Power Electronics and Distributed Generation
Prof. Vinod John
Department of Electrical Engineering
Indian Institute of Science, Bangalore

Lecture - 7
Modeling of Distribution System Components

Welcome to class seven on topics in Power Electronics and Distributed Generation, in the last class we were looking at symmetrical components techniques; and looking at models of the line transformer, etcetera. Today will continue with the transformer model, we will look at the phase relationship between the windings of the transformer. And if you look at a typical three phase transformer, you can have y y, delta y, delta delta variety of four combinations and a typical assumption is that y y and delta delta is at a 0 degree phase shift.

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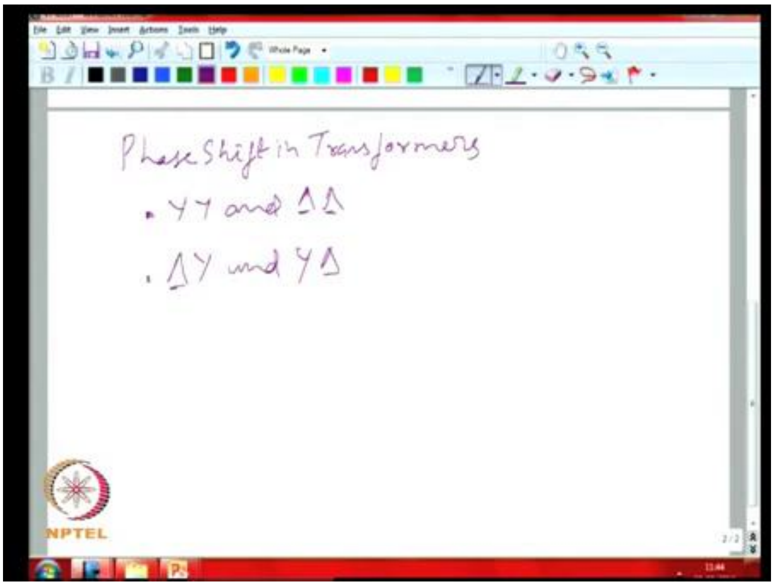

So, typically these are considered 0 degree phase shift, but by selecting the dot points and the appropriate interchanging the terminals of the transformer, it is possible to get 180 degree shifts, 60, 120 degree shifts etcetera, depending on how the actual terminals are labeled. If you look at a delta y or a y delta transformer, again you would typically expect them to have phase shifts of 30 degrees, we will see that it is possible to get a 30 degrees, 90, 160 degrees etcetera, depending again on the sense of the winding; and how the windings are connected, we will do this through a couple of examples.

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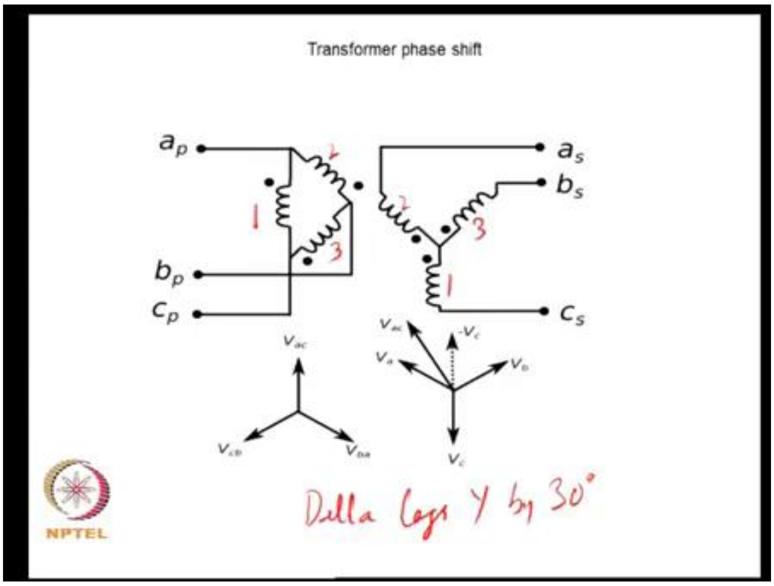

So, if you look at a delta y transformer which is shown in this figure, so your primary is connected in delta and if you look at the windings, say winding 1 is connected between phase a and c, winding 2 is between b and a and winding 3 between b and c and b. And then, you look at the corresponding windings on the secondary, you will see that phase a on the secondary is in phase with winding 1, so this is winding 1 on the secondary, similarly you would have this is winding 2 on the secondary and this is winding 3 on the secondary.

So, you have V a c on the primary side in phase with V a on your secondary and you have now if you look at the line to line voltage on the secondary, you take V a minus V c to be V a c and you can see that your delta leads your y by 30 degrees. So, if you now look at the second case over here, where you have a change and the dot points and the way the windings are connected, you have now windings 1, 2 and 3 connected on the delta side as in the previous case. And the corresponding windings on the secondary is winding 1, winding 2 and winding 3 and the dot points are brought in.

So, if you look at V a c on the primary now, that is now having a going to the secondary winding on c and you can look at what V a, V b and V c would be in this particular case. And you can see, now if you plot V a c it is V a minus V c, now your delta is lagging your y by 30 degrees, so you can have a delta y transformer depending on your winding configuration, you can have plus 30 minus 30, plus 90 minus 90. And now if you look at both the y y, delta y transformers, it is possible to have every 30 degree point on your clock can be obtained with the winding connections on your transformer.

In this particular case and then, to get the actual phase shifts you can the straight forward way to do it, would be to actually look at the wave forms on your transformer to see your what actual phase shifts are or you have to go in, take a look at your dot points, the sense of the windings and how it is connected in the physical transformer to find out what the expected phase relationship between your primary and secondary is going to be. So, you cannot just say this is going to be just 30 degrees lag all the time, you have to actually look at what exactly is the physical device that you are handling.

So, if you look at then the next component which would be machine, you can have synchronous machine and if you want to look at it is sequence components, then you have to ask in what time frame are you looking at the sequence components of the machine.

