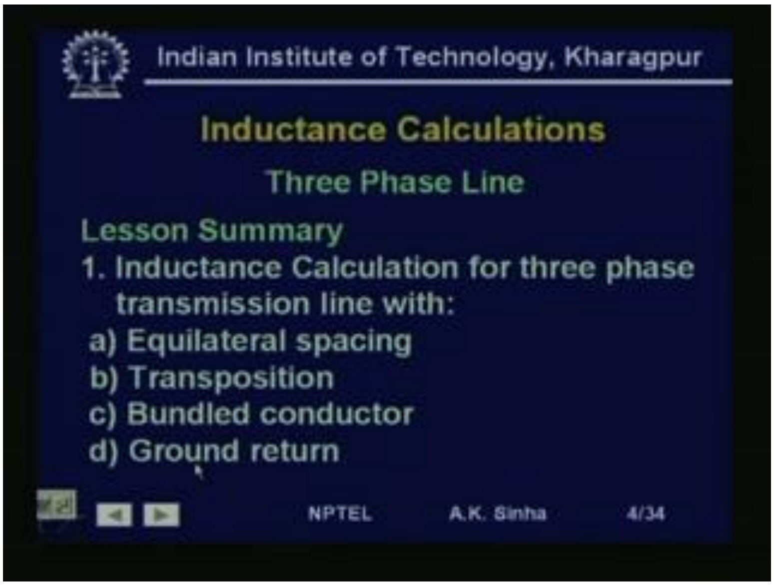

Now, we will start our lesson 4, which will be on inductance calculations for three phase transmission lines. Well, in this lesson, we will discuss inductance calculation for three phase transmission lines with equilateral spacing, then with transposition. Again, with, when we are using bundled conductor lines and finally, lines with ground return. Well, first, we will take the calculation of inductance for a 3 phase line with equilateral spacing or equal spacing.

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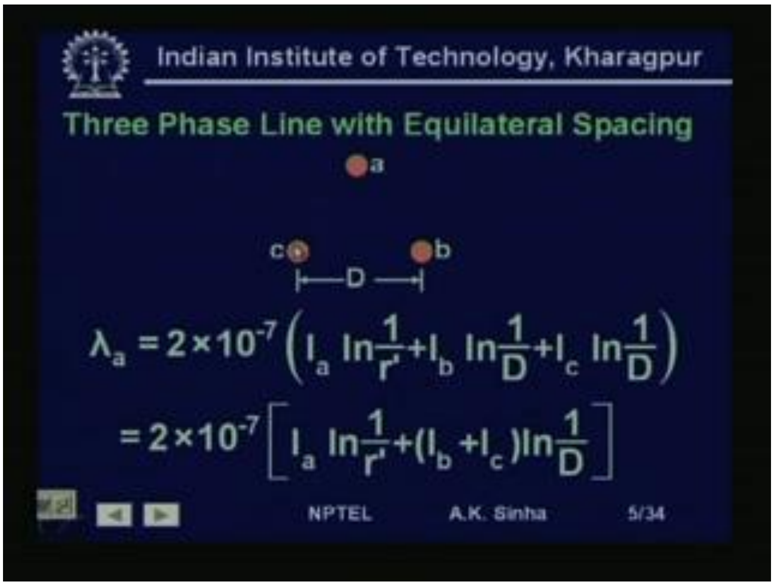

Now, here in this diagram, you can see a, b, c are the three conductors, which are placed at the vertices of an equilateral triangle. That is the distance, among all three conductors are same. That is distance D. Now, if we calculate the flux linkage of conductor a, due to currents flowing in conductor a, b and c. Then, it will be equal to 2 into 10 to power minus 7 into I a log n 1 by r dash, where r dash is the effective radius of conductor a.

As we have seen, the effective radius of conductor a, is generally lower. It is about 0.7788 times the radius of the conductor, plus I b into log n 1 by D. That is the distance of conductor b from conductor a plus I c, the current flowing in conductor c into log n 1 by D, again the distance between conductor c and conductor a. This is equal to 2 into 10 to power minus 7, I a log n 1 by r dash plus I b plus I c log n 1 by D. That is, we have combined these two terms, we have got this.

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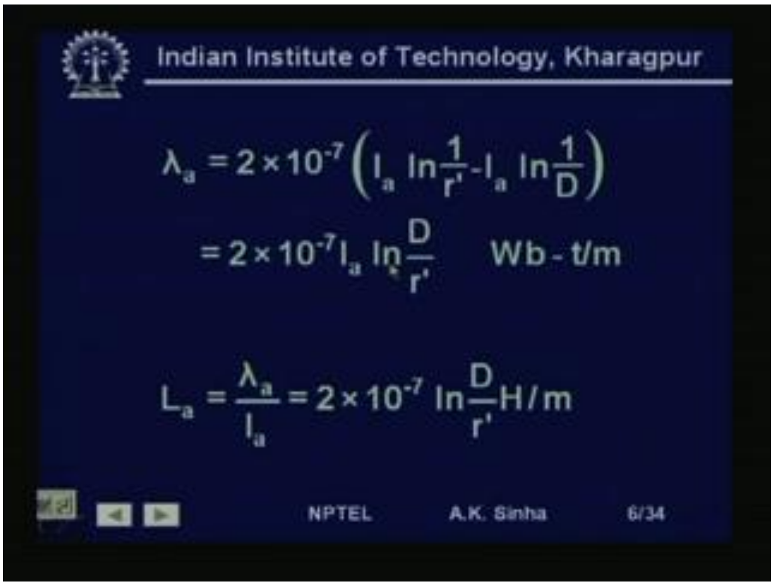

Now, we know that, for a 3 phase three conductor line I a plus I b plus I c is equal to 0. Therefore, I b plus I c is equal to minus I a. Therefore, we can write lambda a is equal to 2 into 10 to the power minus 7, I a log n 1 by r dash minus I a log n 1 by D, which results into 2 into 10 to power minus 7, I a log n D by r dash Weber turn per meter.

Now, once we have got the flux linkage. We can calculate the inductance very easily, L a inductance of conductor a is equal to lambda a by I a, which comes out to be 2 into 10 to power minus 7 log n D by r dash Henry's per meter. Since, all the three conductors are equally space. Therefore, inductance of phase b and phase c conductors will also be same.

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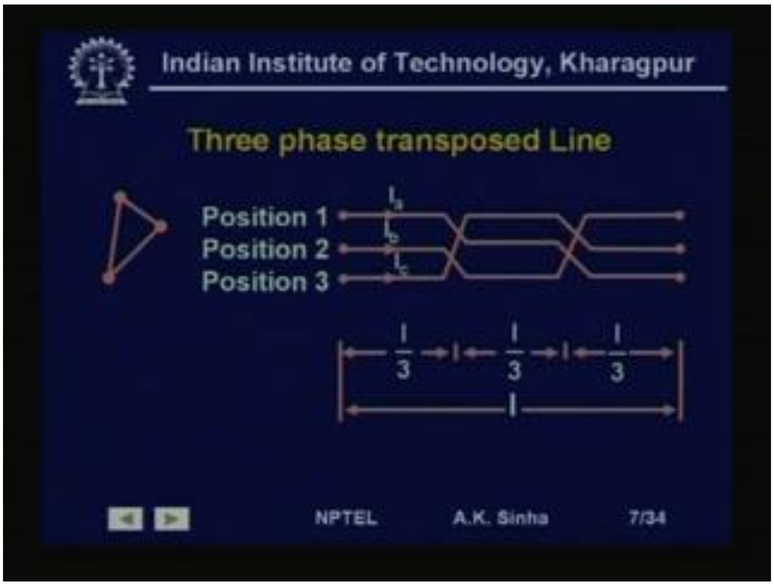

Now, we take the inductance calculation for a 3 phase transpose line. As we have said earlier, because of physical limitations, it is not always possible to have an equilateral configuration for the conductors. So, by transposition, what we do is, we try to make the flux linkage of all the three phase conductance's more or less same. Now, what we do here is, if we have transmission line, say from this point to this point is three phase line.

What we do is, we change the position of the three phase conductance over one-third of length of the line. Like, if we see here for first one-third length of the line. The position of conductor of phase a is in position 1, phase b is in position 2, phase c is in position 3. Now, for the next one-third length, what we do is, the phase a conductor goes to position 2, phase b conductor goes to position 3 and phase c conductor goes to position 1.

And similarly, for the next one-third length of the line, that is the last one-third length of the line. The phase a conductor, now moves to position 3, phase b conductor moves to position 1 and phase c conductor move to position 2. In this way, the each phase conductor has gone through all the three positions for one-third length of the line.

And therefore, the total flux linkage for each of the phase conductors will be almost same. And this, because of this, the inductance will also be on the average being same for the three phase conductors. This makes the transmission line more balanced.

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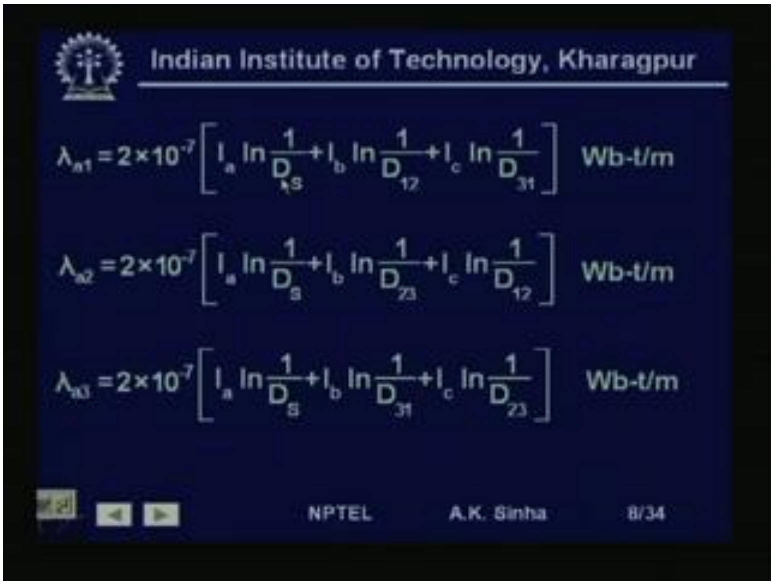

So, now, let us find out the flux linkage of phase a conductor in first one-third position of the conductor. This is, we write as lambda a 1, this is equal to 2 into 10 to power minus 7 into I a log n 1 by D s. Here, I am writing instead of r dash, because sometimes, we use, instead of one conductor more conductors. So, we are taking about the self distance, which is r dash for a single solid conductor line.

