Power System Analysis

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Lecture - 28

Unbalanced Fault Analysis

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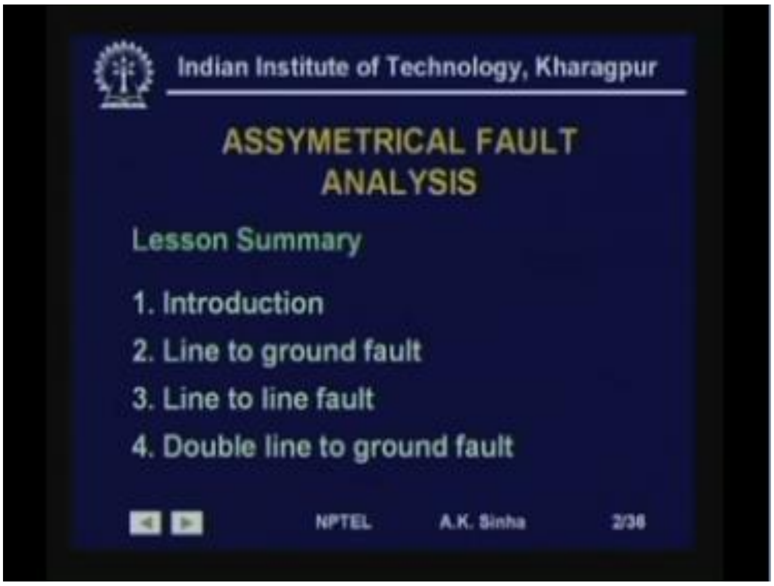

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ASSYMETRICAL FAULT ANALYSIS

Lesson Summary

1. Introduction
2. Line to ground fault
3. Line to line fault
4. Double line to ground fault

Discuss about the Analysis of Unbalanced Faults. We will first start with an introduction to unbalanced faults. Then we will talk about how to solve for fault currents, in case of line-to-ground fault, in case of line-to-line fault and double line-to-ground fault.

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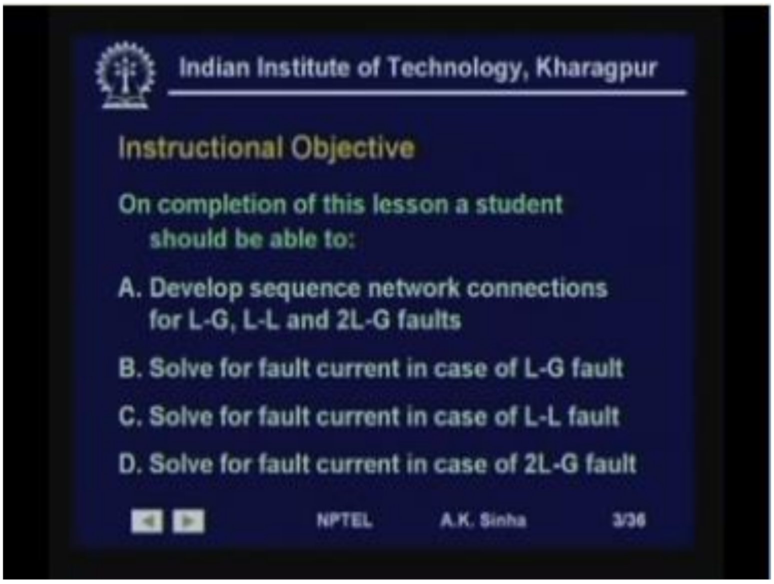

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Instructional Objective

On completion of this lesson a student should be able to:

A. Develop sequence network connections for L-G, L-L and 2L-G faults

B. Solve for fault current in case of L-G fault

C. Solve for fault current in case of L-L fault

D. Solve for fault current in case of 2L-G fault

On completion of this lesson you should be able to develop the sequence network connections for line-to-ground line-to-line and double line-to-ground faults. You should be able to solve for fault currents. In case of line-to-ground fault, in case of line-to-line fault and in case of double line-to-ground fault.

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Types of Faults

L – G Fault
L – L – G
L – L
→ Asymmetrical Faults

3ϕ – G → Symmetrical Fault

1ϕ – Open
2ϕ – Open
→ Asymmetrical Faults

Well as we had discussed earlier about the types of faults the we have said the most common fault which occurs is line-to-ground fault. The next most common is line-to-line-to-ground or double line-to-ground or line-to-line faults. These three faults which are much more common than the three-phase to ground faults are basically asymmetrical faults. Because, they create asymmetry in the current and voltage in the three-phases of the system.