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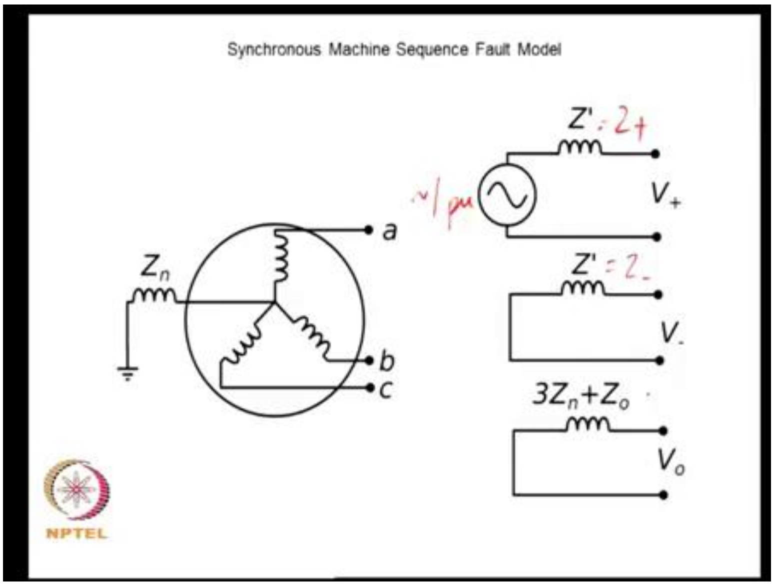

And you if you are doing it for fault analysis and you are fault time durations of the order of a few cycles, say 10 to 100 milliseconds or 100' s milliseconds, then you are looking at the transient time constant of the synchronous machine. So, for the analysis you can, then look at what you are positive sequence, negative sequence and 0 sequence models would be and your positive sequence model is that of your induced voltage, which is your EMF, which would be closed to 1 per unit. And then, your transient impedance which would be your value for your z plus, if you look at your a negative sequence model of the machine.

Then you have your no back EMF, because the induced voltage is positive sequence, your impedance again is your transient time constant z minus. If you look at the 0 sequence, it would be the 0 sequence of the machine, this is for a machine where you connect to the neutral point assuming that you need to feed a four wire system, in which case you have a z naught as your 0 sequence impedance. And if you physically connect a impedance to the neutral, then you would have z naught plus three times z n would be your effective 0 sequence model for the machine along with the neutral impedance. So, with these models are we can now look at what would happen when you have a unbalanced fault in a system.

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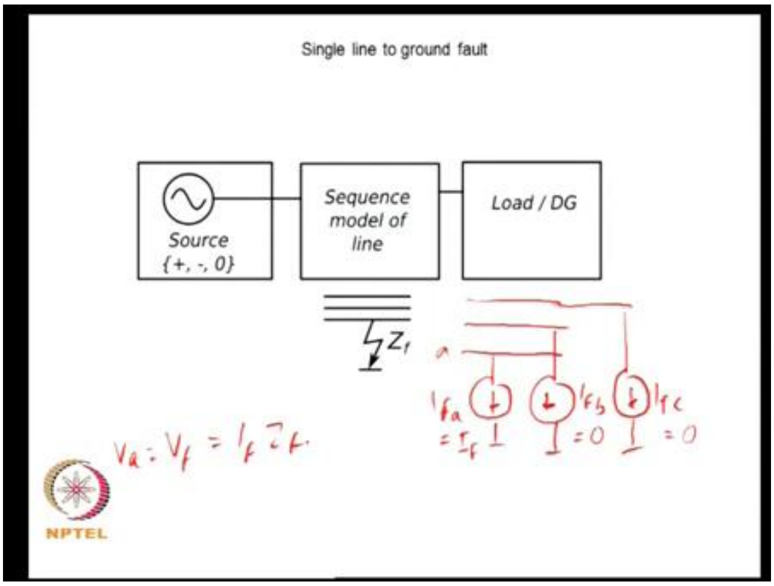

So, to analyze unbalance situation such as a single line to ground fault, essentially you need to identify the source, the line on which the fault is occurring and may be if the load is significant, may be you can have models for the load also. And your source, your line, the loads can be represented with the sequence models and we will assume again without loss of generality that your fault is happening on phase a, it can happen on any phase, but for analysis without loss of generality can assume it is phase a.

So, if you have a fault with fault impedance z f, you have a voltage on your phase a which is equal to V f and you have no fault and you have a corresponding fault current, i f flowing through the fault and you have no fault currents in phase b and phase c, because they are not connected to the point to the ground at which the fault is occurring. So, you can actually model this line by three current sources I f a and I f b and your I f a is equal to your actual fault current and your I f b is equal to 0 and your I f c is equal to 0.

And replacing your fault impedance with these current sources will not change the circuit in any way, because your current that you are actually extracting is exactly the same as what you had with your fault impedance. So, at the point of fault you have V a is equal to V f is equal to I f, Z f, so you can now write your sequence components of your voltage and current at the fault.

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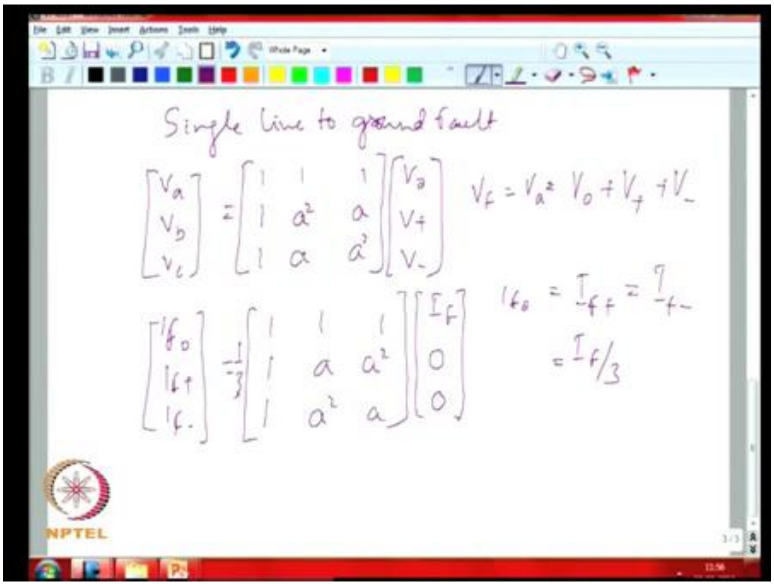