So, it I a log n 1 by D s plus I b log n 1 by D 12, because in this first one-third position current I b is following in the conductor 2. And here, we have the distance D 12. Similarly, this plus I c log n 1 by D 31, which is again I c is flowing in this conductor and the distance between them is D 31. Similarly, for the phase a conductor in the second one-third length of the line will be 2 into 10 to the power minus 7 into I a log n 1 by D s. That is it is own distance plus I b log n 1 by D 23.

If we see here, in this I b's, now in this position I a's is in this position the distance between this two is D 23 plus I c log n D 12. Again, if we see I c is flowing in this and I a is flowing in this. So, distance between them is D 12. Similarly, for the last one-third position portion of the line, we have a flux linkage with phase conductor equal to 2 into 10 to power minus 7 into I a 1 by D s plus I b log n by D 31. Because, now I b is occupying position 1 and I a is occupying position 3 plus I c log n 1 by D 23. As we see here, I c now is occupying this position and I a is occupying this position, this is D 23.

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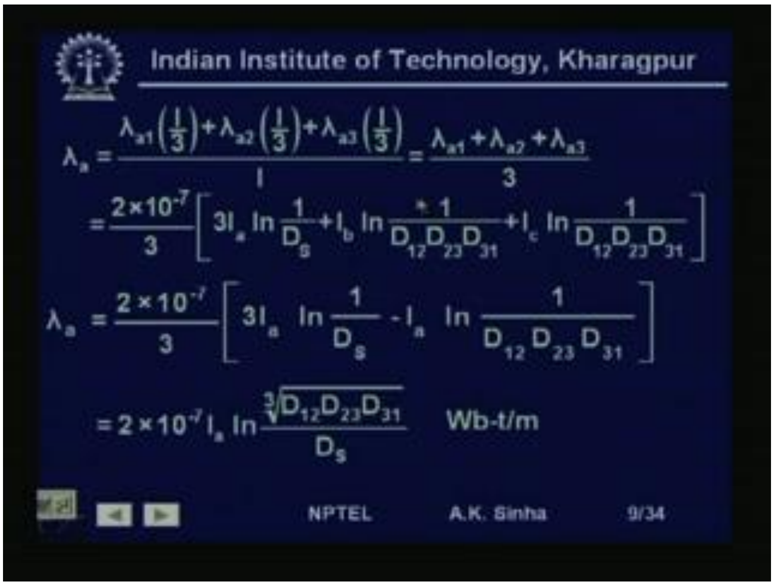

Now, the total flux linkage of the conductor over the whole length, can be given by sum of these multiplied by their lengths. And if you want to take average per meter length, the flux linkage will be lambda a 1 into l by 3 plus lambda a 2 into l by 3 plus lambda a 3 into l by 3 divide by l. Or the average flux linkage of phase a conductor, which occupies all the three position is going to be the average of lambda a 1 plus a 2 plus lambda a 3, divided by 3. That is the average of the lambda in all the three positions.

This, when we substitute the values of lambda a 1 lambda a 2 and lambda a 3, comes out to be 2 into 10 to power minus 7, divided by 3 into 3. I a log n 1 by D s plus I b log 1 by D 12 into D 23 into D 31 plus I c log n 1 by D 12 into D 23 into D 31, which will finally, turn out to be, because we can now combine these two terms I b and I c terms. Because, the denominator, the two terms log n terms are same. Therefore, this we can write as lambda a is equal to 2 into 10 power minus 7 divided by 3 into 3 I a log n 1 by D s.

Now, I b plus I c is equal to minus I a. So, we can write this as minus I a log n 1 by D 12 plus D 23 plus D 31. Now, we can combine these two terms and then we will get 2 into 10 to power minus 7, I a log n cube root of D 12 into D 23 into D 31, divided by D s, Weber turn per meter. So, the average flux linkage per meter, for a conductor a, comes out to be this much. And as we have seen, since all the three phase conductors, occupy all the three phases. So, the average flux linkage is for phase b and phase c conductors will also be same.

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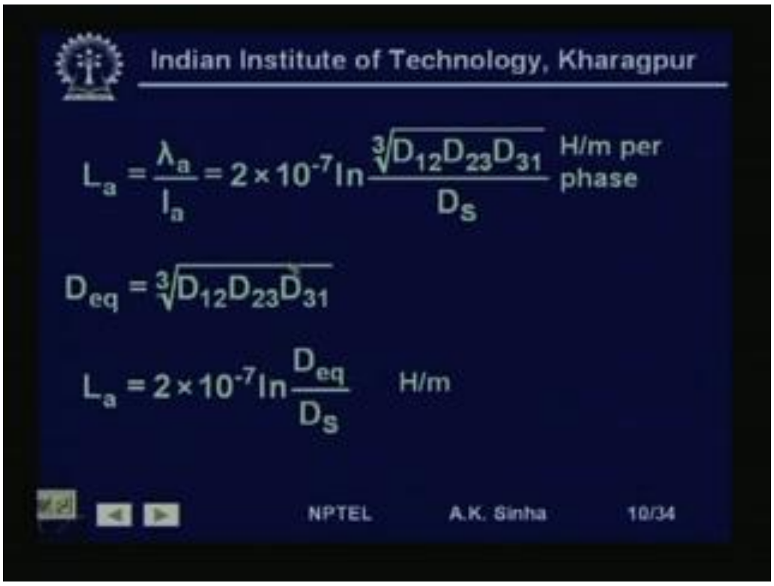

Now, once, we have got the flux linkage, average flux linkage, we can get the inductance, average inductances per meter. Length of the line as lambda a by I a, which turns out to be 2 into 10 to power minus 7, log n cube root of D 12 into D 23 into D 31 divided by D s. Where, this term cube root of D 12 into D 23 into D 31 is called the equivalent distance of the three phase system.

That is the equivalent distance between the three conductances; this is also seen as the GMD of the three phase conductances. Therefore, L a is equal to or the inductance of phase a is equal to 2 into 10 power minus log n D e q by D s, where D e q is the GMD of the 3. Now, as we have said earlier, that in order to reduce the inductances of the transmission system. We can do this by increasing the resistance, increasing the radius of the conductor. That is the effective radius of the conductor, should be increased. And this is can be d1 by means of bundle conductances. In fact, bundle conductances are used for two purposes.

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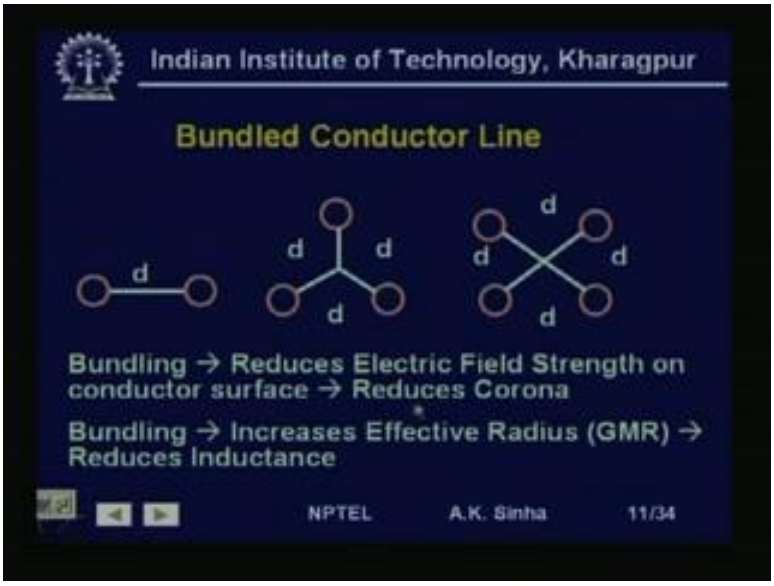

One is it reduces the electric field strength on conductor surface. And therefore, it reduces corona loses and radio interference and audible corona loses all the aspects which is associated with corona get reduced. Now, how does this happen. Now, if you see, if we use the conductor with the radius r, then it is volume will be phi r square. Now, if we take two conductors with the same, sorry, it is surface area is phi r square.

If we take the two conductors with the same cross sectional area, then it is radius is not going to be r by 2, it is radius is going to be r by root 2. Now, if we have this, then the surface area of one meter length of the conductor. In case, we are using two conductors instead of 1, will be now, phi into r by root 2 multiplied by 2. So, it will be root into r, whereas in the other case, it will be phi r only.

So, here, what we see the surface area of the conductor increases considerably and because of this the electric stress reduces. Another effect, that we get, when we bundle the conductors is that, it increases the effective radius or the GMR of the self distance of the conductor considerably. And this reduces the inductance and this is one of the reasons, why we use this bundle conductors.