Whereas a three phase or a three phase to ground fault is basically a symmetrical fault. Because they are in case of this fault the current and voltage symmetry in the three phases are maintained. Some other type of faults which are not short circuit faults, but open circuit faults are also present. And these are single line open faults or single phase open faults and two-phase open faults or two lines open.

Now, these faults again create asymmetry in current and voltage. Because, all these three-phases had do not have the same symmetry of current and voltages. When, these faults occur. Because, if you take single phase open, then there is no current in phase a. If the line in phase a is open whereas, there will be current flowing in phase b and c and so on

Therefore these are also asymmetrical faults. In this lesson we will deal with the first three faults that we had talked about here. That is line-to-ground fault line to line-to-ground, that is double line-to-ground fault and line-to-line faults. These are short circuit faults. And basically when these short circuit occur heavy currents flow in the system. And in order to protect the system we need to isolate the faults, which as we had discussed earlier is done by the circuit breakers, which gets the command from the protective relays, and therefore to arrange for the settings of these protective equipment. That is the relay setting and the circuit breaker ratings. We need to compute the fault currents in the system in the event of these faults.

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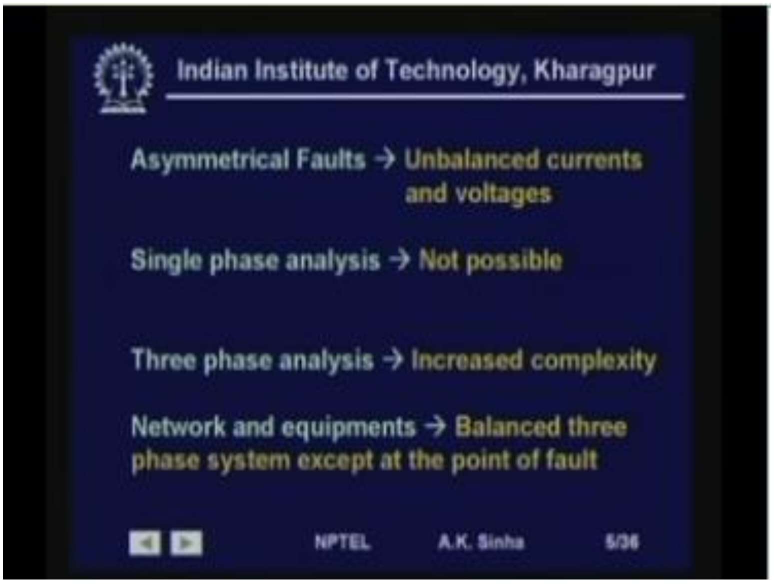

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Asymmetrical Faults → Unbalanced currents and voltages

Single phase analysis → Not possible

Three phase analysis → Increased complexity

Network and equipments → Balanced three phase system except at the point of fault

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Now, we will talk about asymmetrical faults as we have said, a asymmetrical faults create unbalanced currents and voltages in the system. That is the three-phase symmetry of current and voltages are no longer maintained. Therefore the single phase analysis which we could do can no longer be used in this case, should we repeat them. Therefore, we need to do a three phase analysis in this case. Because, all the three-phase currents and voltages need to be found out.

And this increases the complexity of the solution enormously. That is solving for the three phase system on a three phase basis is a much complex problem. Specially, in case of loss power systems. Now, we would like to understand what happens and how we can try and solve this problem. One of the things that we understand is that. Power system all the equipments are designed to operate as a balanced three phase system.

That is under normal operating condition the power system is always operating as a balanced three phase system. This may not be exactly true, but more or less this condition is maintained in normal operating condition. The all the generators the transformers the motors all these are designed as a balanced three phase system. So, generators will generate a balanced three phase voltage. And if a balance load is connected to the system that balanced three-phase currents will be flowing through the systems.

As far as transmission lines are concerned. We have discussed that we do make the transmission lines symmetrical by using transposition. And therefore, in this analysis we will assume that all equipment. And elements in the power system are balanced three-phase equipments. And therefore, the system or the model for all the three, all the components in the power system are same as a balanced three-phase system.