So, you have you have V a and we know our V f is equal to V a and is equal to, now if you take the first row of this matrix multiplication you get V 0 plus V plus V minus. And if you look at your corresponding currents, you can write your fault currents I f 0 I f plus I f minus as 1 3rd, I f is a fault current which is happening on phase a, phase b and phase c has 0 current at the fault. So, if you look at your fault current in terms of the sequence components, you have I f 0 is equal to I f plus is equal to I f minus and this is equal to I f by 3.

So, essentially now if you look at that constraints that you have, you have your V f to be equal to V 0 plus V plus plus V minus and the magnitude of the currents flowing through this sequence component models are equal. Then essentially what it reflects is a circuit that is connected in series, where the total voltage is a some of the individual voltages and the value of currents going through is the same, so you have components that are connected in series.

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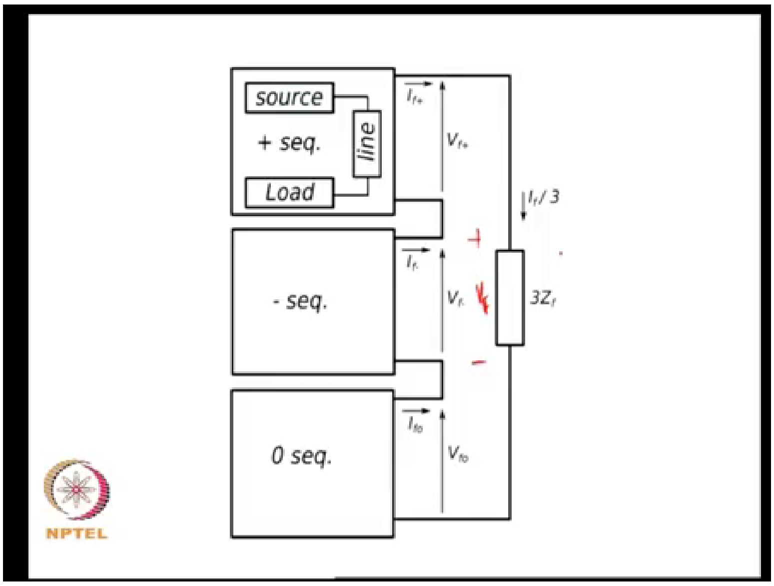

So, if you look at the model of what would be the equivalent sequence model to analyze this particular fault, you would have the three components connected in series. So, if you look at what goes into each of these box you have the positive sequence part of your circuit, put in to one particular part of the model, then you have negative sequence part, then you have the 0 sequence part, they are all connected in series. So, your I f plus I f minus and I f 0 they are equal and which is in turn is equal to I f by 3.

And if you look at the total voltage across the three components that is equal to your V f, which also happens to be your V a at the point at which the fault is occurring. And similar to what we have done over here for single line to ground fault, you can actually create models to analyze other varieties of faults such as line to line fault, line to line ground fault, open conductor faults and this type of analysis would be there in a power system text books.

So, we will not going to the detail will just look at a particular example, a common case of fault is single line to ground fault. So, with this we will look at an example where we have a synchronous machine feeding a particular line.

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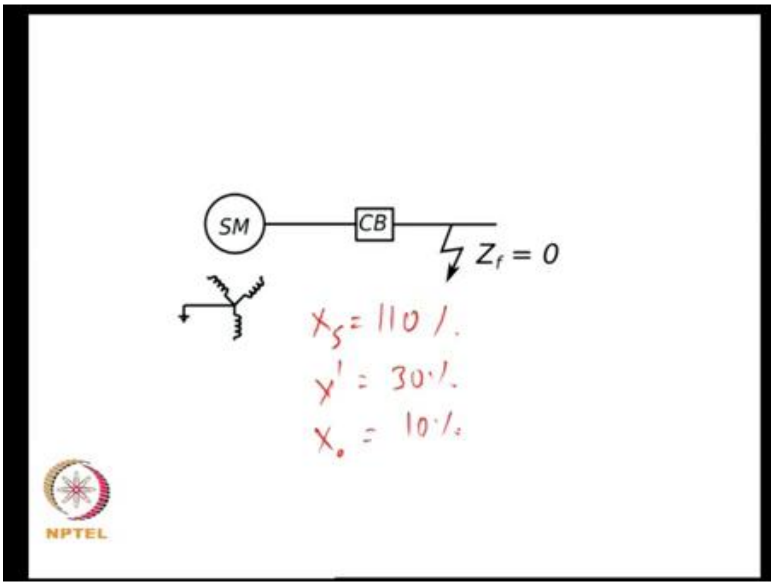

And you have a circuit breaker which you want to protect the line or the loads connected to the line and you have a fault on this line and you want to look at what your three phase fault current would be, and what your single line to ground fault current would be. And then, determine if you connect what would be the value of neutral reactance that you may want to connect to make sure that both the current levels stay similar. So, in this model will take say this is a synchronous machine, this might be a round rotor machine and non-saline pole machine. So, will take x s to be say 110 percent, your transient reactance to be 30 percent and your 0 sequence reactance to be 10 percent. So, if you now look at what the model would be for a three phase fault a on that particular machine.

