Power System Engineering
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Lecture - 07
Cables (Contd.)

Next, we will come to the sheath losses.

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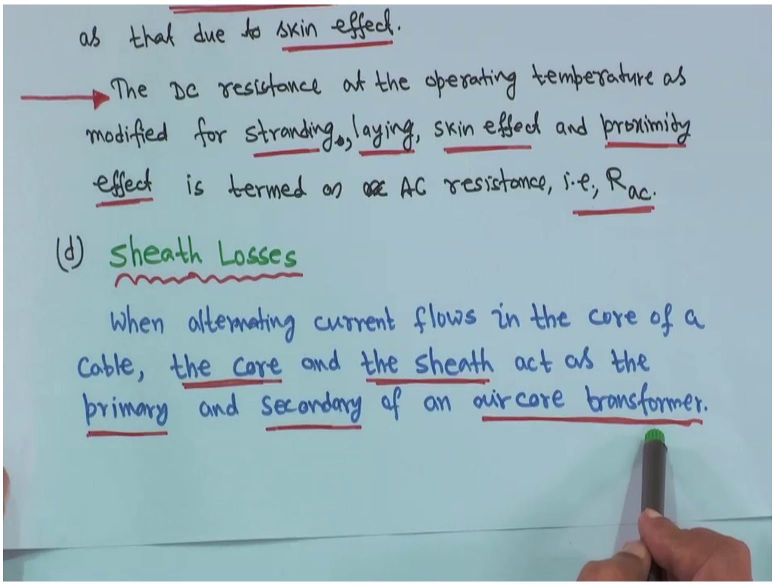

So, because cable we have seen the sheath is there, either lead or aluminum. So, when alternating current flows in the core of a cable, the core and sheath actually it acts like your primary and secondary of an air core transformer, this way you have to imagine. Therefore, voltage will induce in the sheath. So, when alternating current flows in the core of a cable, the core and the sheath act as the primary and secondary of an air core transformer this way you have to imagine. Therefore, what will happen?

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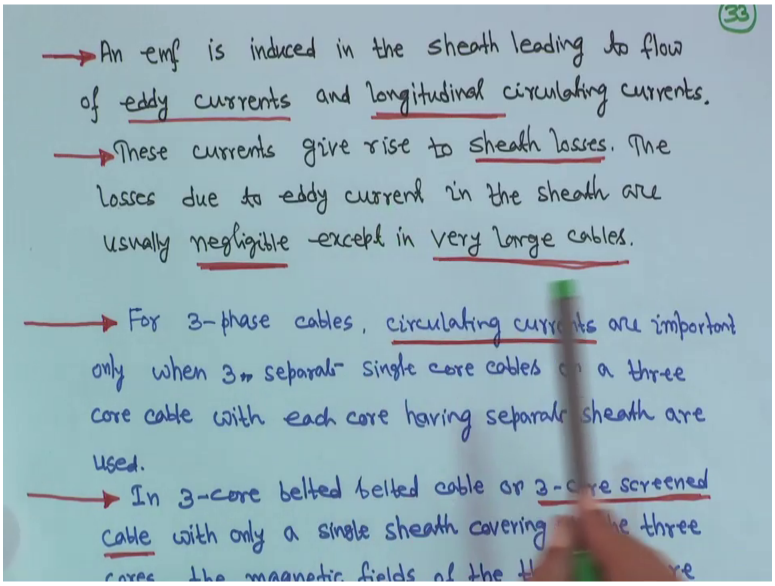

An EMF is induced in the sheath leading to flow of eddy currents and longitudinal circulating currents, but this current give rise to the sheath losses. So, there will be some power loss in the sheath. T he losses due to eddy current in the sheath are usually negligible except in very large cables. Very large cable means high voltage cables, at the same time, long, very long cables in terms of kilo meters. So, otherwise that eddy current loss is negligible.

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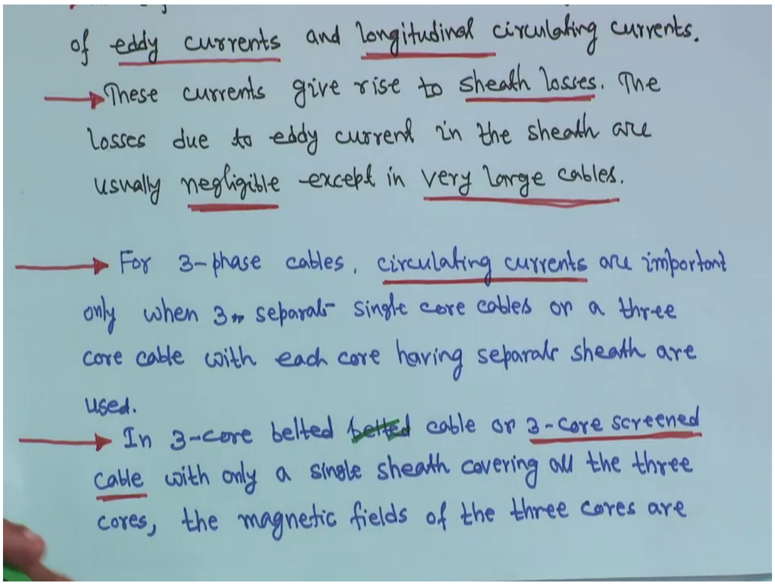

Now, for 3 phase cables circulating currents are important only when 3 separate single core cables or a 3-core cable with each core having separate sheath are used; that is, in a 3-phase cable the circulating currents will be there and this has importance. So, when 3 separate single core cables or a 3-core cable with each code having separate sheath here if we used in 3-core belted cables twice belted has been written, so, the 3-core belted cable or a 3-core screened cable with only a single sheath carrying all the 3-cores the magnetic fields of the 3-cores are partially mutually compensated and the circulating currents are reduced.

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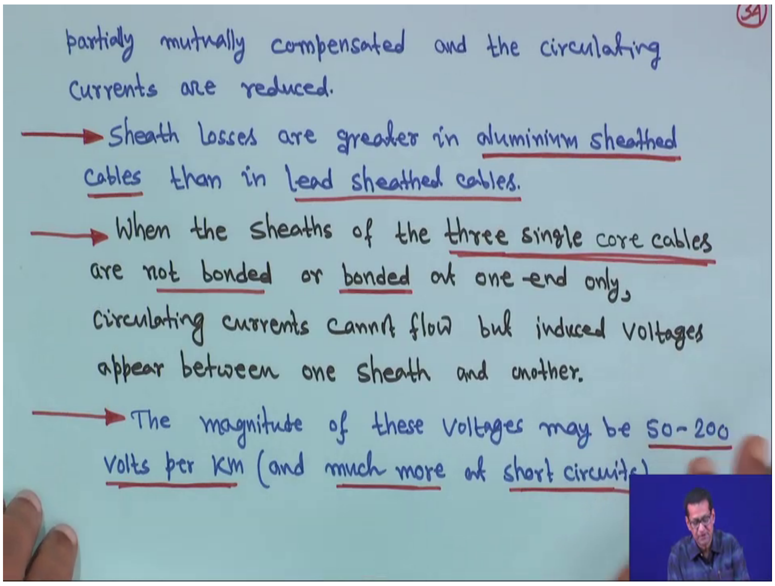

Actually, that in a 3-core belted cables or 3-core screened cables with only a single sheath covering all the 3 belts, I do not know whether I have diagram here or not. So, I do not have the diagram here, it is there also 3-core screen cable with only single sheath covering all the 3-cores, the magnetic fields of the 3-cores are partially mutually compensated and the circulating currents are reduced, but still sheath loss will happen sheath losses are greater in aluminum sheathed cables than the lead sheathed cables.