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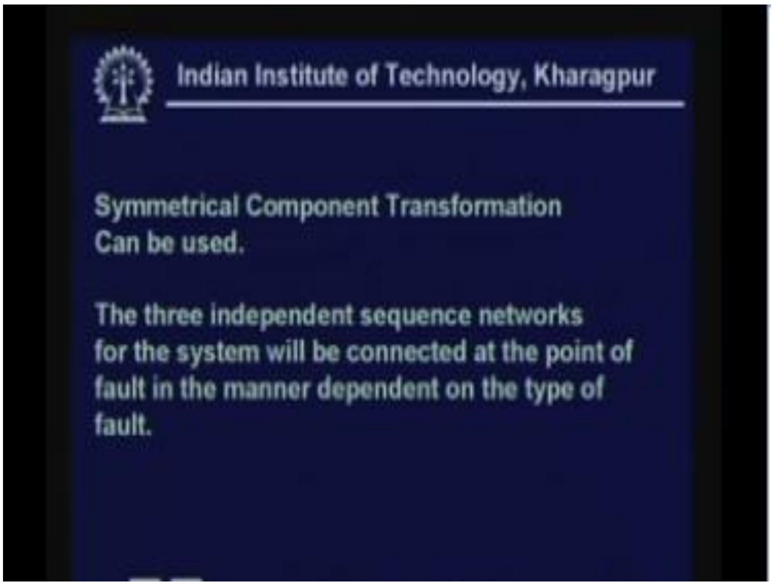

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Symmetrical Component Transformation
Can be used.

The three independent sequence networks for the system will be connected at the point of fault in the manner dependent on the type of fault.

Now, we have also seen in the earlier lesion that, in case we have balanced three phase systems then the, if the two are symmetrical component transformation. Then we will get three sequence networks. That is the positive negative zero sequence networks, which are independent of each other. So, when the system is a balanced three phase system. We get three uncoupled sequence networks.

It is only when the fault occurs which creates a asymmetry, then there is a connection which gets made between the three sequence networks. And the type of connection depends on the type of fault which has occurred. So, the three independent sequence networks for the system get connected at the point of fault in the manner dependent on the type of the fault. That is dependent on what type whether it is aligned to ground fault or a double line-to-ground fault or a line-to-line fault. The connection between the sequence networks will be different. And this connection occurs only at the point of fault. Whereas for the rest of the part of the system, we have the sequence network as we have developed for the system.

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Asymmetrical Fault Analysis

System Representation:

Before fault Power System operates in balanced steady state condition → +ve, -ve and zero seq. networks are uncoupled before fault.

On application of fault → Fault current consists of ac (Sub-transient → transient → steady state) current plus a dc offset current.

We compute the ac fault current and dc offset current is neglected or taken care by a multiplying factor.

Now, in order to do the asymmetrical fault analysis, we need to make a system representation for which we make certain kind of assumptions. For the system representation, we assume that before fault system operates in balanced steady state condition. This is a valid assumption, because when the fault has not occurred as we have said earlier. The system operates as a balanced three phase system.

Therefore the positive negative and zero sequence networks are uncoupled before the fault. On application of the fault current will flow. And this fault current as we have seen earlier consists of an AC component and a DC offset current. Now, this AC component can be a sub transient current. That we are looking at which means the current just after the time of application of fault or after sometime we get the transient currents and if we are looking at a larger time frame. Then we get the synchronous or the steady state current flowing in the system.

Generally as we have earlier discussed sub-transient impedances are much smaller. And therefore, sub-transient currents are larger. And therefore, most of the time we would be interested in finding out the sub-transient current, because that will determine the largest current. And therefore, will be useful in finding the ratings for the equipments.

Now, what do we do about this DC offset current. Generally what we do is we compute only the AC current. And for the DC offset current, what we do is we use some kind of a multiplying factor to create or to get a maximum asymmetrical fault current flowing in the system.