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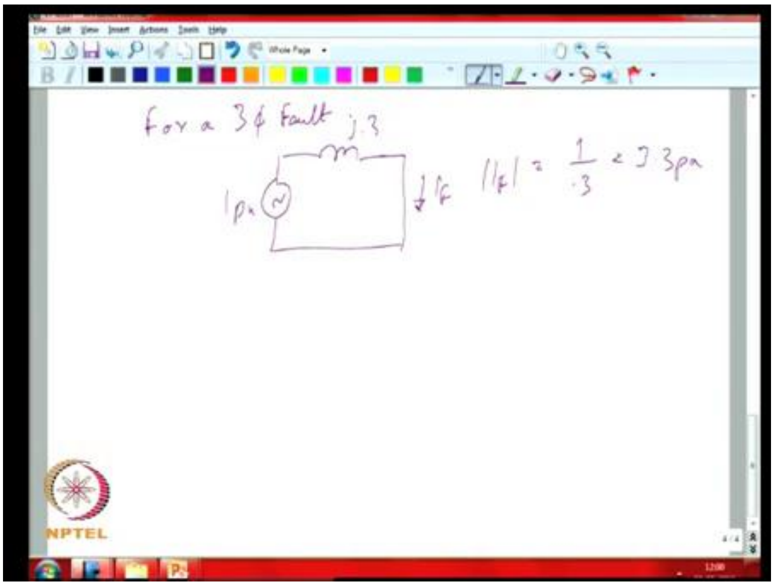

The circuit model would be straight forward 1 per unit, your reactance that limits the current is j point 3 and you are considering a solid fault and the resulting current is your I f and you can get your magnitude of I f. So, you would expect fault current of the order of 3.3 per unit, to flow when you have a solid three phase fault at the output of the machine.

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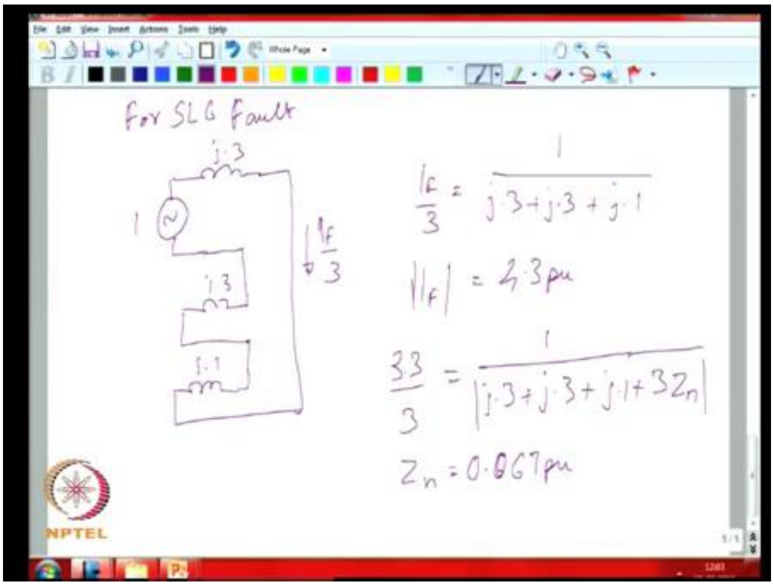

So, now the question is what happens when you have a single line to ground fault, so for the single line to ground fault you take your sequence components and assemble the network in series. So, your negative sequence model is just the impedance your 0 sequence model, so you get I f by 3 and you can calculate I f magnitude to be 4.3 per unit, so you can see that your single phase fault, now results in higher fault current than your three phase fault.

So, next you could ask what would be the value of a reactance that you would connect to the neutral of the machine, to make sure that your fault current stays similar to the three phase fault. So, if you connect a neutral impedance, essentially what you would have is your I f by 3 you want to be 3.3 per unit divided by 3 and you can calculate your Z n to be about 7 percent. So, if you had a added a 7 percent reactance to the neutral, then your single line to ground fault current level would be similar to that of the three phase fault current level.

So, now that we have seen how to calculate faults under a different fault conditions including unbalance, then we can ask the question what does it mean to protect some component, so the will look at the simplest case where you are protecting conductor, a piece of wire.

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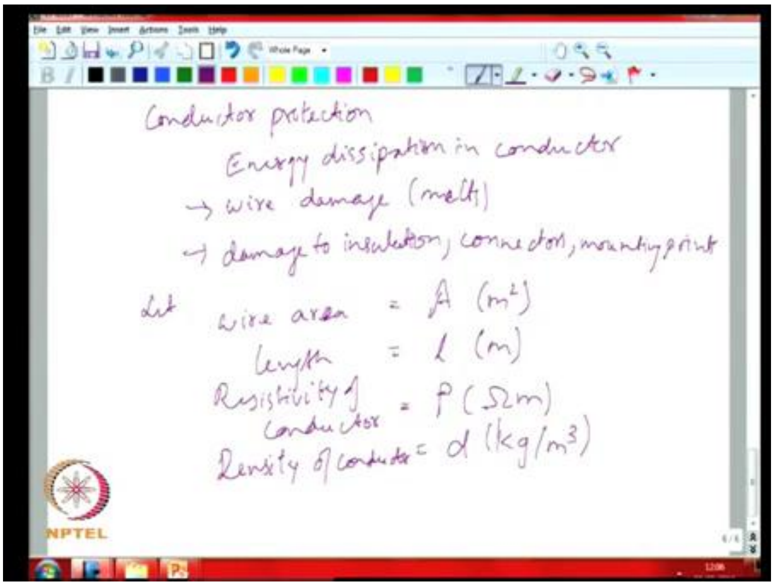

So, if you want to protect a piece of wire, it means that if you have fault you cause energy dissipation in the conductor, and you want to ensure that the energy dissipation does not cause damage either to the wire or to the insulation to the wire, can be damaged to insulation or to connectors where or the mounting points. So, whatever is required to ensure that the wire is in place, those things also need to be factored end when you are looking at conductor protection.

So, will take a look at wire, so if you have a wire of a given wire gauge we know it is a cross sectional area, if it is A m say meter square and the length of the wire is l in meters. And the resistivity of the conductor is rho in ohm meter and the density of the conductor is say d, so this is Kg per meter cubed.