These bundled conductors are used by having more than 1 conductor, which are supported by a conducting frame at regular intervals, along the transmission line. Here, you see a bundle conductor with two conductors here. This is a bundle conductor with three conductors and bundle conductor with four conductors. In fact, for very high voltage line, sometimes we use more than four conductors also.

In India, normally we are using two conductors or four conductors for 400 kV line. And two conductors sometimes are used for 220 kV line.

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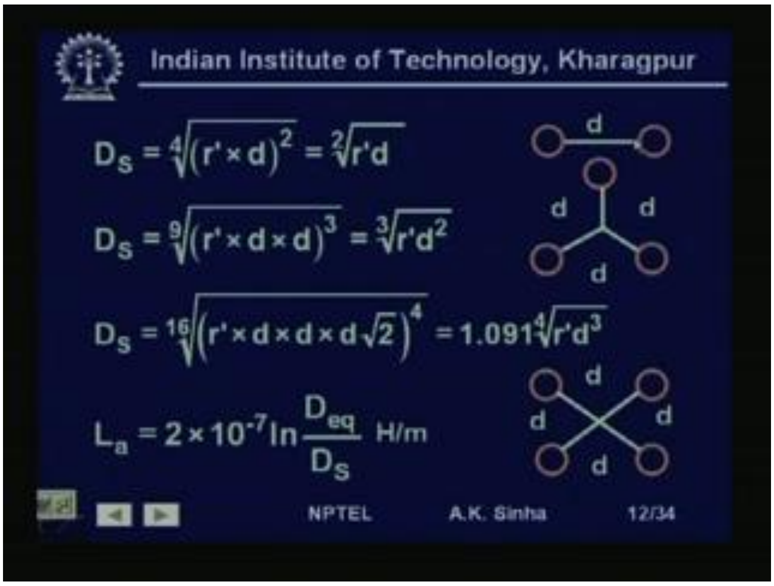

Now, if you look at the effective radius of the conductor. When, we are using two conductors, which are placed at a distance d, normally this distance d is approximately 10 times the diameter of the conductor. So, here, if we look at this two conductor consideration a bundle with two conductors, then D s will be equal to, we are taking all the distances. The distance, it is own distance from itself will be r dash.

Then, it is distance from this conductor will be d, then distance of this conductance with itself will be r dash and distance of this conductor with this will be d. So, there are four distances involved and it will be 4th root of r dash into d whole square. That is r dash square into d square, which is equal to square root of r dash d, which is certainly much higher than r dash, because d is much larger than r dash.

Same thing, for three conductors we can get, line distances. That is, three distances for each conductor, one is self distance and two for the other two conductors and same thing, for each one of the three conductors. Therefore, we get self distance D s as 9th root of r dash into d into d whole cube. This is equal to cube root of r dash into d square. Similarly, when we are using four conductors, we are got 16 distances, one for itself and three more for the other three conductors distance, from this conductor to other three conductors.

Therefore, we get the self distance D s is equal 16th root of r dash into d into d into d root 2. This is the distance between this conductor and this conductor. Same thing will happen for this and this conductor and so on. So, in 2 to the power to 4, which is comes out to be 1.091 into 4th root of r dash d cube. And as we have seen, earlier an inductance, we can get for these bundle conductances as l is equal to 2 into 10 to the power minus 7, log n D e q by D s.

Where, D s, is what, is the GMR for the bundle conductance. Since, this has increase considerable as compared to single solid conductor, having the cross sectional area. Therefore, the inductance, get reduced considerably.

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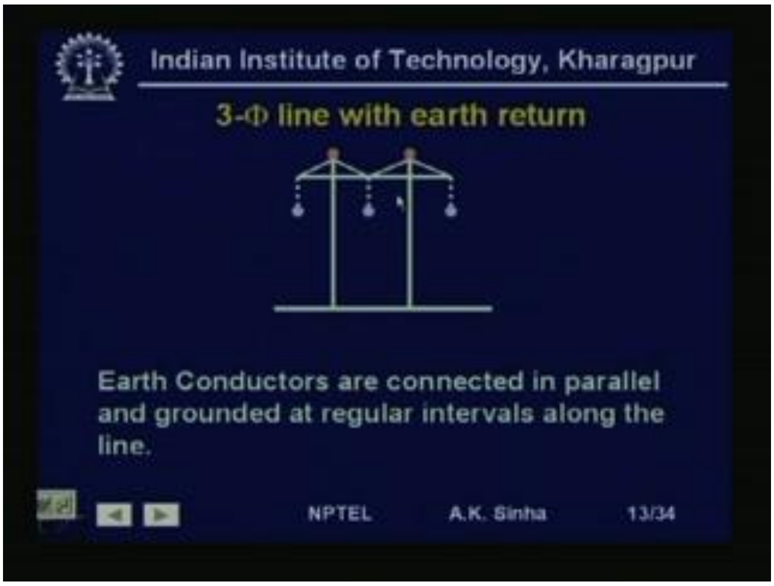

Now, we will take up three phase line with earth return. Now, this is a normal situation. Those three conductors may be horizontally placed and we have at the top of the transmission tower earth wires or the ground wires. These ground wires as I have said earlier in lessons 2. That these ground wires are used to protect the phase conductors from direct lightening stroke.

Now, these ground conductors are normally conducted or connected to the tower and at each tower footing, they are grounded. So, earth conductors are connected in parallel and grounded at regular intervals along the transmission line. If they are not grounded at each tower, may be, they will be grounded at every alternate tower or so. So, how do, we find out the inductances for such a system?

Normally, when the system is working as a balance system, they would not be any return current flowing. Because, the sum of the three currents will be 0 all the time, but in case of unbalance current flowing in the system. We have some currents flowing through these return conductors, which will again go to the ground and will flow through the earth.

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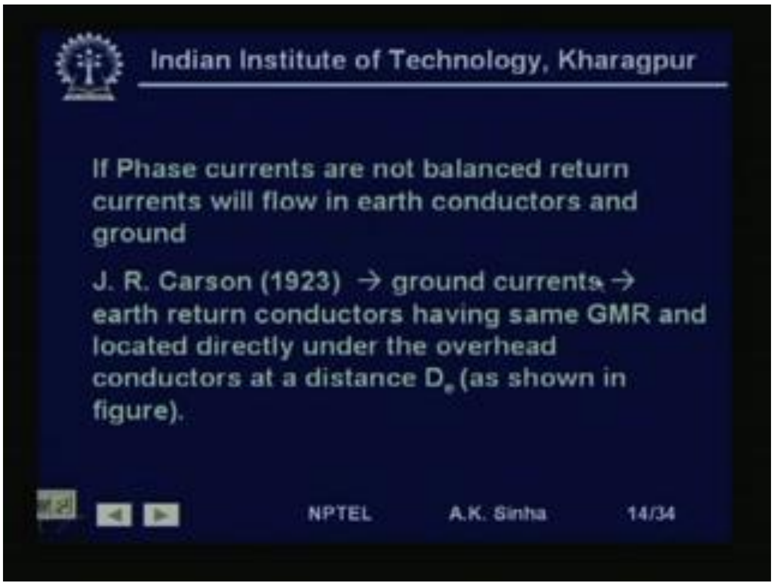

So, if phase currents are not balanced, return currents will flow in earth conductors and ground. Because, since these earth conductors are connected to the tower and again, there are grounded by the footing, ground tower footing. So, the current flowing in these earth conductors will go into the ground. And will this disperse and flow in the ground also.

Now, it was J.R. Carson in 1923, who effectively or who proposed, how to take care of these ground currents in the system, in the transmission system. So, which was later modified, he was the first person to model this ground currents into a system. What he did was, he said that, earth return conductors are basically or the earth current can be basically, represented by earth return conductors, which are having the same GMR as the overhead conductors.

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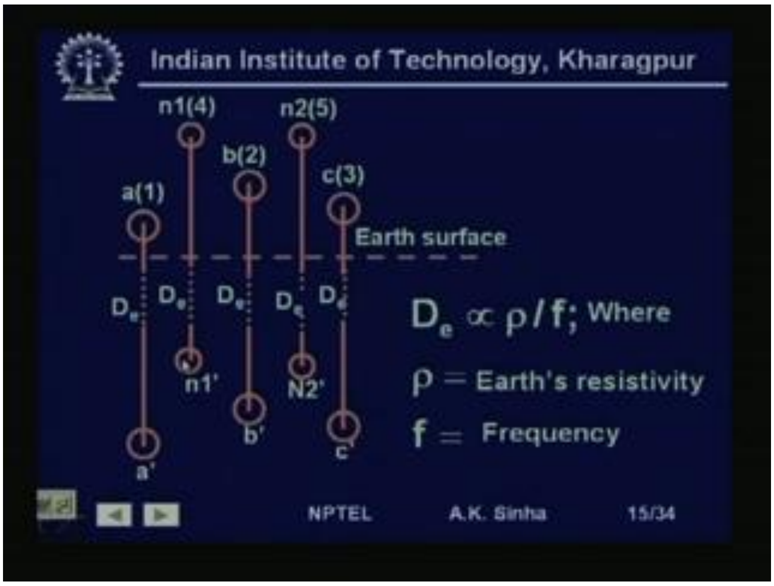

And are located directly below the overhead conductors, at a distance D e, as shown in this figure, that is here we have three phase conductors a, b and c. And we have two earth conductors are the ground conductors, which are n 1 and n 2. Now, what we he proposed as for such a system. He said that, the ground current flowing can be represented by conductors a dash, which is directly below a into the ground at a distance D, from that conductor.

Same thing for n 1, we have a conductor n 1 dash, which is in the ground or which is directly below this in the ground at a distance D and so on. Where, he said D e, the distance at which these conductors are from the overhead conductors is proportional to rho, the earth resistivity. And inversely proportional to frequency of the system or the frequency of the current, which is flowing in these conductors.