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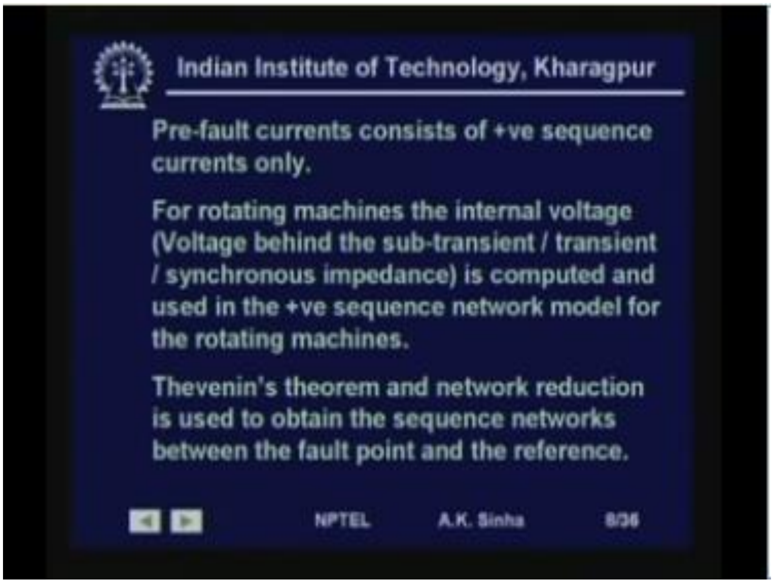

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Pre-fault currents consists of +ve sequence currents only.

For rotating machines the internal voltage (Voltage behind the sub-transient / transient / synchronous impedance) is computed and used in the +ve sequence network model for the rotating machines.

Thevenin's theorem and network reduction is used to obtain the sequence networks between the fault point and the reference.

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Now, as we have said earlier before the fault occurred the system works as a balanced three phase system. Therefore, pre-fault current consists of only positive sequence current. Because, we know that pre-fault condition the system is balanced and only the positive sequence network has the voltage sources.

Whereas the negative and zero sequence network do not have any voltage source. And therefore, if they are uncoupled from the positive sequence network, they are dead networks and no currents can flow in that. And therefore, only positive sequence current flows in the system under pre fault condition that is when the system is balanced.

For rotating machines, the internal voltages, that is the voltages behind the sub-transient transient and synchronous impedance is computed and used in the positive sequence network. This is what we had seen when we talked about the symmetrical three phase fault analysis in lesson 26.

So, we compute the internal voltage of when the load current is flowing. And we compute the internal sub transient voltage. And we use this voltage with the sub transient reactors as the source voltage in the positive sequence network, for the rotating machine models. Then we use Thevenin's theorem and network reduction to obtain the sequence network impedance between the fault point and the reference. So, we use the network reduction methods to obtain the Thevenin’s equivalent reactance or impedance between the fault point, and the reference for all the three sequence networks.

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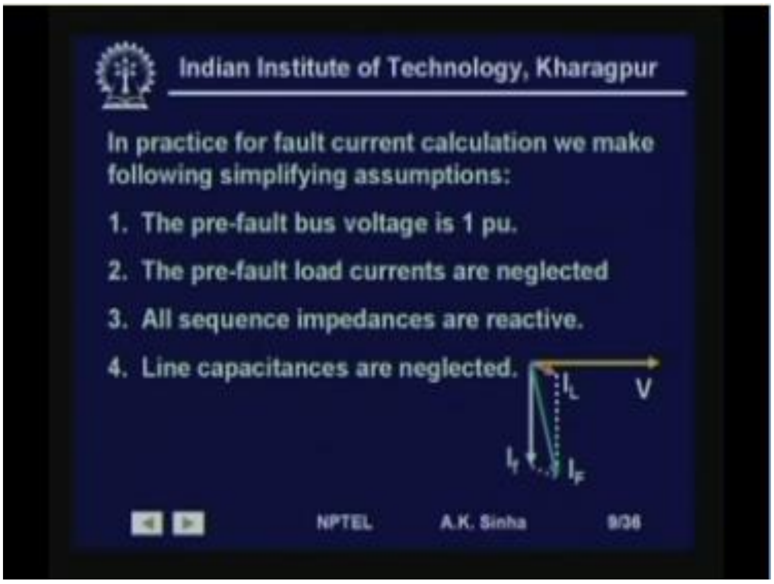

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In practice for fault current calculation we make following simplifying assumptions:

1. The pre-fault bus voltage is 1 pu.
2. The pre-fault load currents are neglected
3. All sequence impedances are reactive.
4. Line capacitances are neglected.

However in practice we make some more assumptions, because we have said earlier that pre fault currents are generally much smaller compared to the fault currents. So, most of the time we neglect the load impedances from the system representation. The main assumptions, that we make in case of fault analysis is that pre-fault bus voltage is 1 per unit. Now, this assumption is very much valid because under normal operating condition. The bus voltages in the power system are very near equal to 1 per unit.