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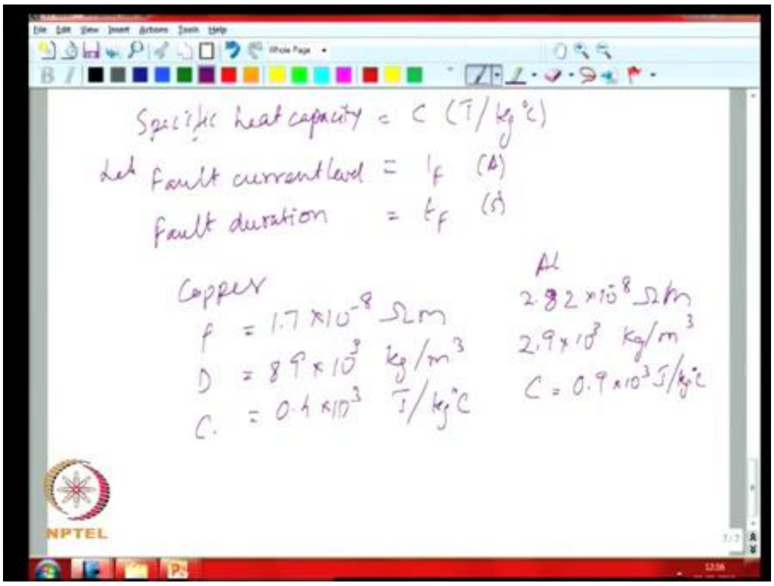

And we will assume that specific heat capacity of the conductor is C and this is in joules per Kg per degree centigrade, so you are talking about temperature rise, so centigrade and Kelvin is equivalent. And will also assume the fault current level is I f, so the fault current level is determined by your upstream impedance and your voltage behind it. And your fault duration is t f in seconds and this is determined by your protective device, which has to clear the fault.

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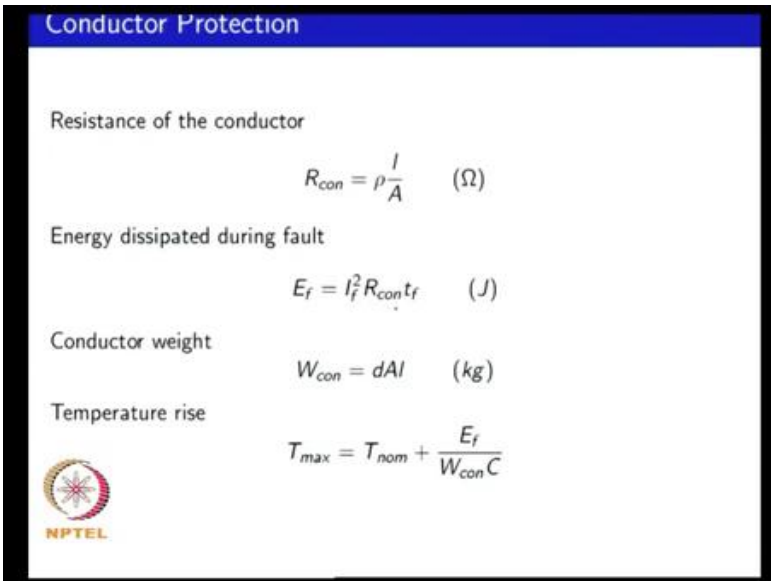

So, if you look at then, the resistance of the conductor, you know the resistance of the conductor is rho l by A is the value of resistance in ohm' s. And the energy dissipated during the fault is I square r is the power dissipated and I square r for a duration of t gives you the energy in joules, so E f is a energy dissipated in joules. So, if you have a conductor of weight will assume that the area of the wire is A, the length is l and d is the densities, so d, A, l is the weight of the wire, you can assume may be some cylindrical tube or...

So, you could make some assumptions and look at what the weight of the wire is and you get the weight, then you can calculate the temperature rise as a the maximum temperature would be your nominal temperature at which it is operating before you had the fault. Plus your energy that deposited during the fault divided by the weight in to a specific heat capacity.

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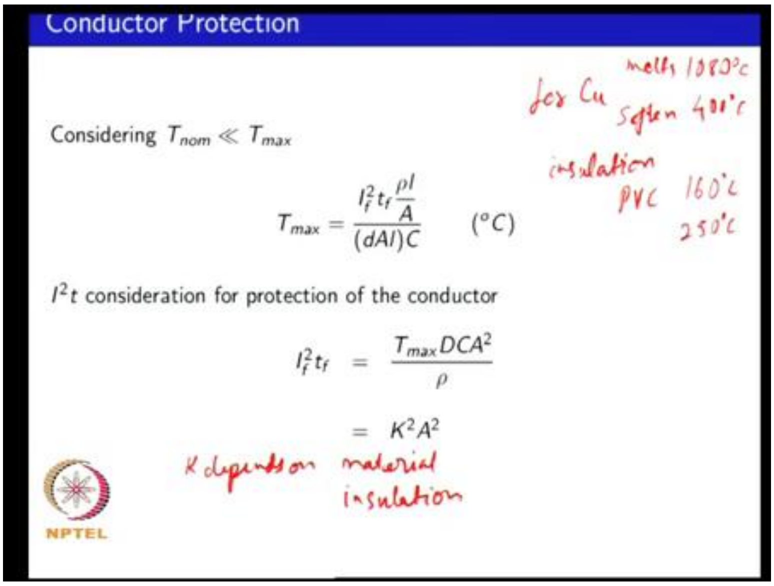

So, if you now write down the values of this particular components, essentially what would you get is a relationship between what you are a maximum temperature is and your parameters of the circuit, you could assume that a say for example, for a copper conductor, copper melts at about 1080 degrees. But, you do not have to wait till it melts, you can have copper softening, so if you are having it under compression in some crimped circuit you might see softening at around 400 degree centigrade, beyond which you can have mechanical deformations etcetera.