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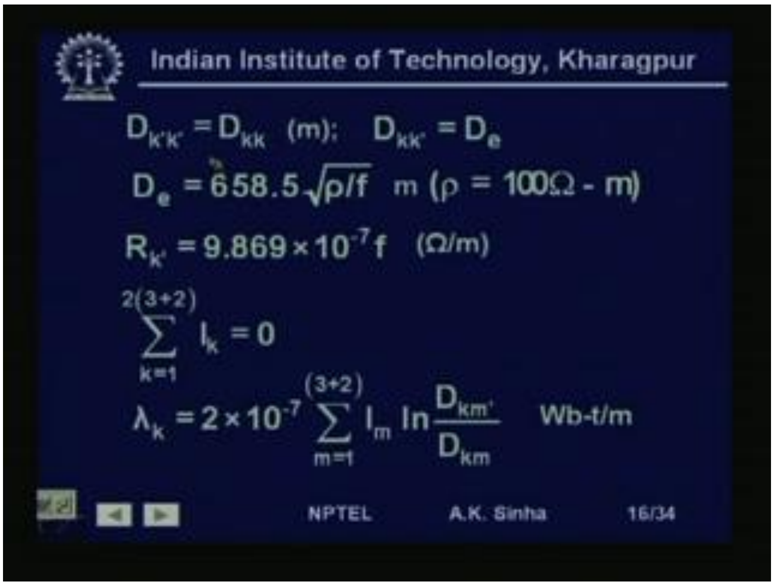

So, now we can see that, D for any conductor k, we have the ground conductor D k k dash. The distance of it is own, that is same as D k k, which is the GMR of that conductor. And the distance D k to k dash for any conductor k to k dash is D e. And the D k k dash, which is the distance of this conductor to itself is same, as the GMR of this conductor. And he said that, D e is equal to 658.5 into square root of rho by f.

Now, this is an empirical formula, which was found after lots of experimentation. Where, rho is as resistivity and if one does not know the earth resistivity properly. Then, one can always choose 100 ohm meter as the earth resistivity, which is the resistivity for that earth. He also found out, that the resistance of these image conductors are the conductors, which are representing the ground current is given by R k dash is equal to 9.869 into 10 to power minus 7 f, where f is the frequency per ohms per meter.

So, these D e and R k dash are empirical values and these have been found out after lots of experimentation. Now, for this system, that we have, we have five conductors here and five conductors as images, below these conductors at a distance D e, from the overhead conductors. Now, this makes a total of 10 conductors. Now, some of the currents in all the 10 conductors will have to be equal to 0.

So, in this system, sum of the current I k is equal to 0, for k is equal to 1 to 2 times into three phase conductors plus 2 neutral conductors. That is sum of all the 10 conductor currents is equal to 0. Now, for such a system, we can find out the flux linkage, for any conductor very easily. And lambda k, in this case is given by 2 into 10 power minus 7 sigma m is equal to 1, 2, 3 plus 2. That is three phase conductors plus 2 ground conductors, I m log n D km dash.

That is distance from the conductor to the conductors, which are the image conductors divided by D k m, the distance between 2 overhead conductors. And these include ground conductor as we are seeing. So, lambda k is 2 into 10 to power minus 7, sigma m is equal to 1 to 5, I m log n D k m dash by D k m Weber turn per meter.

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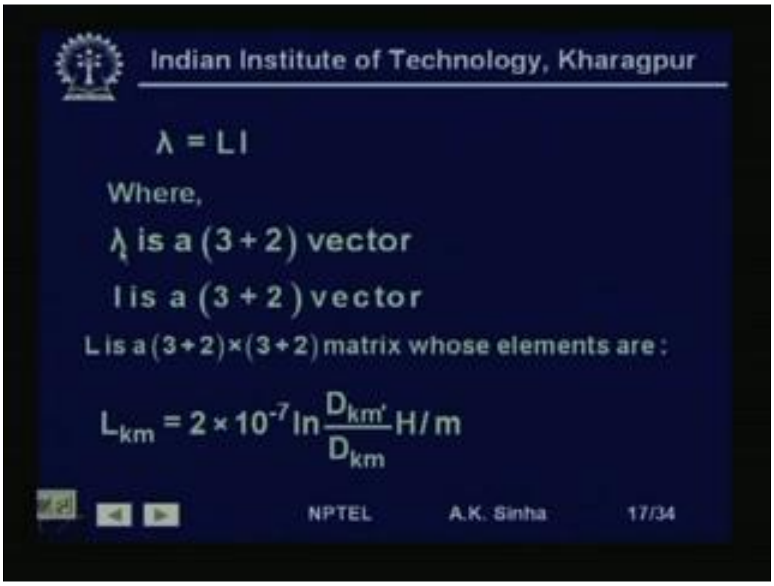

Since, lambda is equal to L I, where L is the inductance and I is the current. Now, in this case, since there are five conductors, we have lambda for all the five conductors. That is lambda a, lambda b, lambda c and lambda n 1 lambda n 2. So, lambda is a 3 plus 2 vector, I again, since the current is following in all these five conductors. So, I is a 3 plus 2 vector.

Now, L which is the inductance matrix is also a 3 plus 2 into 3 plus 2 matrix. Whose elements L k m is equal to 2 into 10 to power minus 7 log n D k m dash by D k m. This comes out from the previous relation of lambda k. So, lambda k, we know. So, if we sum this up and then we find out the inductance, sorry, the conductors, then L k m will come out to be this much.

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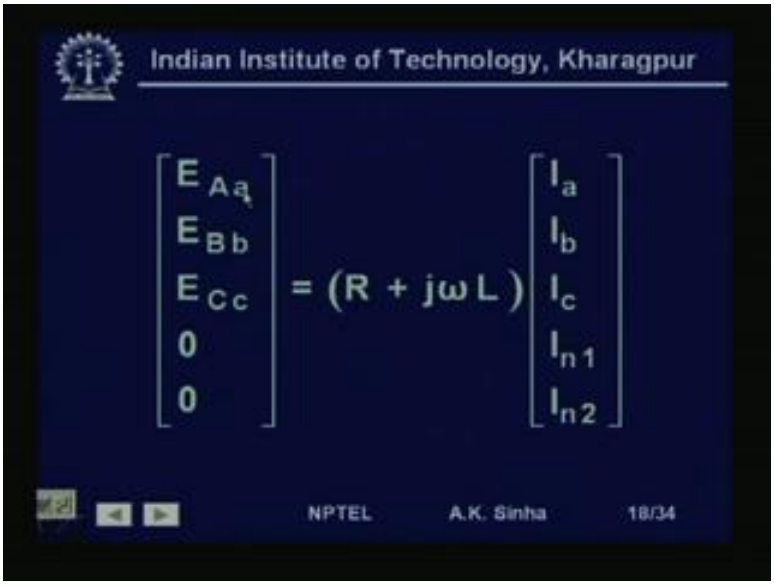

And therefore, we can write this as matrix equation, where we are saying E A a is the voltage drop in phase A conductor. E B b is the voltage drop in phase B conductor. E C c is voltage in phase C conductor. For the neutral conductors is there are grounded, there potential is 0.

So, voltage drops are going to be 0, for the two ground conductors, this is equal to R plus j Omega L, which will be again a 5 by 5 matrix into I a current in phase a. I b current in phase b. I c current in phase c, I n 1 current in neutral 1 and I n 2 current in neutral 2 or ground 2.

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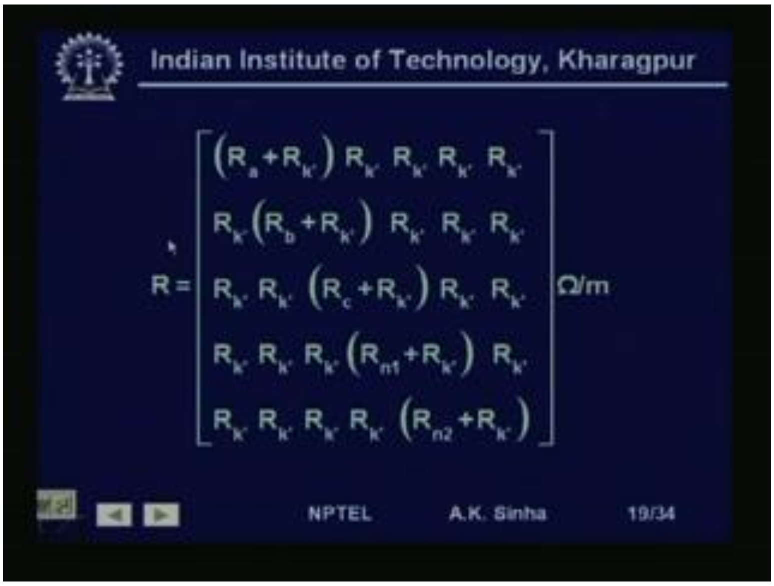

Here, the matrix R is a 5 by 5 matrix and this is represented by for R A a, what we have is, R a plus R k dash. That is this is for R a, the resistances for conductor A. Now, R k dash is the resistances for the image conductor, which is below A. Then, we have R k dash for the other 4. Similarly, for R will be R 12 will be R k dash R 2 with 2 will be R b plus R k dash R 23 will R k dash and so on. So, this is a 5 by 5 matrix, which is a resistance in ohms per meter for this five conductor system.