The voltages may be of the order of 0.98 to 1.02 per unit kind of values. So, it is a valid assumption to assume that pre fault bus voltage is 1 per unit. We make another assumption that pre-fault load currents are neglected. That is we are assuming that before the fault occurred the system was unloaded. Now, this assumption appears to be somewhat erroneous, because certainly the system operates and it is operating under some load conditions.

However, if we look at this phasor diagram, where this is the voltage phasor. Then the load current phasor will be very much in phase with this voltage phasor, because the load currents will be having a power factor of the order of 0.85. 0.9 or so. So, therefore, the angle between the load current and the voltage will not be large.

Whereas, we know that the resistance of most of the equipments and power system are much smaller than the reactance. So, basically when a fault occurs it will be the reactive current, which will be flowing. That is the current that we get, when the fault occurs will be something like this. So, if on a unloaded system if the fault occurs the fault current will be something like this. That is it will be lagging the voltage by almost 90 degrees.

Now, if we want to see what will be the fault current, when the fault occurs. When the system was working under a load I L, load current I L. Then we will get that fault current by doing the phasor addition of the load current and the fault current I F. So, we will this I F I capital F will give us the actual fault current. Therefore, if we see these two currents we will find that these two currents will be very much in phase as well as very much equal in magnitude.

In fact, if there is, if the load the fault current is say about 8 to 10 times larger than the load current. Then the error that we get in case of neglecting this load current is only of the order of 1 percent or so. Therefore in most of the cases, we do make this assumption that the load current can be neglected. That is system is working unloaded before the fault.

So, pre-fault load currents are neglected. Another assumption that we make is that all sequence impedances are reactive, as I already said earlier that for most of the equipments in power system. The reactance is much larger compared to the resistance. And therefore, the resistance value is neglected most of the time. Also another assumption that we make is line capacitances are neglected.

Well, this assumption is made mainly because the line capacitances are basically trying to charging current. And discharging current is much smaller than the load current even the load current. And therefore, it is effect is hardly there when the fault current flows. And therefore, we can neglect this charging current, which means we can neglect the line capacitances.

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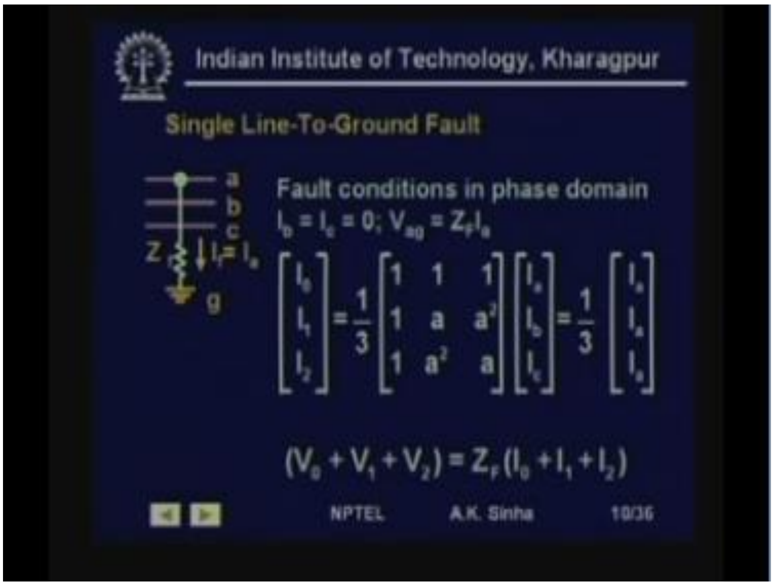

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Single Line-To-Ground Fault

Fault conditions in phase domain

$I_b = I_c = 0;\ V_{ag} = Z_f I_a$

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \frac{1}{3}\begin{bmatrix} I_a \\ I_a \\ I_a \end{bmatrix}$$

$$(V_0 + V_1 + V_2) = Z_f(I_0 + I_1 + I_2)$$

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Now, we will take up single line-to-ground fault. Now, here we are showing three phases a, b and c of r it may be a transmission line, may be terminal of an equipment, may be a bus. Here we are shown the fault has occurred on phase a which an impedance Z f 2 ground. So, this is a single line-to-ground fault or phase a with an impedance Z f.