Now, when the sheath of the 3 single core cables are not bonded or bonded at one end only, circulating currents cannot flow, but induced voltages appear between the sheath and another. I mean when the sheath of the 3 single core cables if you have are not bonded or bonded at one end only then circulating currents cannot flow, this is true; but, induced voltages appear between the sheath and another. This way that voltage will appear between one sheath and another for your 3 single core cables.

So, the magnitude of this voltage may be 50 to 200 volt per kilometer and much more at short circuits; that means, if 3 your sheaths are there if it is single core cable it is not bonded your then there will be your what you call circulating current cannot flow even if it is bonded at one side also circulating current cannot flow, but voltage will be induced and this voltage range is 50 to 200 volts per kilo meter and it is much higher at short circuit.

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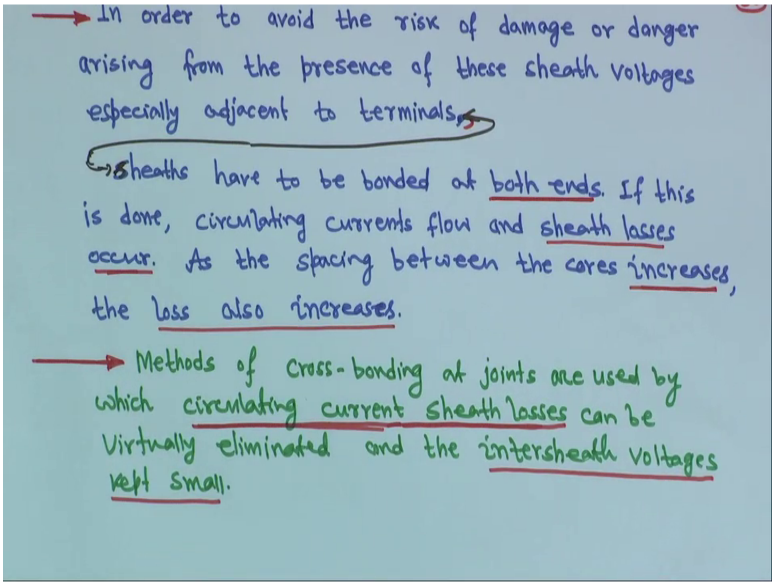

In order to avoid that the risk of damage or danger arising in the presence of these sheath voltages especially adjacent to terminal, sheaths have to be bonded at both the ends, that means, we are allowing the circulating current to flow. Later I will show you some diagram in order that now the transposition the sheath also has to be changed like this at a regular interval. In order to avoid the risk of damage or danger arising from the presence of these sheath voltages especially adjacent to terminals, sheaths have to be bonded at both the ends. If this is done circulating current can flow because it will get a path both side it is bonded and sheath losses occur, but as the spacing between the core increases the loss also increases.

So, methods of cross band bonding at joints are used by which circulating current sheath losses can be virtually eliminated and the internship voltages kept small.

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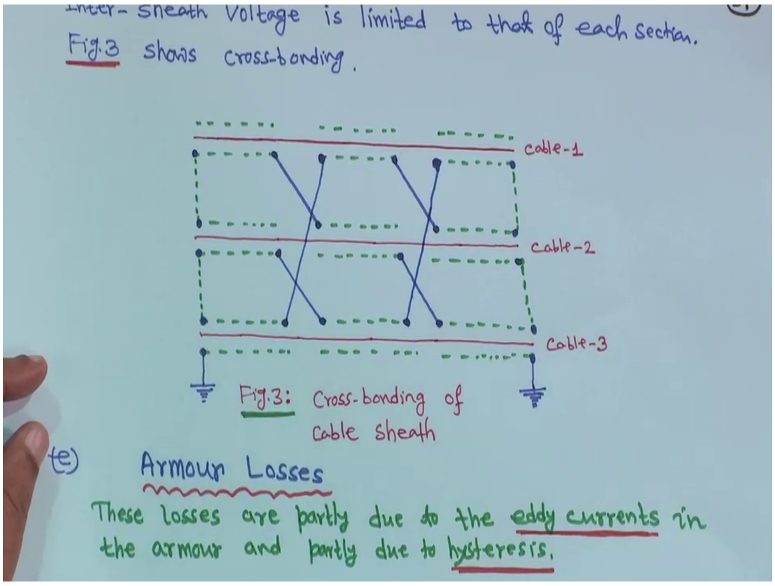

So, how they are doing it I will come to that that before going to the previous this thing this the way this is; suppose cable-1, cable-2, cable-3 the 3 conductors are there the way the transposition, cross bonding of cable sheath these are actually sheath, this dash green dash lines are the sheath. So, the way we do that transposition here also after sometime it will take the position here, it will take the position here, for this one also it will take position here, it will take position here, it will come here, it will take the position here and it will take the position of these thing.

So, it is something like your transposition of the transmission line. That way it is done. Just hold on if I have that diagram I will see if it is there or no, it is not here, but anyway. So, this kind of your what regular interval this is changing is possible then what will happen circulating current will almost be many eliminated.

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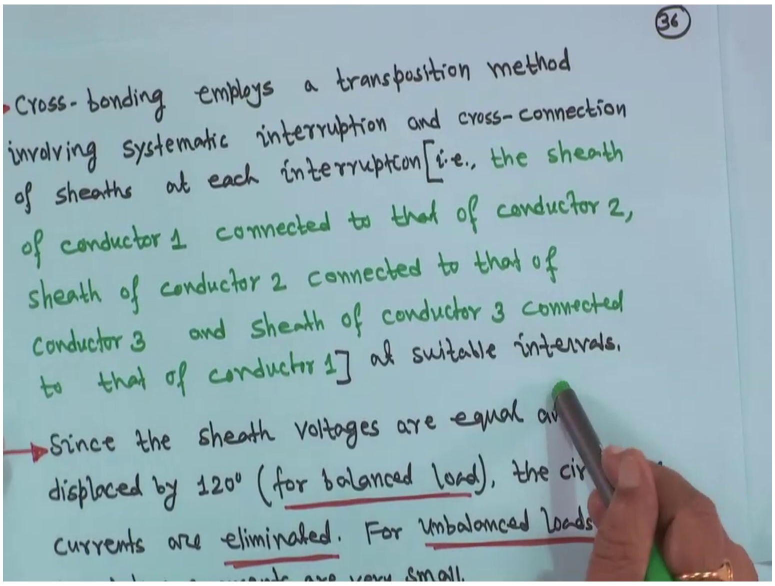

So, cross bonding implies a transmission your transposition method; involving systematic interruption and cross-connection of sheath at each interruption. So, these way things are done. The sheath of conductor 1, here diagram is here sheath of conductor 1, this is the conductor 1, cable-1, sheath of conductor 1 connected to conductor 2 then sheath of conductor 2 that is the sheath of connected to conductor 3 and sheath of conductor 3 connected to conductor 1, then that way at regular interval, at suitable intervals. So, these way circulating current can be minimized.