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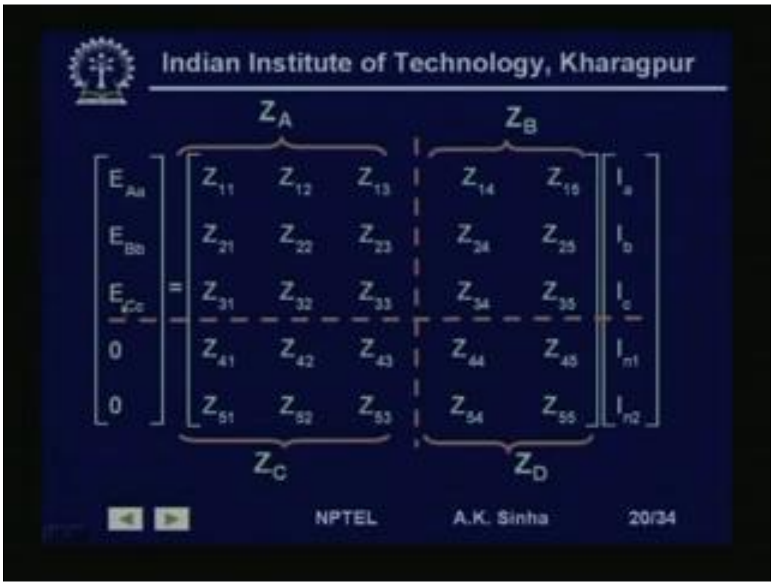

Now, if you write the complete system equation for the voltages across the line conductors. Then, we will have the voltage as E A a, E B b, E C c. That is the voltage across the two points of the phase A conductor, phase B conductor and phase C conductors. Similarly, for the neutral conductors, since the neutral conductors are grounded, this voltage will be 0.

This voltage is going to be equal to the impedance, multiplied by the current which gives the voltage drop across the two points. Now, here the impedances will be Z 11, Z 12, Z 13, Z 14, Z 15. All these impedances, this will give a 5 by 5 matrix. And the currents will be the, three phase currents I a, I b, I c, I n 1, the current in neutral conductor 1 and I n 2 in the conductor 2.

So, this for the five conductor system, we have five set of equations and this impedance matrix is a 5 by 5 matrix, which we can divided into four different sub matrices. As shown here, Z A which is 3 by 3 matrix, which indicates the Z 11, Z 12 Z 21, Z 22, Z 23, Z 31, Z 32,, Z 33. These impedances are relating the voltages across the phase conductors with the currents following in the phase conductor.

Similarly, the voltages across the phase conductors, due to currents following in the neutrals, can be given by the impedances as shown in the Z B. That is Z 14, Z 15, Z 24, Z 34, Z 35. And Z C indicates the voltage across the neutral conductors, due to currents in the phase conductors. These impedances are Z 41, Z 42, Z 43, Z 51, Z 52, Z 53. Similarly, for the voltage n th across the neutral conductors, due to currents in the neutral conductors will be given by this matrix Z D, which is Z 44, Z 45, Z 54, Z 55. So, we have three sub matrices Z A, which is a 3 by 3, Z B which is 3 by 2 matrixes, Z C, which is 2 by 3 matrixes and Z D, which is a 2 by 2 matrix. This is the complete system equation that we have, where the impedance terms are given as for the diagonal elements.

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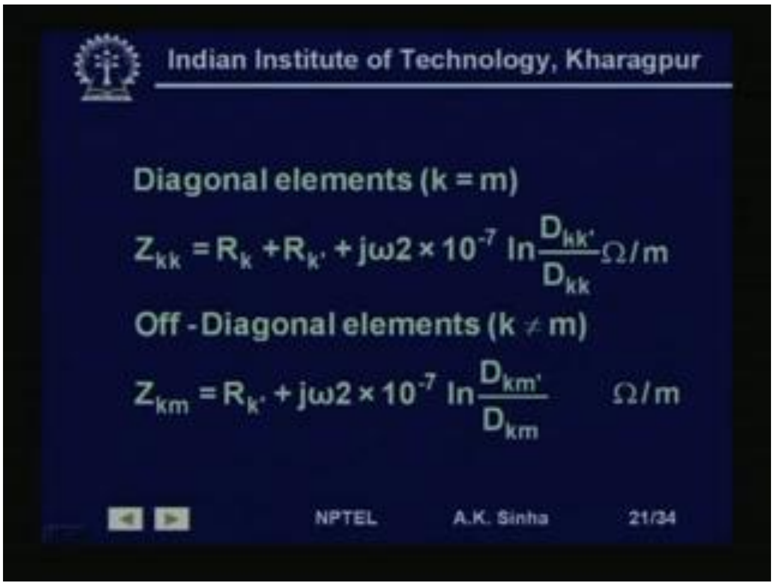

That is Z k k, which means Z 11, Z 22 and so on are given by R k plus R k dash plus j omega 2 into 10 to power minus 7, log n D k k dash by D k k ohms per meters. Whereas, these are the distances, as we have seen in the system in the system diagram earlier. Off diagonal elements that is Z k m, which is basically Z 12, Z 13 or Z 54, all these off diagonal elements.

That is, when k is not equal to m is given by R k dash plus j omega into 2 into 10 to power minus 7 log n D k m dash by D k m ohms per meter. So, we can compute all these diagonal and off diagonal elements, that is the elements of this imperial matrix using these relationships.

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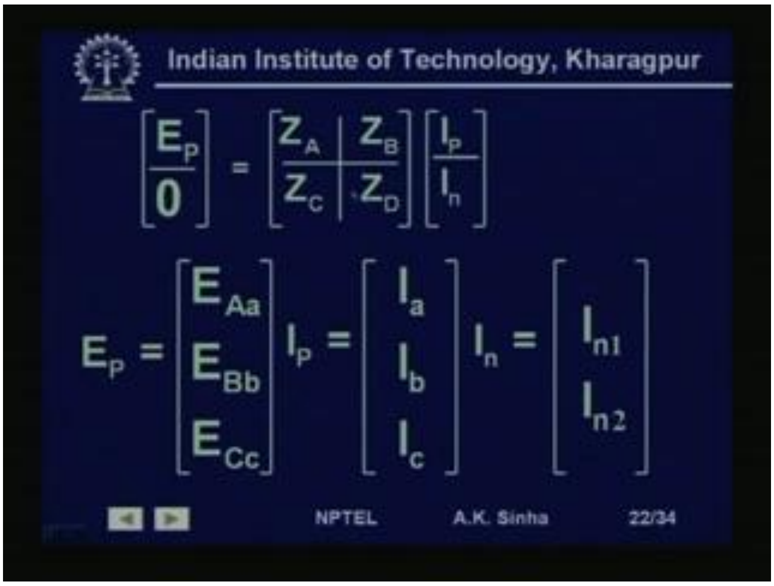

Now, what we can do, since we have already divided this system into four sub matrices. Now, we can write this whole system of equation in a short form like E p, where E p is the voltage drop across the face conductors, 0 is the voltage drop across the neutral conductor, this is equal to Z A, Z B, Z C, Z D into I p. Where I p is the current flowing through the face conductors and I n is the vector of current flowing through to neutral conductors.

As shown here, E p is equal to E A a, E B b and E C c are three phase conductor voltage drops, I p is equal to the phase currents I a, I b, I c. And I n is the current following through the two neutrals I n 1, I n 2. Now, from this set of equations, we can write this into two separates sets of equation as E p is equal to Z A, I P plus Z B I n. E p is equal to Z A, I P plus Z B into I n.

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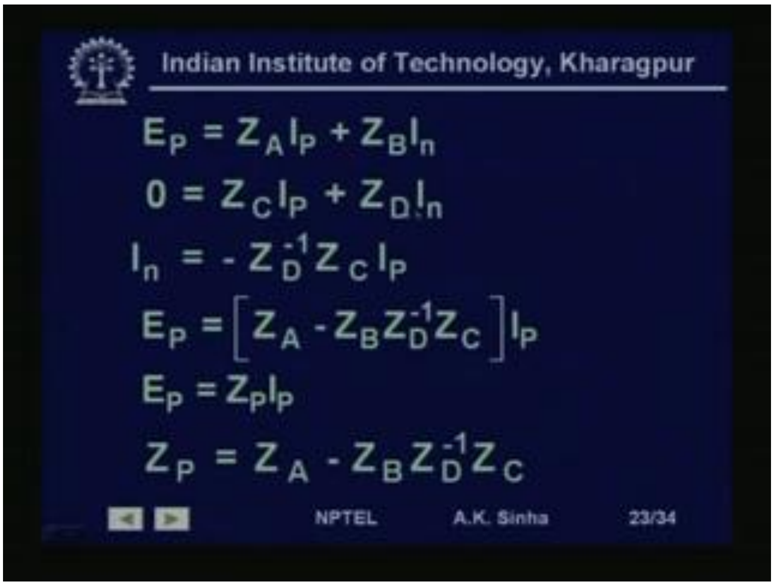

Similarly, 0 is equal to Z C into I P plus Z D into I n. 0 is equal to Z C into I P plus Z D into I n. Now, from this second equation, we can take this term. This term on the other side then we have I n is equal to minus Z D inverse Z C into I P. That is I n is here and we have taken this on this side. So, it is minus Z C, I P. Now, we pre multiply both sides by Z D inverse.

So, we will get I n, I n is equal to minus Z D inverse Z C into I P. And therefore, putting for this I n here in this first equation, we will get E P is equal to Z A into I P minus because this minus term is coming Z B into I n. So, I n is given by this relationship, so minus Z B into Z C into Z D, sorry, Z B into Z D inverse into Z C, I P. So, we have substituted for I n from here and then we are writing this expression like this.

Now, we can write this whole as E P is equal to Z P into I P, where ZP is this matrix. Here, this will be a 3 by 3 matrix Z p is equal to Z A minus Z B, Z D inverse Z C. So, this is what we will get, that is we have eliminated in this equation, the current I n and we are writing the all the equations in terms of the phase variable. Only thing is, this is taken care by using Z D inverse and Z C from this expression.