Now, we could have taken fault on any phase, this a, b and c they have been put by s only. So, we could have put here b and c here and a here it does not matter. So, we could take fault on any phase a, b or c. For convenience we have taken this single line-to-ground fault on phase a. So, if we remembered the assumptions that we have made. There we had said that the pre-fault currents are zero.

That means the currents on phase b and c will be zero. That is I b and I c will be zero phase a is faulted. So, there is going to be current flowing into the fault. And therefore, this is the current that we would like to find out.

So, the conditions are I b and I c is equal to 0 and also for this faulted phase a, we have voltage between the fault point and ground. That is V a g is equal to Z f the impedance into I f, the current which is flowing through this impedance due to fault. So, Z f into I f, which is the same as the current I a, because pre fault currents are 0.

So, we have another condition as V a g, which is the phase a voltage is equal to Z f into I a. Now, if we write these conditions to find out the symmetrical components currents flowing into the fault. Then we will write get I 0, I 1, I 2 the symmetrical component currents at the fault point.

This is equal to the inverse of the symmetrical component transformation matrix which is 1 by 3 1 1 1 1 a a square 1 a square a this into the phase currents I a I b and I c. Of course here for the single line-to-ground fault condition we have I b is equal to I c is equal to 0. So, these two currents I b and I c are 0. So, if we now do this matrix multiplication. We will get this as equal to 1 by 3 I a. That is 1 by 3 1 into I a plus 1 into 0 plus 1 into 0. So, this makes it 1 by 3 I a.

Similarly, 1 by 3 into this 1 into I a plus a into 0 plus a square into 0, this again makes 1 by 3 I a. In the same way we have also this I 2 is equal to 1 by 3 into 1 into I a plus a squared into I b plus a into I c. So, that again gives us this I b I c being 0, this again gives us 1 by 3 I a. So, what we are getting is that at the fault point for a single line to ground fault the three sequence currents I 0 I 1 I 2 all are equal to 1 by 3 I a that is the sequence currents are equal.

From the other condition, that we have for the voltage V a g is equal to Z f into I a. We can write in terms of symmetrical component for V a, we have V 0 plus V 1 plus V 2 that is V a g you have the voltage at on phase a at the fault point. Is V 0 plus V 1 plus V 2 and this is equal to Z f into I a. And I a is equal to I 0 plus I 1 plus I 2. So, we have these two relationship, the sequence currents at the fault point I 0 I 1 and I 2 all are equal to 1 by 3 I a. And the voltage relations at V 0 plus V 1 plus V 2 is equal to Z f into I 0 plus I 1 plus I 2.

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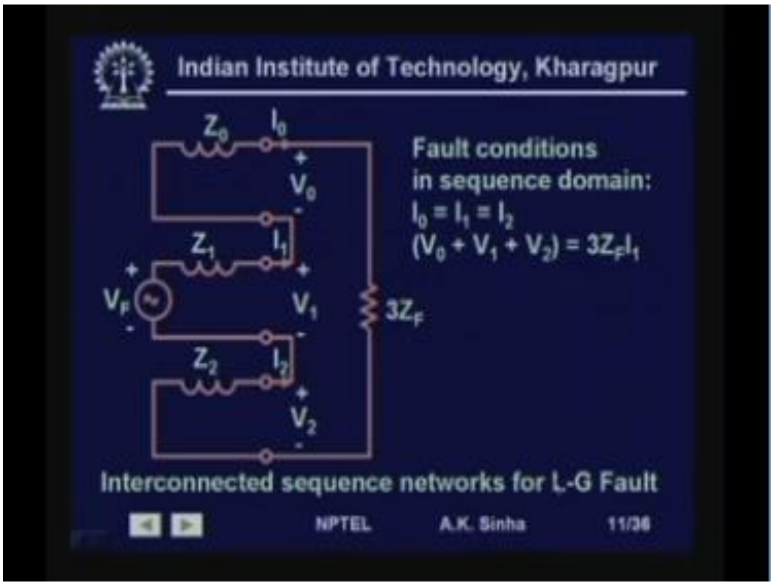

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Fault conditions
in sequence domain:
$I_0 = I_1 = I_2$
$(V_0 + V_1 + V_2) = 3Z_F I_1$

Interconnected sequence networks for L-G Fault

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So, here we get 3 times Z f into I 1. So, V 0 plus V 1 plus V 2 is equal to 3 times Z f into I 1. So, with these conditions for the sequence currents and voltage, if we draw the sequence network, then we have the positive sequence network, which is having the voltage at the faulted point pre-fault voltage at the faulted point V f.