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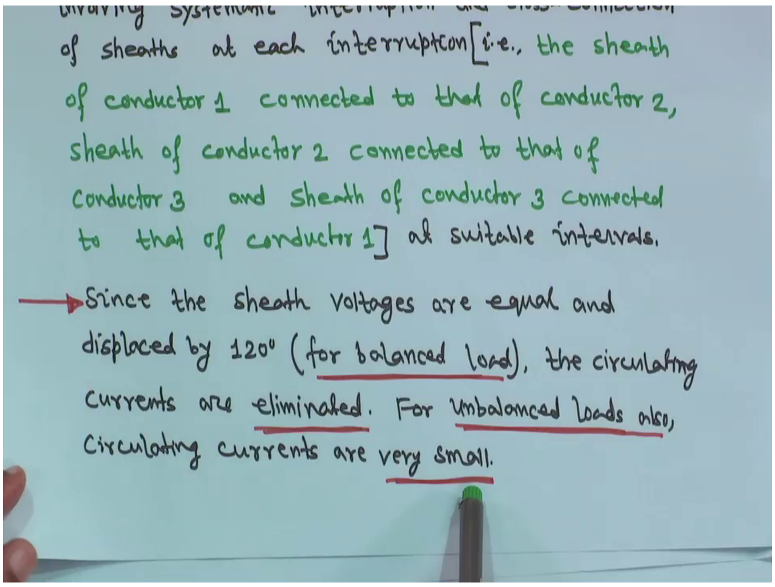

Since the sheath voltage are equal say and displaced by 120 degree for balanced load the circuiting current are eliminated. It is a balanced it has to be, for unbalanced loads also circulating currents are very small. Even if the unbalance is there particularly for 11 kV cable and if it is a distribution system then it will be unbalanced, but any way in that case your circulating currents are very small. So, this is actually the diagram, figure-3. That inter sheath voltage is limited to that of each section figure-3. So, this is a cross-bonding this is a cross-bonding.

Next is armor is the cable. So, we have to come to the armor loss also. Armor loss is a partly due to the eddy current in the armor and partly due to hysteresis. So, eddy current and hysteresis both are there in the armor you have to consider all these.

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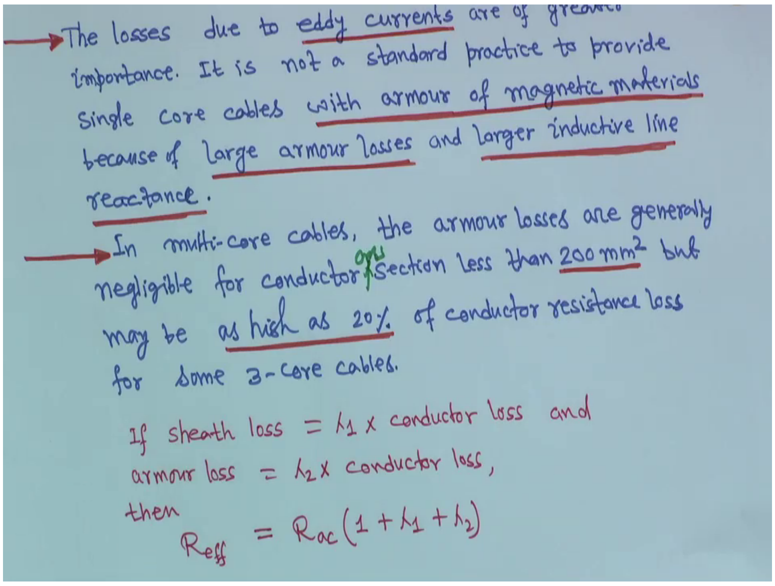

So, the losses due to eddy currents are of greater importance. It is not a standard practice to provide single core cables with armor of magnetic materials because of large armor losses and larger inductive line reactance. Therefore, in multi-core cables, the armor losses are generally negligible for conductor section less for conductor section less than 200 sorry conductor it will be cross sectional area, cross section less than 200 millimeter square, but maybe as high as 20 percent of conductor resistance loss for some the same 3-core cables. So, armour loss also you have to consider, I mean everything you have to consider.

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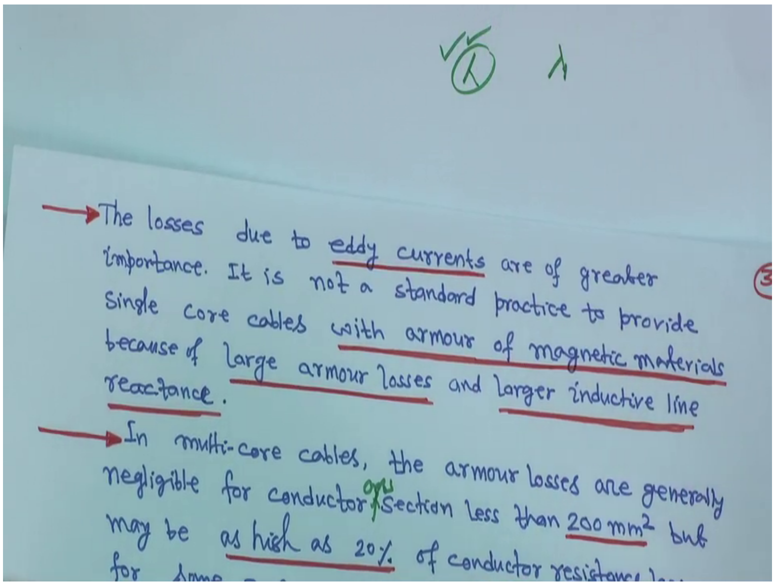

If sheath loss is equal to say, lambda 1 into conductor loss; actually I those who have taken my previous course, actually my habit has become lambda like this, but actually it is like this, but anyway throughout this I will use this. So, if sheath loss is equal to lambda 1 into conductor loss and armour loss say is equal to lambda 2 into conductor loss; therefore, R effective is equal to R ac plus you have to consider that your lambda 1 into conductor loss. So, hence it will be R effective will be R ac into 1 plus lambda 1 plus lambda 2, see all this things you have to find out to get the cable resistance this is R effective. So, this is for resistance.