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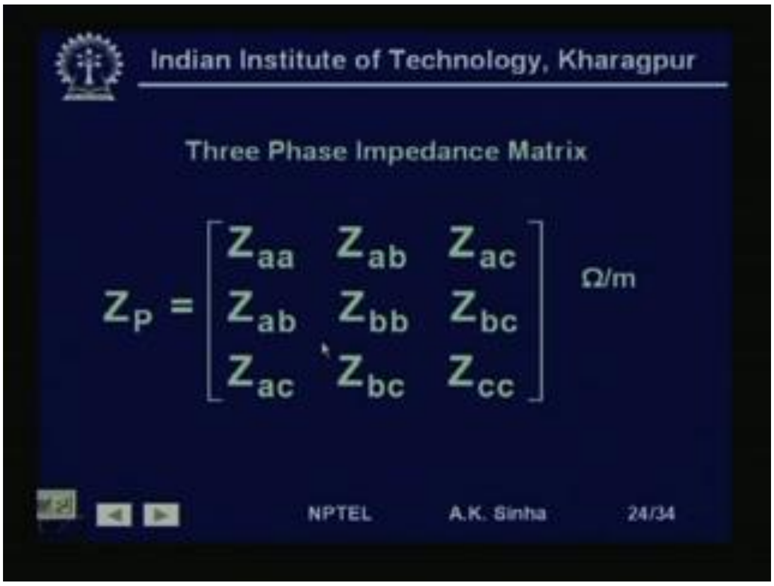

Therefore, we will get now Z p, which will be a 3 by 3 matrix as Z a a, Z a b, Z a c, Z a b or Z b a will be same Z b b, Z b c and Z a c, Z b c, Z c c. So, this is now a 3 by 3 matrix, from where we have eliminated the currents in the neutral conductors or the ground conductors. So, here we are getting a relationship, only for the phase conductors, E p is equal to Z p into I p.

So, the current following in the ground conductors or the ground is now eliminated. And we can now get a relationship, only for the conductor's currents. In the phase conductors relating the voltage drop in the phase conductors. Now, for a fully transpose line, what we will have is since these phase conductors will be occupying all the three positions for one-third length of the line. Therefore, we will get the average values for all the three flux linkages and the inductances. And therefore, we will have the same impedance for all the three phased.

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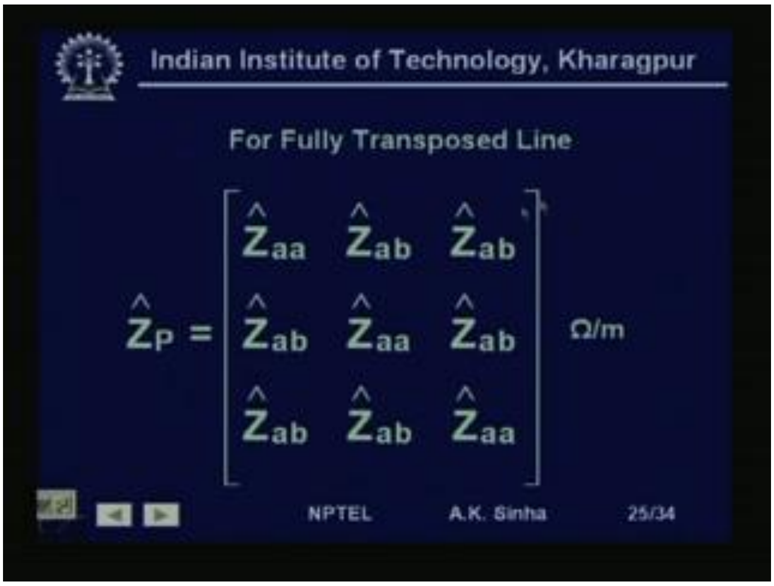

So, self impedance Z a a, will be same as Z b b, will be same as Z c c. That is all the three phase will have the same self impedances. And the mutual impedances will also be equal for all the three phases. So, Z a b and Z a c will be equal which will be also equal to Z b c and Z c a.

So, we get finally, for a fully transpose line, we get the values or thus impedance series impedance for the three phase system with ground return. As Z p is equal to Z a a, Z a b, Z a b, Z a b, Z a a, Z a b, Z a b, Z a b, Z a a. This matrix will give me the impedance, series impedance of the transmission line, with ground return.

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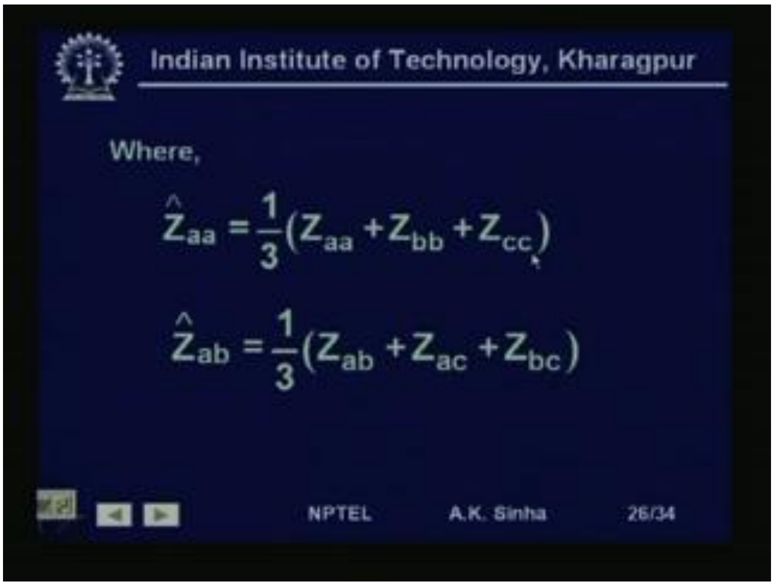

So, Z a a is equal to as I said the average value and Z a b will be also equal to the average value the mutual and the self, will be given by these two relationship.

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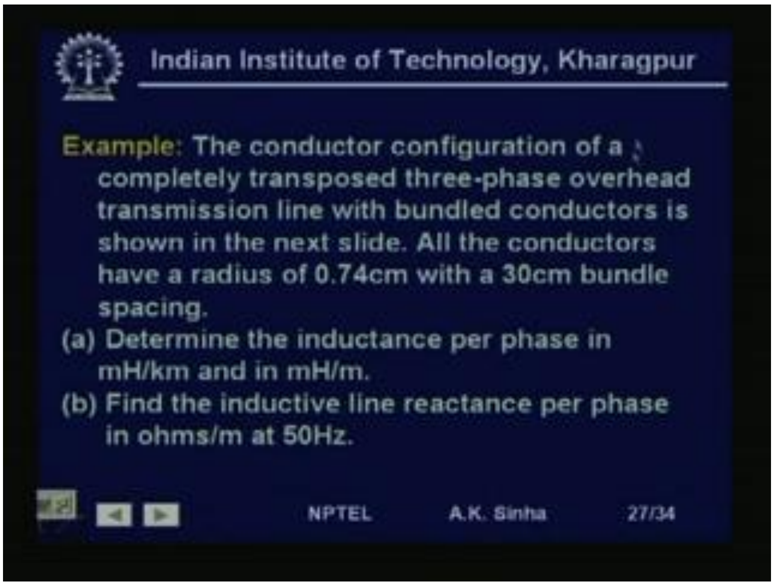

Now, let us take an example, for finding out the inductance of a three phase transmission system. The example, that we are taking is for the conductor consideration of a completely transpose three phase over a transmission line, with bundle conductor is shown. All the conductors have a radius of 0.74 centimeter with is 30 centimeter bundle spacing.

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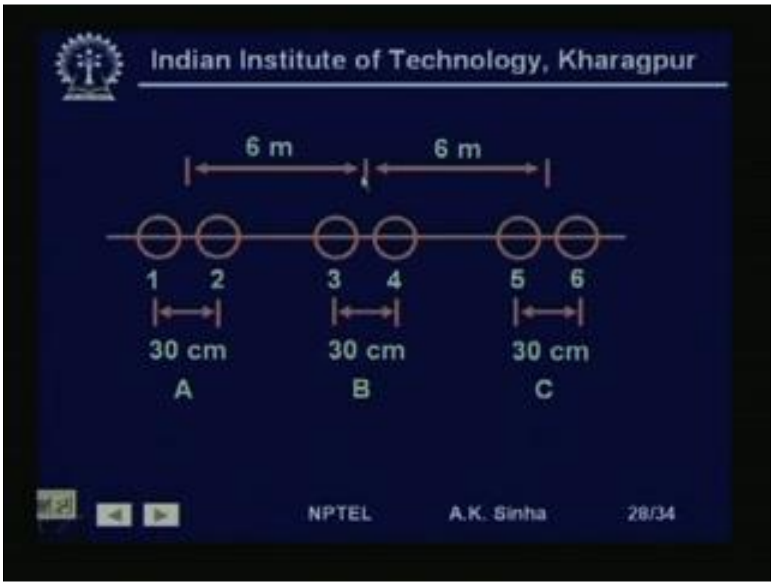

That is, we have a 30 centimeter bundle spacing for the conductors and each conductor as a radius of 0.74 centimeter. The distance between the two phase conductors is 6 meters. That is from center to center. And this is a horizontally spaced configuration. The line is fully transposed. For this line, determine the inductance per phase in milli Henry per kilometer and in milli Henry per meter. Find the inductive line reactance per phase in ohms per meter at 50 hertz.

So, this is the question, that we will have to find out the inductances per phase of the line in milli Henry per kilometer or a milli Henry per meter. We will also need to find out the inductive line reactance per phase in ohms per meter at 50 hertz.