If you look at the insulation your PVC insulation will start getting damaged at 160 degree centigrade, and if you look at more sophisticated insulations such as x l p e or cross length polyethylene you are talking about may be 250 degree C. So, you get a feel for what the temperature can go up to and now you can write your maximum temperature as now I square t f times resistance divided by the weight into specific heat capacity. So, you can bring out your I square t f and you will get a relationship between I square t f for the conductor.

And the maximum temperature that you are allowing for the conductor, times the density specific heat capacity divided by the resistivity, times your cross sectional area square. So, you can think of it as some K square A square is essentially the I square t beyond which the particular piece of wire, particular conductor will get damaged and essentially what this means is that, if you have a protective device, which is protecting this particular conductor it is I square t has to be less than the value of the I square t at which your causing damaged to the wire.

So, the protective device should have lower value of I square t compared to the value that you have for your conductor. The second thing is if you want say a to look at what as you could do if for a piece of wire, if you double the area of cross section, essentially its ability to be stand a fault is getting enhanced by a factor of 4. So, you take a wire which is twice as thick, it can end your four times the I square t as the wire of half the cross sectional area.

So, with that we also need to keep in mind the assumption that you have, so we are assuming in this particular case all the heat that is deposited in is going into raising the temperature is, so we are neglecting or cooling effects. So, given the short time duration over which this is happening that it might be reasonably true, but if your fault is occurring for much larger time duration, you may have to give factors for your cooling effects, might change the T max it also ignores that the parameters that you typically take for resistivity etcetera is temperature dependent.

So, if you take a fixed parameter then; obviously, you are going to have an error, so this gives you a an idea of what the value could be your actual I square t can have need additional factors to be considered to look at what exactly would be the point at which your wire can get damaged. Because, you know that; obviously, at higher temperatures the resistance would increase, essentially reflecting in the resistivity being a function of temperature.

So, similar to what you have done for the wire, you could actually do similar analysis for other types of components, such as windings, coils, in transformers, machines, etcetera, to look at what would be the level at which you can cause damaged to the conductor. So, the other thing that you could look at is what could be the typical parameters, say if you are considering different types of materials, ((Refer Time: 35:53)) if you look at say copper.

So, you have coppers resistivity is 1.7 into 10 to the power of minus 8 ohm meter it is density is 8.9 into 10 to the power of 3 kilo gram per meter cubed, it is specific heat capacity is 0.4 into 10 to the power of 3 joules per kilo gram per degree centigrade, if you look at for aluminum say you have aluminum conductors rather than copper conductors, you have 2.82 into 10 to the power of minus 8 ohm meter for density it is 2.9 into 10 to the power of 3.

So, the resistivity of aluminum is not as good as that of copper is density is having a smaller value because it is lot lighter, it is specific heat capacity is 0.9 per degree centigrade. So, you could get a feel for what would be the resulting properties, if you have these different types of conductors.

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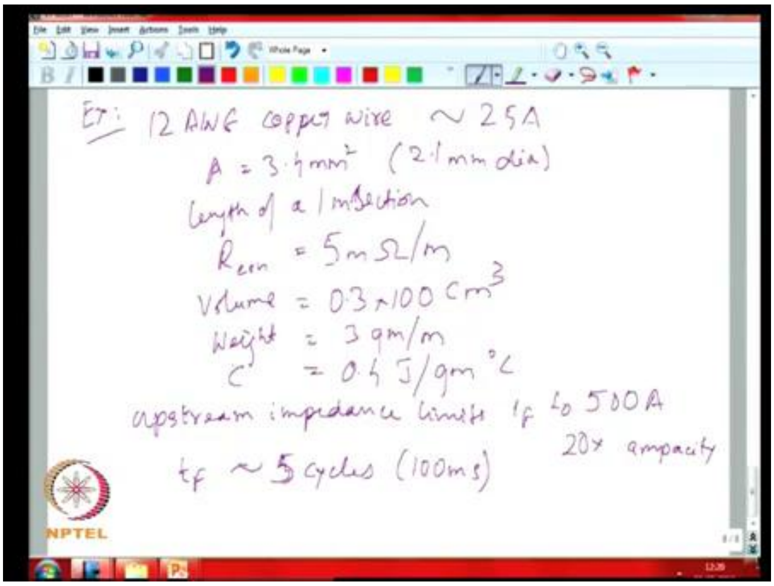

So, will look at an example to look at a piece of say 12 gauge wire and see what it takes to protect it. If you look at the ampacity of the wire it is roughly 25 amps, if you look at the wire tables, so you should be able to carry that level of current and if you look at again the wire tables would give it is cross sectional area of the wire is 3.4 m m square it is diameter is 2.1 m m corresponding to 12 wire gauge will consider a unit section as you saw in the formula previously, the lengths get cancelled out in the I square t expression will consider a unit length of wire.

So, if you look at the resistance of the conductor this is now 5 milli ohms per meter would be the resistance on a per unit length bases. And it is volume again for a unit length is 0.3 I would say it is volume per into 100 c m cubed, 100 centimeters in 1 meter. So, that gives you it is volume and then you can use that to calculate the weight is it turns out to be about 3 grams per meter. If you look at the specific heat, this turns out to be 0.4

joules per gram per degree centigrade and if you look at the fault current level, the fault current level is limited by the upstream impedance to 500 amps.

So, it is about 20 times it is ampacity, so doing a fault you get a high current flowing through the circuit. And then you can calculate, say you have a circuit breaker which now clears it on newly instantaneous bases, say will assume that your t f the fault duration is 5 cycles or 100 milliseconds. So, next you can calculate what is the energy dissipated during the fault duration.