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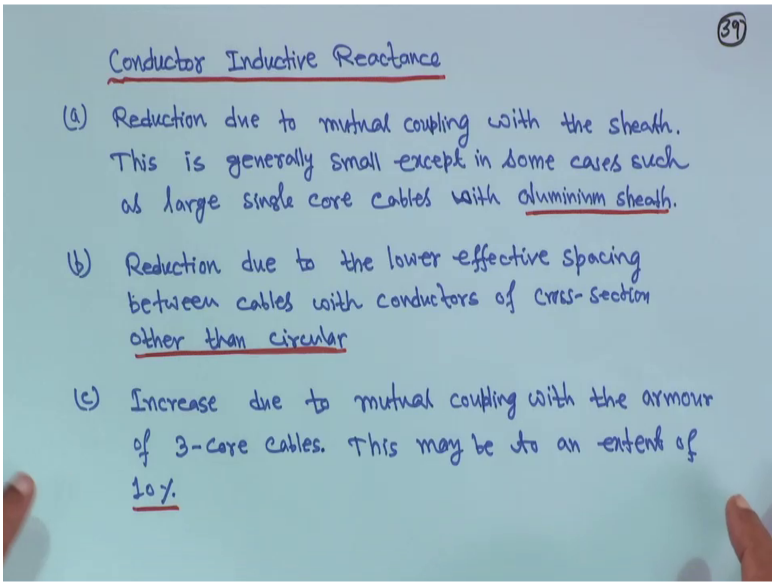

Next one is that conductor inductive reactance. So, the reduction due to mutual coupling with the sheath this is generally small except in some cases such as large single core cables with aluminum sheath. So, that your conductor inductive reactance. So, it will reduces due to the mutual coupling with the sheath, but this is generally small except in some cases such as a large single core cables with the aluminum sheath. Reduction due to the lower effective spacing between cables with conductors of cross section other than circular; if you do not use circular, other cross section then it will be there, but generally circular conductors .

Increase due to mutual coupling with the armour of 3-core cables. This may be to an extent of 10 percent. So, increase the mutual coupling with armour of 3-core cable this may be due to an because you have a mutual coupling and if mutual coupling is there naturally that your inductance will increase. So, up to this almost of the theories and my suggestion is that just I read a book and if you have any doubt we will answer your all questions.

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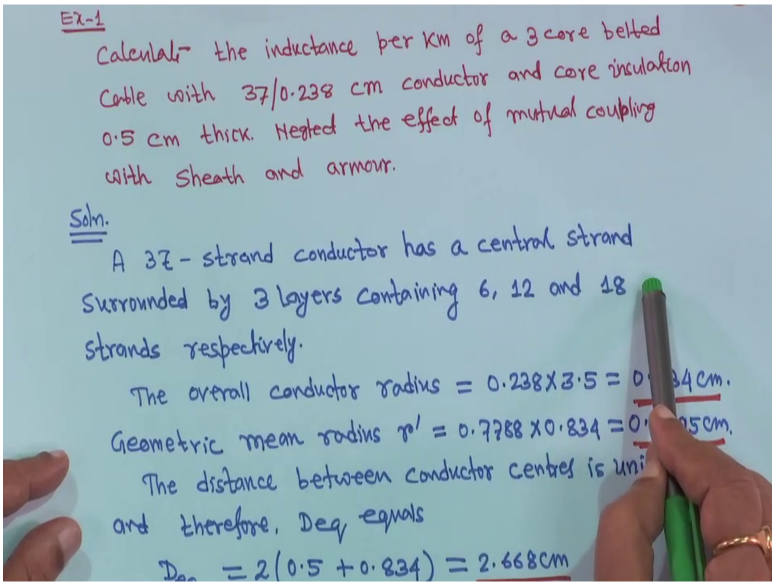

So, now, one example; this example, when I will give you before going to theory part that one thing I will not tell you. This you will do it that, calculate the inductance per kilo meter of a 3-core belted cable within the 37 slash 0.238 centimeter, what is this 0.238? I will solve, I give the solution, but I will not tell, you will find it. 37, I will tell and core insulation 0.5 centimeter thick. Neglect the effect of mutual coupling with sheath and armour. So, mutual coupling we will not consider, we neglect it.

So, 37 means it is 37 strands, that inductance chapter we have seen know 37 first conductors, above that 6 conductor, then 12, then 18. So, that means, 37 standard conductors has a central strand surrounded by advanced center stand surrounded by 3 layers containing 6, 12 and 18. So, that means, it is strands respectively this is single centre conductor then above that 6, then about that 12, then about that 18.

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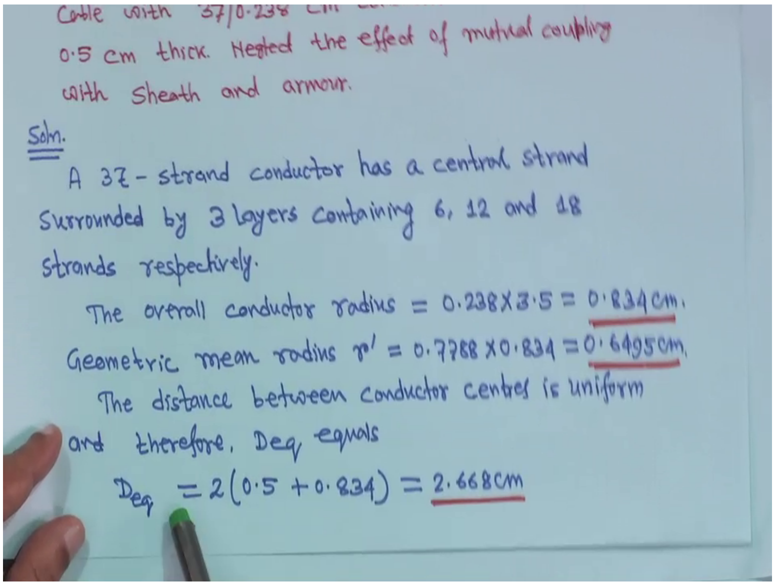

Now, the overall conductor radius 0.238 into 3.5, 0.8354 centimeters we are making it. Now, my question is it has written 0.238 then what is 0.238 for the conductor and why I am multiplying by 3.5. You will draw the diagram first one contactor then 6 conductor then 12 then 8 and then you try to find out this is an exercise for you.

So, the geometric mean radius is 0.78 into 0.834 it is coming 0.6495 centimeter. Now, distance between the conductor centres is uniform and therefore, D eq equal to it will be 2 into 0.5 plus 0.834, this you draw and this is an exercise for you and you do this. So, 2.668 centimeter, this is D equivalent.