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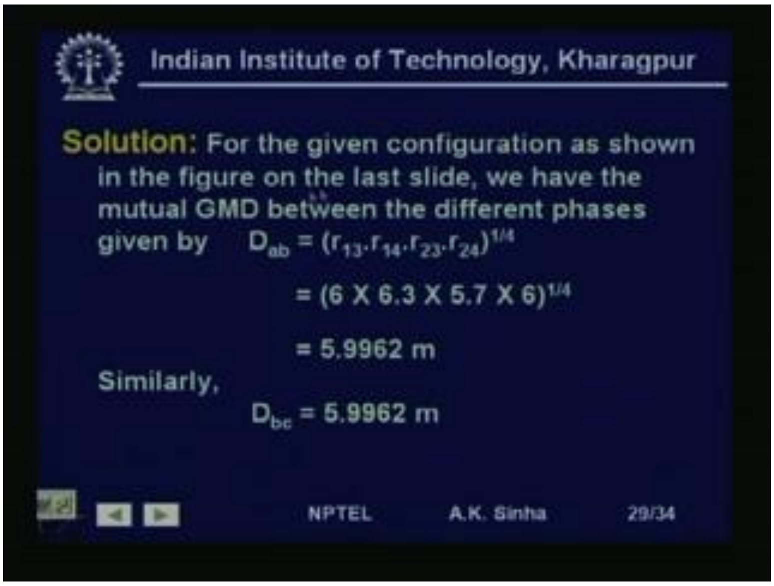

So, for this system, what we have to do is, we have to find out the equivalent distances. So, for the given configuration as shown is figure, we have the mutual GMD between the different phases given by D a b is equal to r 13, r 14, r 23, r 24. That is distance from here to this conductor, distance from this to this conductor, distance from this to this conductor, distance from this to this conductor.

And 4th root of that, because again if you take the distances from this to this and this to this, this to this and this to this, that will also be same. So, it will 4th root of D a b is equal is the 4th root of distance between 13, 14, 23, 24. So, this is equal to 6 into 6 .3 into 5.7 into 6. That is 13 is 6, 23 is 5.7, 14 is 6 plus 30 centimeters. So, 6.3 and 24 is 6. So, we take the 4th root, it comes out to be 5.9962, it is same as almost 6 meters.

Similarly, for between B and C, if we do this, we will get that same distance or the same GMD. But, for D c a, if we look at this between C and A, then we have the distance as A 1 to 5, 1 to 6, 2 to 5 and 2 to 6.

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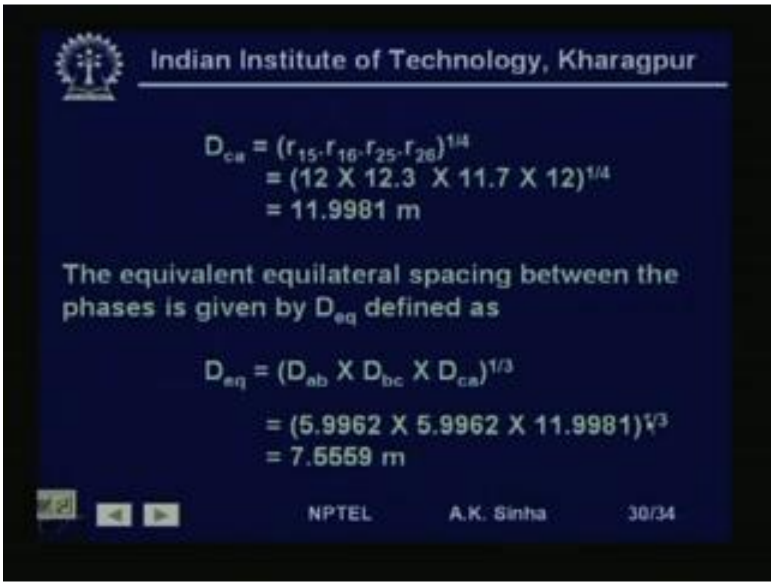

Therefore, D c a is equal to r 15 into r 16 into r 25 into 26, the 4th root of this. That is equal to 12 into 12.3 into 11.7 into 12, 4th root of that is 11.9981, which is very near to 12 meter. Now, the equilateral spacing between the phases is given by the D e q defined as D e q is equal to D a b into D b c into D c a and cube root of that. So, if we find out the equilateral spacing. The D e q, that comes out to be 5.9962 into 5.9962 into 11.9981 cube root of that, that comes out to be 7.5559 meter.

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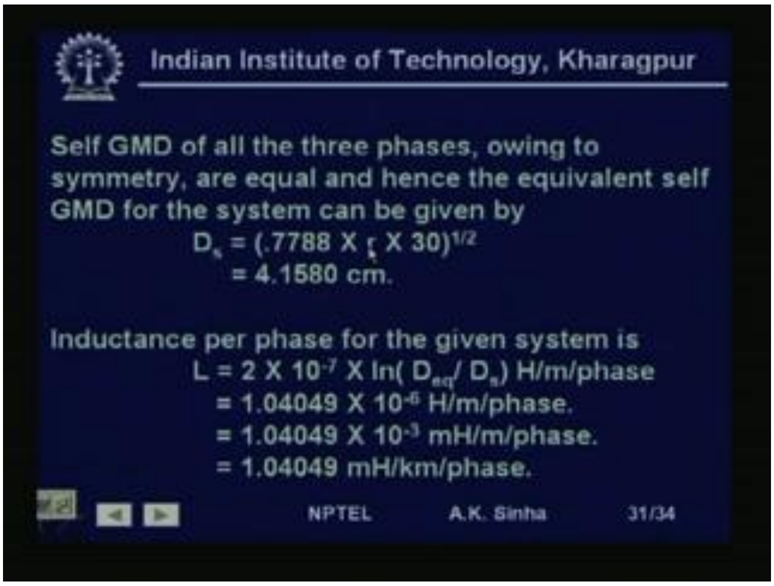

Now, the self GMD of all the three phases point to symmetry are equal. That is, the self distance each conductor has the same radius and the distance between the two conductors of a bundle is same. That is 30 centimeter. So, therefore, the D s for each phase conductor is going to be equal to r dash. That is 0.7788 into r for the conductor into 30 centimeter, which is the distance between the two conductors of the same bundle.

The square root of this comes out to be 4.1580 centimeter. In fact, we could have taken in all the four distances as we have seen earlier D s is r dash into D square root of that. So, this is equal to 4.1580 centimeter. Now, you see this is much larger than 2 times of 0.7788 into r which is 0.74 centimeter. Therefore, bundling has increased the effective radius considerably.

Therefore, now we can find out inductance per phase for the given system as L is equal to 2 into 10 to power minus 7 into log n. D e q by Ds Henry's per meter per phase, which is equal to 1.04049 into 10 to power 6 Henry's per meter, per phase, which can be written as 1.04049 into 10 power minus 3 milli Henry per meter, per phase or 1.04049 milli Henry per kilometer, per phase.

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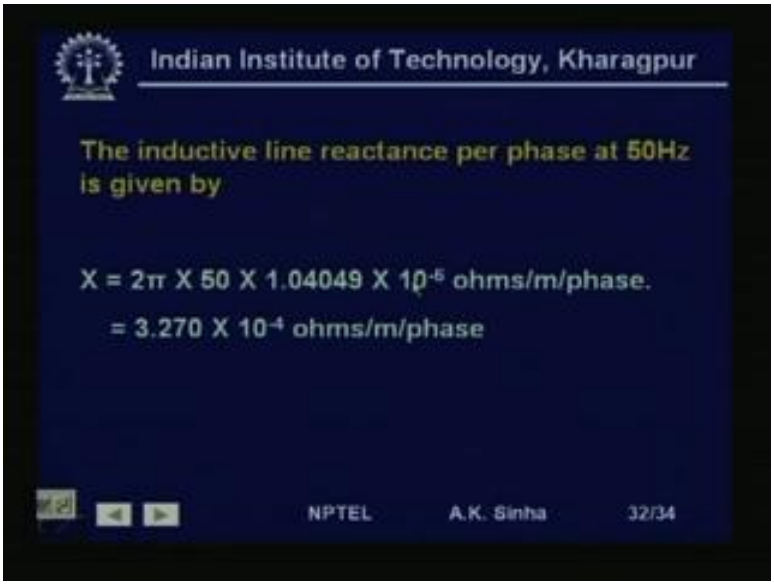

The inductive line reactance per phase at 50 hertz is given by x is equal to 2 phi f into the inductance. So, this is 2 phi 50 into 1.04049 into 10 to power minus 6 ohms per meter per phase. This comes out to be 3.270 into 10 to power minus 4 ohms per meter per phase. So, this is, how we can calculate the inductance and the inductive reactance for any given three phase transmission system.