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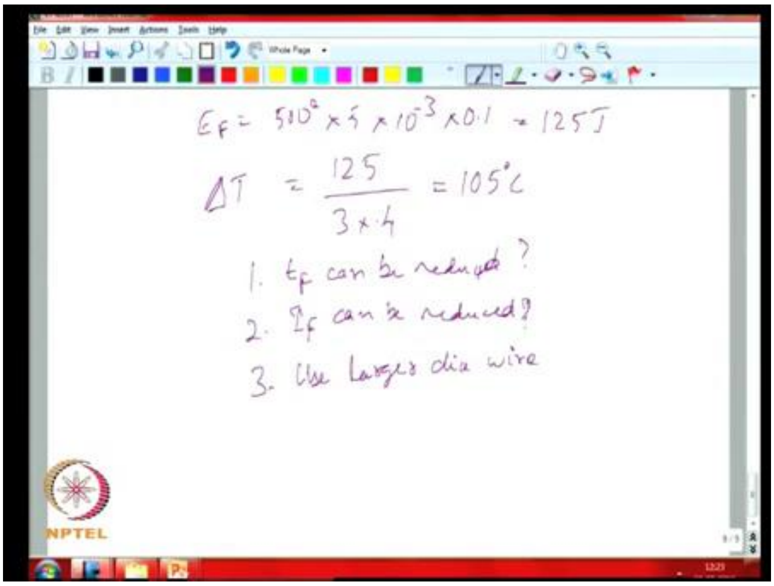

So, your E F I square r into your fault duration, so this is about 125 joules per unit length of the wire and if you look at then your corresponding temperature rise your delta T is the energy dissipated divided by your weight into specific heat capacity. So, that turns out to be about 105 degree centigrade, so if you are using a conductor where with P V C type of insulation and your ambient was under nominal conditions your wire was operating a closed to 50 degree centigrade in your cabinet.

Then during fault, if you have rise of 105 it is getting closed to the point where it is damaging the insulation. So, you could consider a few options at this point, one option is maybe you could look at a protective device, which can operate in a quicker manner may be 3 cycles rather than 5 cycles, many times you do not want to design your own special circuit breaker, you want to use the commercially available device.

So, you might be restricted in terms of how quickly it acts, it the commercially the available design might be 5 cycles might be what it is instantaneous trip duration is. The other thing that you could do is maybe you could see if your fault current level can be reduced below 500 amps, which would give you again margin in your temperature. Again it may not be possible to increase your temperature under your source impedance because it may not be directly under your control.

So, your first option was to see if t f can be reduced, the second was whether I f magnitude can be reduced. The other thing that you could do, which might be more directly under control is may be instead of a 12 gauge wire you use a thicker wire, you might choose a 10 gauge wire because you saw that your I square t goes as a square. Now, using the thicker wire will reduce the temperature to which it would go during the fault duration.

So, some of the things that you can see from this example is the fault, which stand capability of the wire is the parameter k that you saw in the expression over here ((Refer Time: 42:19)) depends on number of factors, it depends on the material. Whether it is copper or aluminum or some other alloy it depends on your insulation, whether it is P V C or X L P or whether it is a varnish or whether it is exposed conductor sitting on a ceramic.

So, you will have to look at the surrounding materials, you will have to look at the configuration, whether this cable is sitting within a sheet or whether there are multiple conductors, whether the reinforcement within the cable. So, you will have to look at these factors to actually determine what is the level at which you can you need to protect the wire. And then select the appropriate protective device in a appropriate manner or change the configuration in your design of what is the conductor that you would be using.

So, with this background now will look at what it means to actually do coordination in on a distribution system. So, we will look at the example, where say you have couple of circuit breakers a upstream breaker and a downstream breaker and you want to coordinate the operation of the two breakers.

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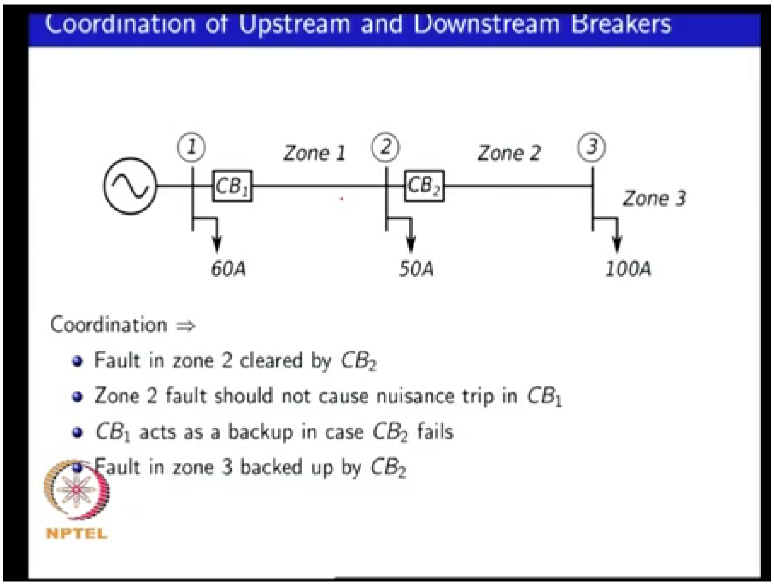

So, will look at an example where you have source you have 3 buses, bus 1 2 and 3 and you have the load set each of these buses 60 amps at bus 1 50 amps at bus 2 100 amps at bus 3. And you have two circuit breakers, circuit breaker 1 protecting zone 1 and circuit breaker 2 protecting zone 2 zone 3 is whatever is downstream of bus 3 and you have these wirings could be having different ampacity levels. So, you need to protect them appropriately, which could be reason why you have couple of breakers.

And then the question is what does it mean by having coordination between the two breakers, circuit breaker one and circuit breaker two. So, if you have a fault in zone 1; obviously, the protective device that needs to operate is circuit breaker 1 and if you have a fault in zone 2 the fault has to be created by C B 2. If you have fault in zone 2 what you want to avoid is new sense tripping of circuit breaker 1 because you want to may ensure that C B 2 operates before C B 1 acts.