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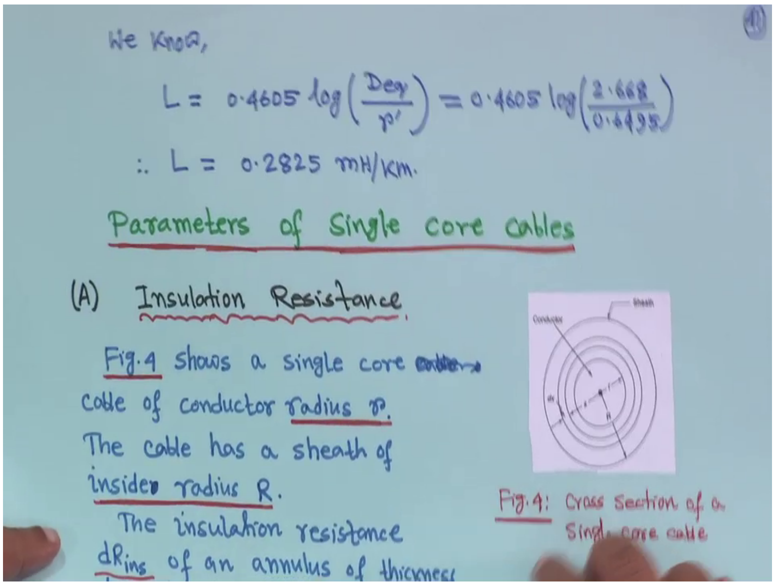

In the power system analysis course many student directly sent to the mail that regarding clarification. But I think I have answered to everyone and may be just next day I have given the answer to all their questions.

Next, we know L is equal to 0.4 this formula we get from induction inductance chapter. So, 0.4605 log that is base 10, D eq r dash that is whatever it comes it will become 0.2825 millihenry per kilo meter. Next, numerical will come later. Next, let us come to the your what you call ins parameters of single core cable so insulation resistance we have to find out, look how it is.

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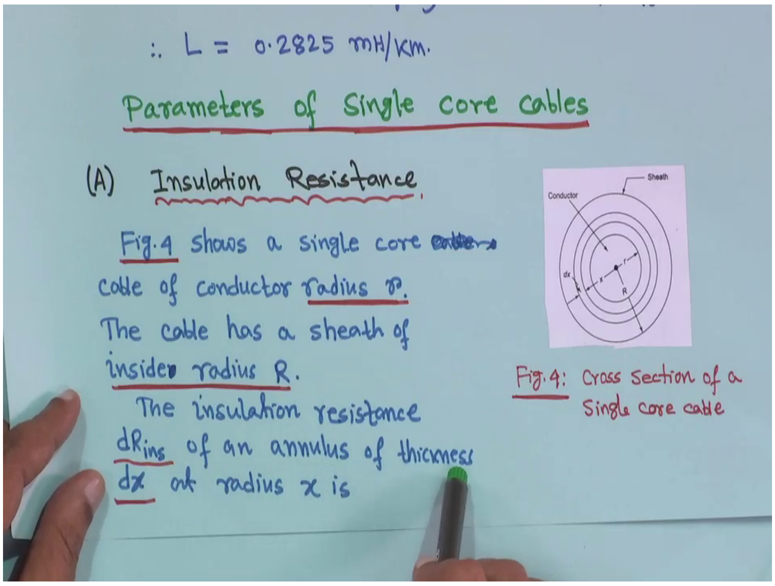

Now, this is figure 4, this I have taken from a book instead of drawing it. So, this is a conductor and this is a sheath and whatever it is, shows a single core cable of conductor radius r it is radius is r, the cable has a sheath of inside radius r. So, this is capital R inside radius is capital R, the insulation resistance dR, d capital R ins that is the suffix insulation stands for dR ins of an annulus of thickness dx at radius x is. So, we are considering at a distance x this annular ring of thickness dx the way you are doing for your what you call for your inductance capacitance calculation same philosophy, only formulas are different. So, this is the cross section of a single core cable.

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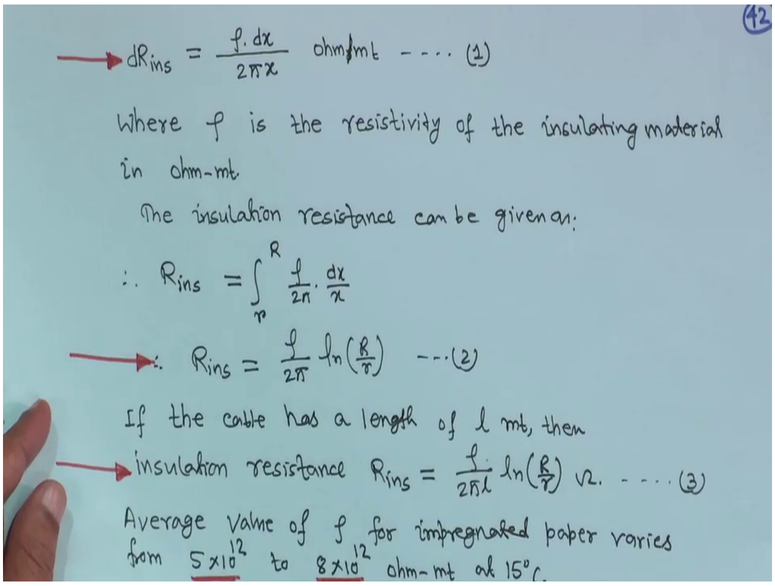

Therefore, we can write we know that therefore, dR insulation is equal to rho into dx divide by divided by 2 pi x ohm per meter, this is the equation 1. Rho is the resistivity of the insulating material in ohm meter. The insulation resistance can be given as limit your small r to capital R, this is your small r to capital R. Therefore, your R insulation integration R to r rho upon 2 pi then dx upon x.

So, r insulation is rho upon 2 pi l n capital R by small r, this is equation 2. If the cable has a length of l meter then insulation resistance is rho upon 2 pi l, l n R by r ohm because if you think the dimension wise this is actually ohm meter. So, rho is the resistivity of the insulating material in ohm meter. So, dx is meter, pi is dimension less, so, rho is ohm meter. So, it is ohm meter therefore, if the cable has a length l. So, its dimension is ohm meter, but if the cable has a length of l meter then you divide by l then insulation resistance will be rho upon 2 pi l, l n, R by r ohm because this is actually ohm meter.

So, average value of rho for impregnated paper varies from 5 into 10 to the power 12 to 8 into 10 to the power of 12 ohm meter at 15 degree Celsius. So, this is how we find; we will take a small rho is the your what you call resistivity of the insulating material, this value is known into dx divided by 2 pi x because we want to find out in ohm meter then we are changing it to length of that cable is l then we are dividing it by rho upon 2 pi l, l n R upon r ohm.

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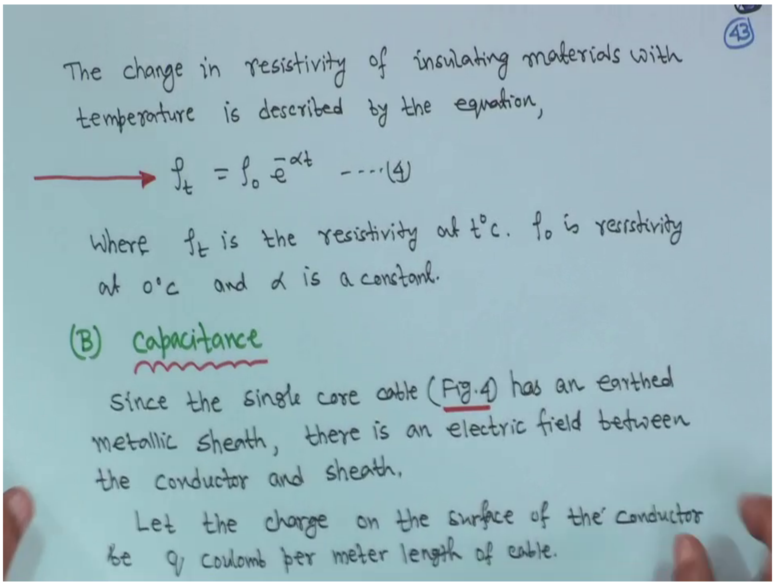

Therefore, the change in resistivity of insulating materials with temperature is described by the equation these rho t is equal to rho 0 e to the power minus alpha t, this is equation 4. Now, where rho t is the resistivity at t degree Celsius, rho 0 is resistivity at 0 degree Celsius and alpha is a constant.