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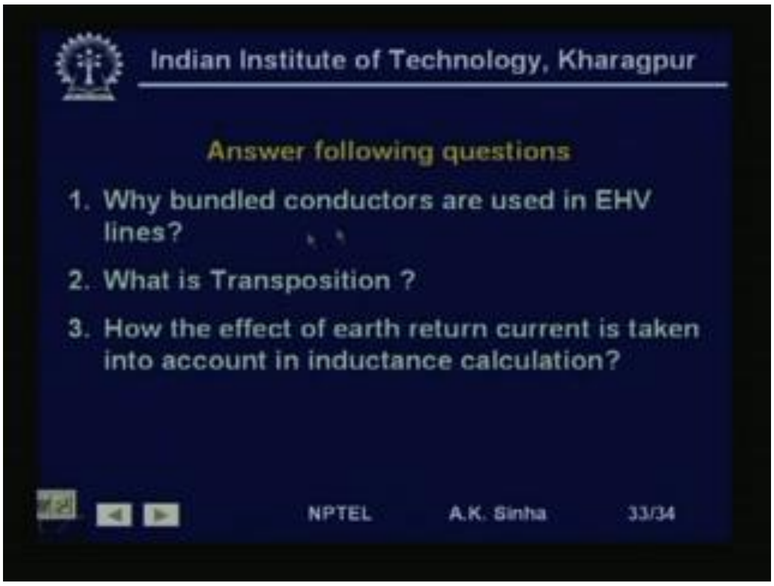

Now, before we finish I would like you to answer the following questions. First is, why bundled conductors are used in EHV lines. Second question is, what is transposition. And third question is, how the effect of earth return current is taken into account in inductance calculation for a 3 phase line with ground return system. Specially, when this system is carrying unbalanced current, so with this we finish these lessons.

Thank you very much.

We will meet again for lesson 5. In which, we will talk about calculating the capacitance of the transmission line.

Thank you.

Preview of next lecture

Lecture - 05

Transmission Line Capacitance

Welcome to lesson 5, on power system analysis course. In this course, we will talk about the transmission line capacitance, before we get in to the calculation of transmission line capacitance.

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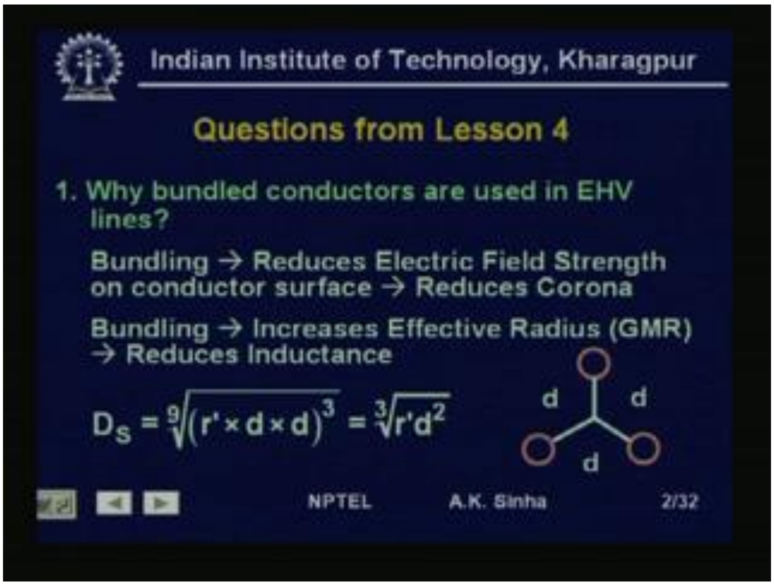

I would like to answer those questions. That I ask in lesson 4. First question was, why bundle conductors are used in EHV lines? Well, the answer to this question is bundling of conductors. That is, instead of using one single conductor, use of a number of conductors connected by conducting frames, reduces electric fields strength on conductor surface, which in effect reduces the corona losses, which result in power loss.

As well as radio interference and audible noise in the system, bundling also increases the effective radius of the conductor. And there by, reduces the inductance of the transmission line. This in effect will improve the regulation of the transmission line. As seen from here, the effective radius for a 3 conductor bundle, which are spaced at a distance d. From the center d, from each other with a radius r is given by 9th root of r dash into d into d whole cube, which is equal to cube root of r dash d square. This is much larger than r dash, which is used, when a single conductor is used. And therefore, bundling helps in reducing the inductance as it increases the effective radius.

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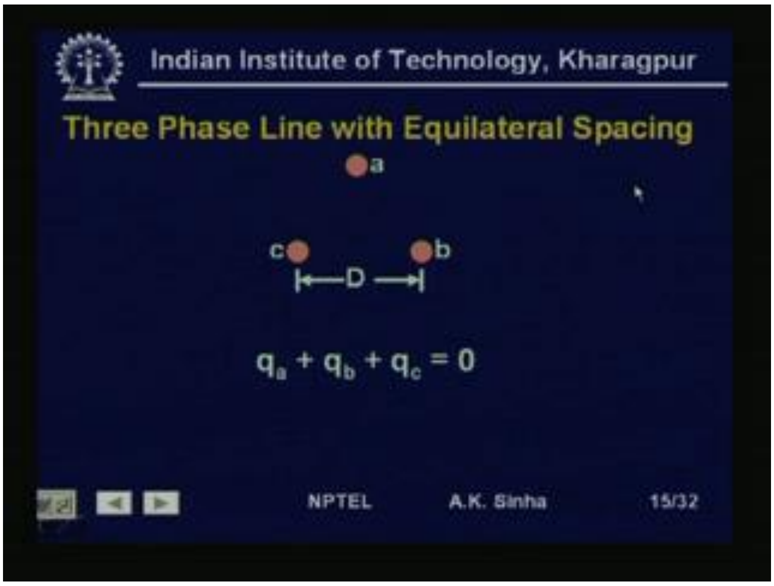

Therefore, we will take the case of a three phase system. We will start with the three phase line with equilateral spacing. Because, as we have seen for inductance calculation, we can always covert, if the line is transpose. We can always convert any system into the equivalent three phase equilateral spacing of the conductors by finding out the equivalent distance D e q. So, here we have equilateral spacing conductor a, b and c, each with a distance d from each other. We also assume that this system consist of only three conductors. So, the sum of the total charges will be equal to 0. That is q a plus q b plus q c is equal 0.

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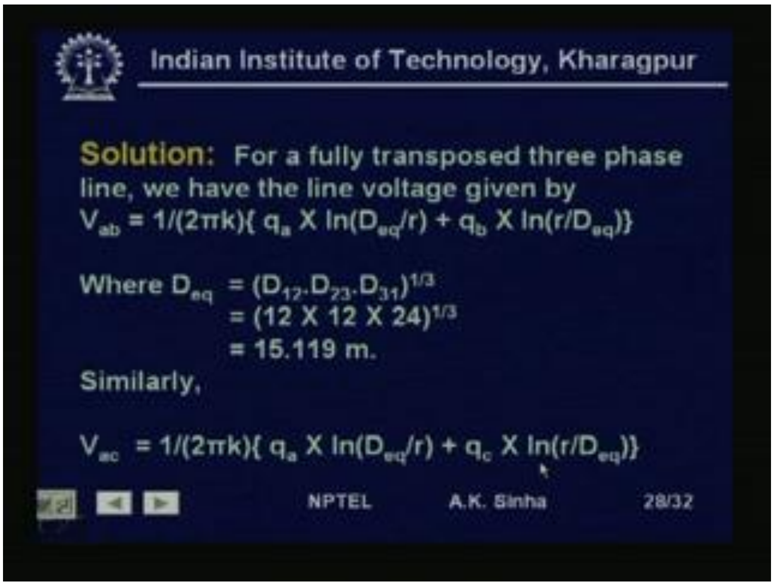

So, for solving this, we will take case of a fully transpose three phase line. So, we have the fully transpose three phase line. The voltage is given by the relationship V a b is equal to 1 by twice phi Epsilon, I am sorry, this is Epsilon into q a into log n D e q by r plus q b into log n r by D e q. Where D e q is equal to D 12 into D 23 into D 31 into the power 1 by 3. That is cube root of D 12, D 23 into D 31.

Now, substituting these values, we get this as equal to 12 meters into 12 meters into 24 meters. That is the distance between the conductor a and c, the cube root of this, will give us equal to 15.119 meter. Similarly, we can write the relationship for V a c and V a c will be equal to 1 by twice pi Epsilon into q a into log n D e q by r plus q c into log n r by D e q. Calculate these quantities for a transmission system.

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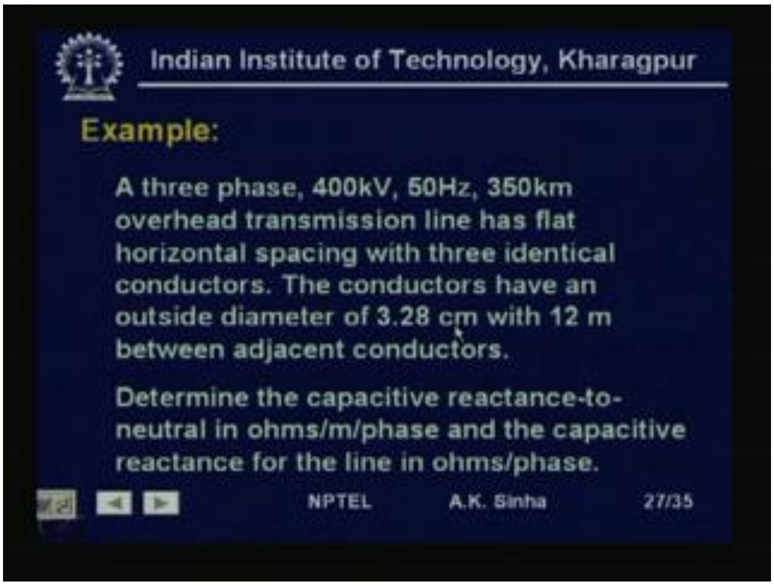

So, next, this example, we have a three phase 400 kV 50 hertz 350 kilometer overhead transmission line. That has a flat horizontal spacing, which three identical conductors. That is, we have three identical conductors, places in a plat horizontal spacing. The conductors have an outside diameter of 3.28 centimeter. And that is the diameter of the conductor is 3.28 centimeter. And the distance between the adjacent conductors is and the distance between the adjacent conductors is 12 meter. Now, for this system determine the capacitive reactance to neutral in ohms per meter per phase and the capacitive reactance, for the line in ohms per phase.

Thank you.