For some reason if C B 2 fails then essentially you want to have C B 1 provide backup protection to the system and by if circuit breaker two fails, they may potentially be some damaged zone 2, but you do not want damage spreading to zone 1. If similarly, if you now have a fault in zone 3, essentially it might have it is own local protective devices, but if those protective devices fail you do not want the damage from zone 3 to actually affect your zone 1.

So, to do this analysis what you have to do is get the data on what would be the ranges of fault current levels that happen. Whether the fault is occurring closed to circuit breaker 1 or further away forced to circuit breaker 2, depending on your location, depending on the type of fault whether it is a 3 phase fault, single phase fault. Whether you have solid fault or some impedance in the fault, you can get a range of current levels that could occur in the circuit and you want to ensure that get a feel for what is the range that you are dealing with.

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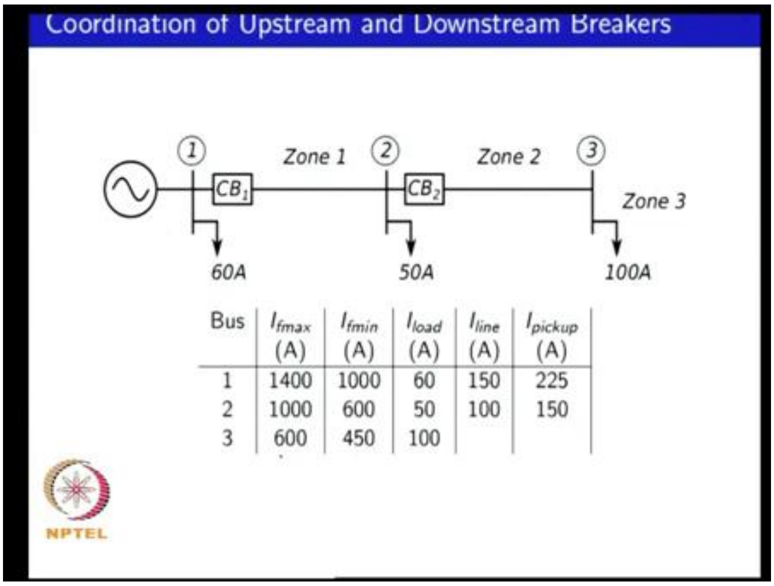

So, will assume that you have done your analysis and you have indentified range of current levels for this particular circuit. And for the circuit now you for example, at bus 1 you found that the range of fault current level is between 1000 and 1400 amps and the load at that particular bus is 60 amps, the nominal current that this circuit breaker would see is essentially the load from down it is downstream load, which is essentially 50 amps plus 100 amps that would be it is nominal current.

So, you put up a factor of safety of 1.5 and say your pickup current level for your circuit breaker 1 is 225 amps. Similarly, for circuit breaker 2 you find that the you do your analysis and find the range of fault current levels, so we have indicated that the fault current level is going to be between 600 and 1000 amps, the load at bus 2 is 50 amps and the breaker itself will see a nominal current level of 100 amps. So, will take a factor of 1.5 and take it is pickup current level as 150 amps.

And the fault downstream of bus 3 in zone 3 has a range of current levels between 450 and 600 amps. So, with this the question is how do we do coordination of these breakers, will also make an assumption on the protective devices that are used.

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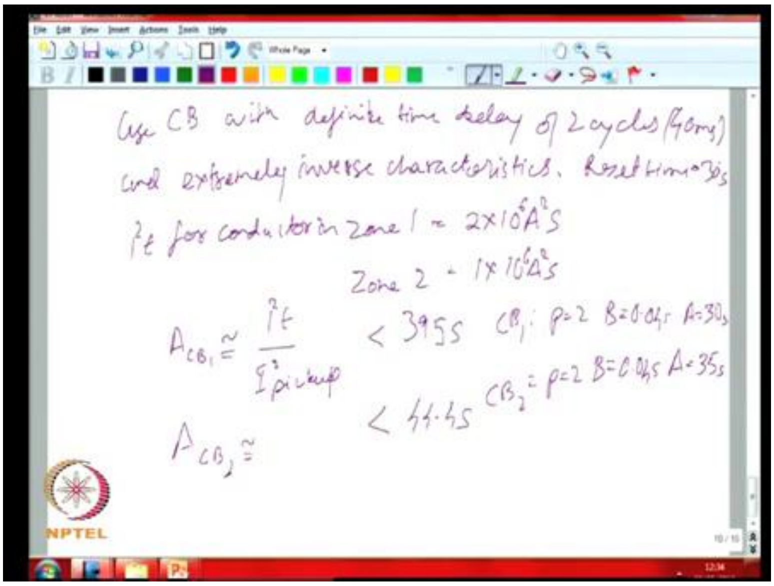

So, will use a circuit breakers with definite time delay of 2 cycles of 40 milliseconds and extremely inverse characteristics will assume that reset time is 30 seconds for both the breakers. And will assume that the I square t in zone 1 is 2 into 10 to the power of 6 ampere square second and for zone 2 is, so next we can calculate what you are A value for the circuit breakers would be and we saw we in a couple of classes back, we saw the relation between you are A and your circuit breaker pickup current and your I square t.

For extremely inverse characteristics we have A for C B 1, which is roughly given as I square t divided by I square pick up because A by m square would be your trip time. So, assuming taking your m to be i by i pickup you get this particular relationship, so you are A of your circuit breaker should now be less than 39.5 seconds for circuit breaker 1. And A for circuit breaker 2 is given should be less than 44.4 seconds, you know the I pickup value for the each section, each zone and you should be able to calculate your value of A.

So, now, you have your parameters for your circuit breaker, we will take circuit breaker 1 P is 2, B is 0.04 seconds and you are A will take a value less than 39, will take A is 30 30 seconds. And for circuit breaker 2 P is 2 because of it is extreme inverse characteristics B is 2 cycles and will take A to be 35 and we will see with this parameters. Whether, you could actually coordination at the range of current levels that where indicated in the data that you got from your analysis of fault current levels, we will do that in the next class.