Next, is capacitance. Since, the single core cable, that is figure 4, has an earthed metallic sheath; I mean this figure, just hold on, that this metallic sheath is there this figure. Since, the single core cable has an earthed metallic sheath there is an electric field between the conductor and sheath. Let the charge on the surface of the conductor be q coulomb per meter length of cable. So, let the assuming the charge on the surface of the conductor q coulomb per meter length of the cable, then what will be the electric flux.

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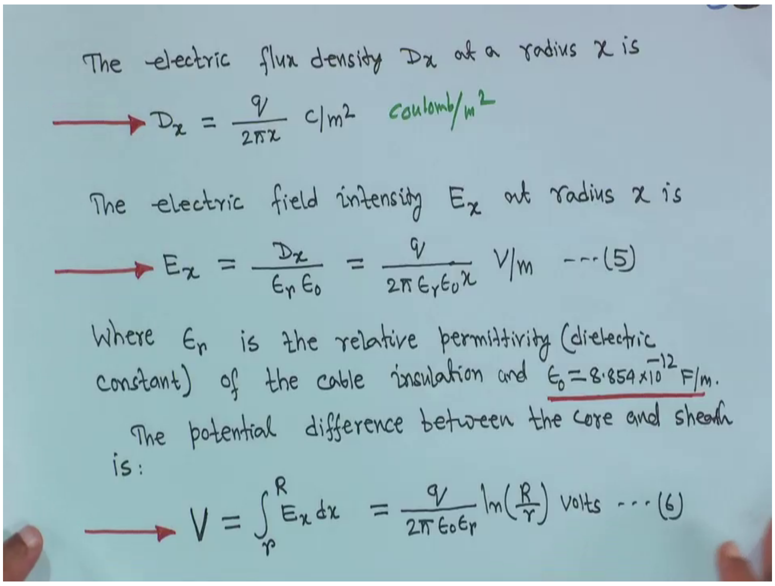

Therefore the electric flux density D x at a radius x is, D x is equal to capital D x is equal to q upon 2 pi x, this is coulomb meter square. This is C I have written actually it is coulomb per meter square. So, the electric field intensity E x at radius x, is given by capital E suffix x, E x is equal to capital D suffix x by epsilon r epsilon 0 is equal to this D x you substitute then you will get q upon 2 pi epsilon r epsilon x volt per meter, this is equation 5. Where, epsilon r is the relative permittivity that is the dielectric constant of the cable insulation and epsilon 0 you know from your capacitance chapter in transcription line 8.854 into 10 to the power of minus 12 farad per meter.

Therefore, the potential difference between the core and the sheath is V is equal to that is integrating from small r to capital R then capital E x dx. So, E x is this much you substitute and integrate you will get q upon 2 pi epsilon 0 epsilon r, l n capital R by small r volt, this is equation 6.

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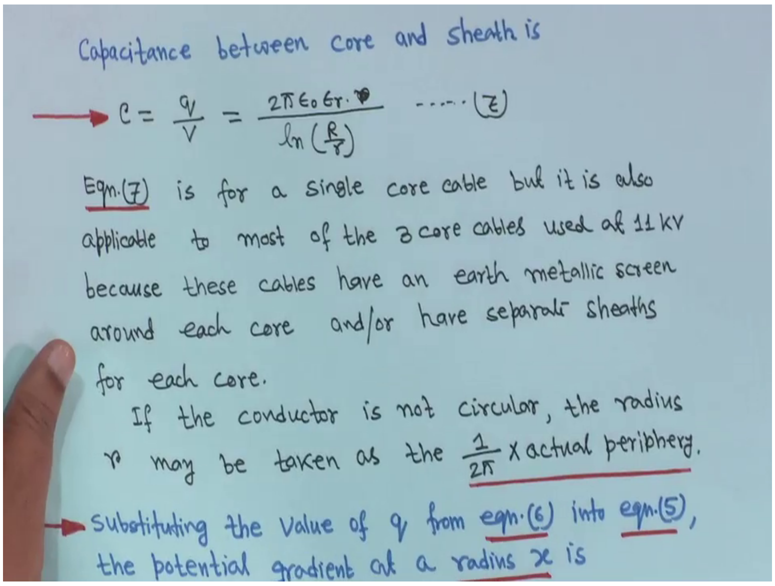

Therefore capacitance will be between core and sheath is your c is equal to q by V if you substitute it will be q by V will be 2 pi epsilon divided by l n capital R by small r, this is equation 7. Next, is that equation 7 is for single core cable, but it is also applicable to most of the 3-core cables. This is the 3-core cable used at 11 kV because these cables have an earth metallic screen around each core and or have separate sheath for each core.

If the conductor is not circular, the radius r may be taken as 1 upon 2 pi into actual periphery, just you will take arc actually, into actual periphery. So, substituting this value of q from equation 6; that means, from this equation from equation 6 this value whatever you have got for this thing, after the value of q from equation 6 from this equation.

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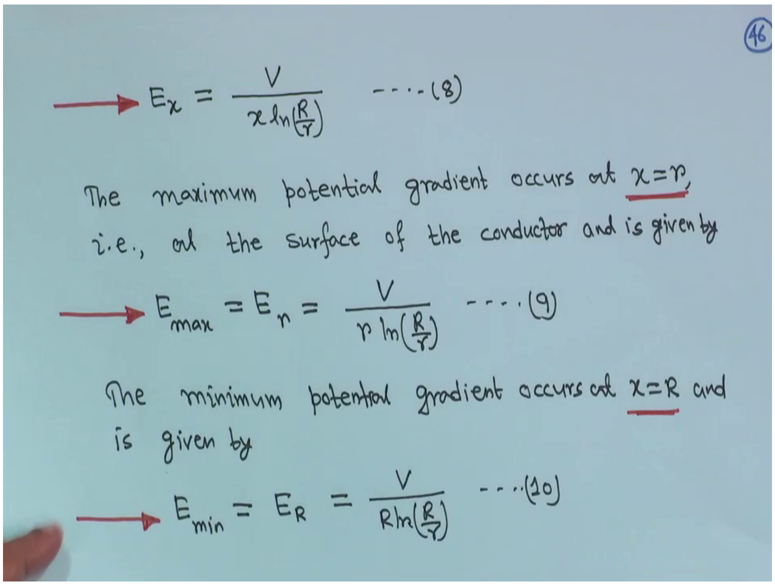

So, in equation 5 if you do, the potential gradient at a radius x can be given as in terms of V this is directly I am doing it, just you please put it, that is all. Then you will get it. So, E x is equal to V upon then x l n capital R by small r, this is equation 8.

Now, the maximum potential gradient occurs at x is equal to r, where x is equal to r that is at the surface of the conductor. When r x is varying a simple because when r is small that is x is equal to r naturally where your E x will be potential gradient will be higher. So, that is at the surface of the conductor. Therefore we write E max is equal to E r is equal to V upon putting x is equal to r, V upon r l n R by r, this is equation 9.

The minimum potential gradient will occur when x is equal to capital r and is given by that that is your outer radius. So, in that case E min is equal to E r capital V upon capital R l n capital R by r when x is equal to capital R. So, maximum is V upon r l n R upon r capital R upon small r and minimum is V upon capital R by l n R upon r, this is equation 10. So, how equation then now what you do you divide equation 9 by equation 10 that is this ratio you will take that E max by E min.

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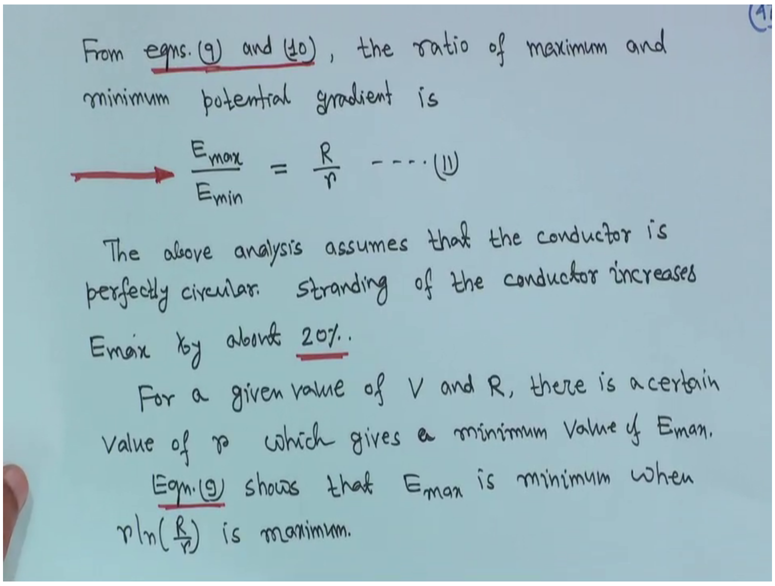

If you do so, then you will get the same thing E max by E min is equal to capital R by small r. Therefore, this above analysis assumed that the conductor is perfectly circular. We are assume this analysis conduct circular conductor stranding of the conductor increases E max by about 20 percent, it is great and for a given value of V and capital R there is a your certain value of r which gives a minimum value of E max, for a given value of V and capital R there is a certain value of r which gives a minimum value of that means you have to find out relationship between capital R and small r, R is of course given, V is also given.

So, equation 9 shows that E max is minimum when r l n R by r is maximum; that means this 1 this E max. E max will be minimum when r l n R upon r is maximum so; that means, there must be a relationship between capital R and small r. So, E max is minimum when this one, what will happen you have to take that derivate of this one and set it to 0.

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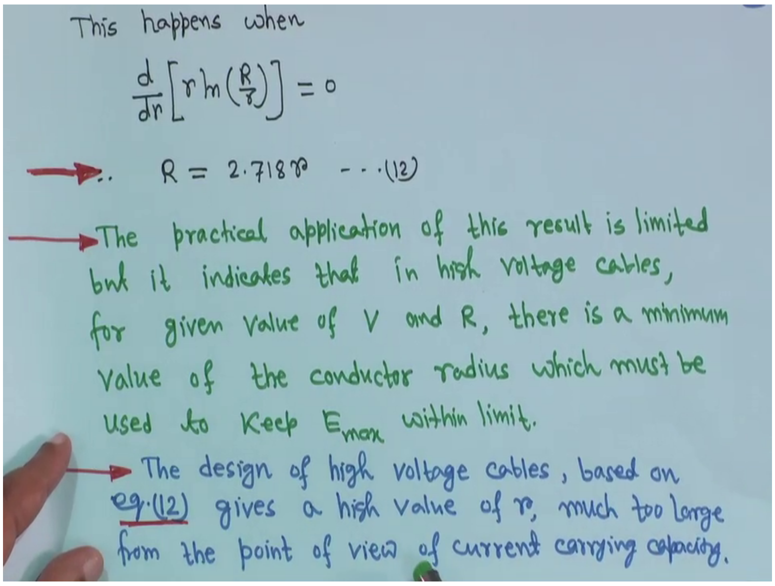

So, this happens while d dr in r l n capital R by small r is equal to 0, you take the derivate and simplify you will get capital R is equal to 2.718 that is your small r. Basically, it is value of you will find that E. So, the practical application of this result is limited, but it indicates that in a high voltage cables for a given value of voltage and capital R there is a minimum value of the conductor radius which must be used to keep the E max within limit.

The design of high voltage cables based on equation 12, this one gives a high value of r which much too much too large from the point of view of current carrying capacity; that means, this your what you call that for I have to choose very high value of r that is much too large from the point of view of current carrying capacity. So, this formula this is mathematics, but in reality it is not used actually, but you have some ideas.

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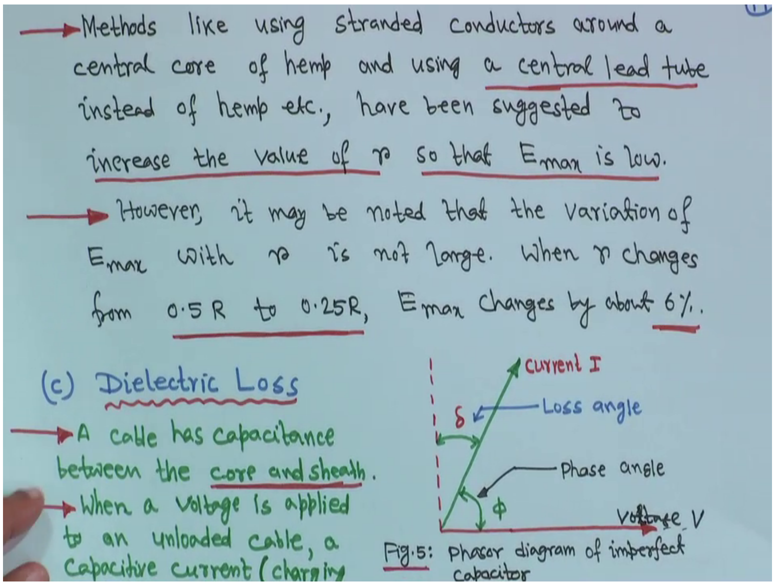

So, method like using stranded conductors around a central core of hemp and using a central lead tube instead of hemp etcetera have been suggested to increase the value of r, so that, E max is low. However, it may be noted that the variation of E max with r is not large, when r changes from 0.5 R to 0.25 R, E max changes just by about 6 percent. But, some ideas you have regarding this E max, minimum value of E max.

So, next is this is I hope this things is understandable to you, only thing is that this derivative one you please do it and find out that R is equal to 2.718 small r, capital R is equal to. So, methods like using standard conductor this is gone.

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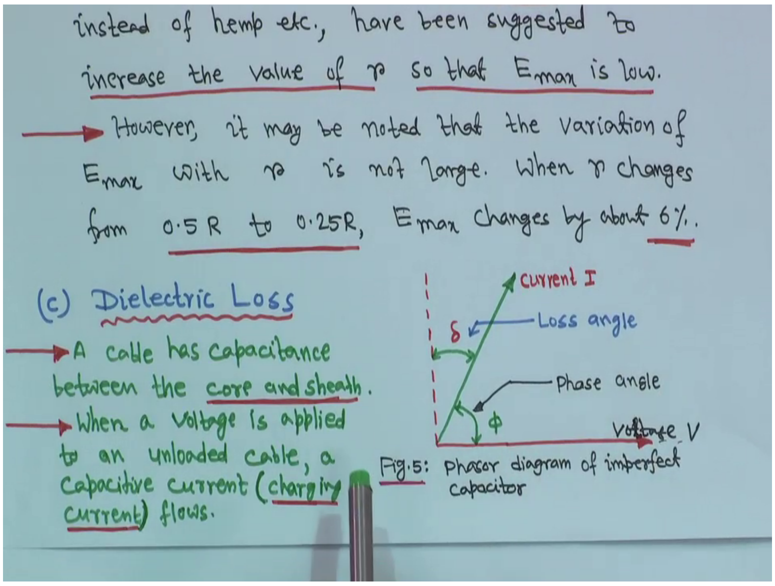

Next, we will come to the dielectric loss; this is another important aspect for the cables. So, this diagram I will come later. So, a cable has capacitance between the core and the sheath that we have seen when a voltage is applied to an unloaded cable, a capacitive current that is charging current flows.

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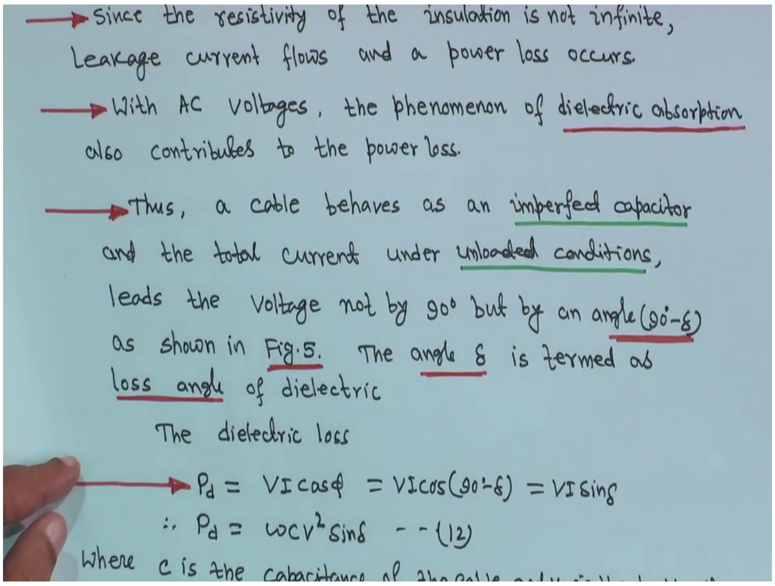

So, in that case what will happen, since the resistivity of the insulation is not infinite, leakage current flows and a power loss occurs because insulation resistivity is not infinity. So, leakage will be there and power loss will be there. So, with AC voltages this phenomenon of dielectric absorption also contributes to the power loss.

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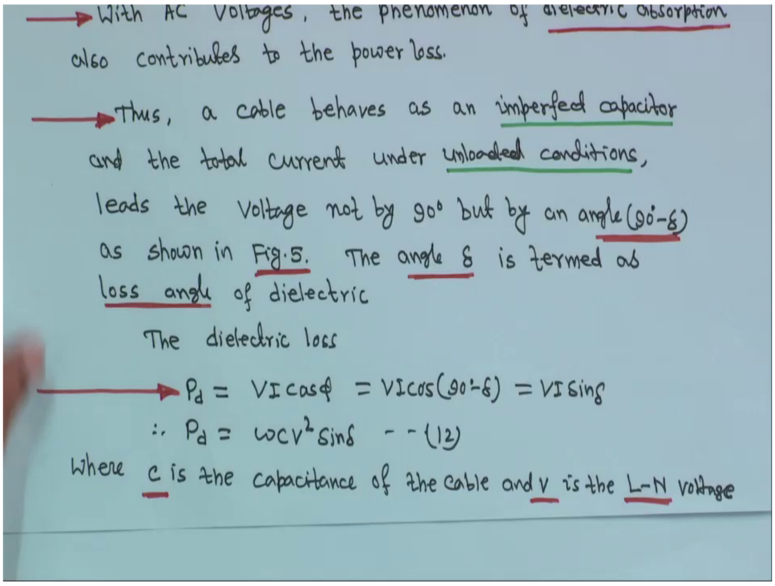

So, thus a cable behaves as an imperfect capacitor and the total current under unloaded conditions, leads the voltage not by ninety degree, but by an angle 90 degree minus delta; that means, it has some what you call it is not a pure capacitance, but it has some imperfect capacitor we call, because losses occurs that dielectric absorption also contribute to the power loss.

So, that is why it shown is figure 5. The angle delta is termed as loss angle of dielectric; that means this is your current say and this is your voltage and this is that phase angle between current and voltage is phi. So, this delta is equal to 90 degree minus phi and delta we call that loss angle. This is actually phasor diagram of imperfect capacitor, otherwise current and voltage should have been 90 degree current leading the voltage 90 degree, but in this case as the loss occur that is dielectric loss that is why this is call loss angle delta.

So, it is the current and voltage it is not 90 degree and phase angle between current and voltages is phi and delta is equal to 90 degree minus phi and this is called actually loss angle, is termed as a loss angle of dielectric. Now that dielectric loss generally we know formula P d is equal to V I cos phi, because this is my voltage, this is current an angle between this is phi, so, it is V I cos phi and phi is an your what you call and your phi is equal to 90 degree minus delta phi is equal to 90 degree minus delta.

So, it is cos 90 degree minus delta. So, it is V I sin delta. Therefore, P d is equal to and your, I is equal to omega C V know, that is why omega C V square is coming. So, basically your, I is equal to omega C into V. So, here you substitute omega C into V, P d is equal to omega C V square sin delta. So, this is equation 12 where C is the capacitance of the cable and V is the line to neutral voltage, it is N stands for neutral. So, this is what you call that loss angle and dielectric loss then happens in the cable. So, this is your this thing.

Thank you.