Since, we have made an assumption that all pre-fault voltages have 1 per unit. So, this will be 1 per unit and this Z 1 the positive sequence impedance up to the fault point. This is what will be the positive sequence network. The zero sequence network will be Z 0 and the voltage across this is going to be V 0 the voltage across this is going to be V 1.

Similarly, this is a negative sequence network, where Z 2 the impedance there is no voltage source for zero sequence and negative sequence network. And the voltage across the negative sequence network is V 2. Now, we have V 0 plus V 1 plus V 2 is equal to 3 times Z f into I 1. Now, since this V f is the only voltage source and I 1 is the current flowing here. And I 1 is equal to I 0, which is equal to I 2. So, it shows that we are going to have a series connection between them. And V 0 plus V 1 plus V 2 is equal to 3 times Z f into I 0 or I 1.

So, this is going to give us the final connection between the sequence networks. So, this is what we get the three sequence networks are connected in series with an impedance three Z f connected in series with this.

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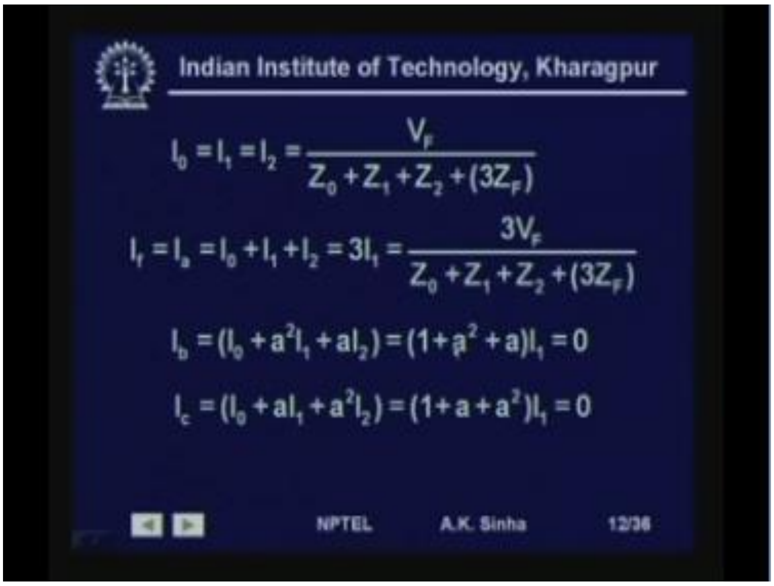

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$$I_0 = I_1 = I_2 = \frac{V_F}{Z_0 + Z_1 + Z_2 + (3Z_F)}$$

$$I_f = I_a = I_0 + I_1 + I_2 = 3I_1 = \frac{3V_F}{Z_0 + Z_1 + Z_2 + (3Z_F)}$$

$$I_b = (I_0 + a^2 I_1 + aI_2) = (1 + a^2 + a)I_1 = 0$$

$$I_c = (I_0 + aI_1 + a^2 I_2) = (1 + a + a^2)I_1 = 0$$

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So, from this network if we need to find out the currents. The current I 0 is equal to I 1 is equal to I 2 will be equal to the voltage V f, here divided by all the impedances which are connected in series, so Z 1 plus Z 0 plus 3 Z f plus Z 2. Therefore we have here I 0 is equal to I 1 is equal to I 2 is equal to V f by Z 0 plus Z 1 plus Z 2 plus 3 Z f. And what is I f, I f is equal to I a, which is equal to I 0 plus I 1 plus I 2, which is same as 3 I 1.

Therefore this is equal to 3 times Z f into Z 0 plus Z 1 plus Z 2 plus 3 Z f. And this V f as we have as we have said earlier we assume it to be 1 per unit. Now, once we know this Ia. Or If we can calculate the other phase currents also I b is equal to I 0 plus a square I 1 plus a I 2, which since I 0 is equal to I 1 is equal to I 2. So, this can be written as 1 plus a squared plus a I 1, which is going to be equal to 0 only. Because 1 a square is basically lagging this by 240 degrees and this a is lagging 1 angle 120 degree.

Therefore this is what we are going to get this is showing a unit phasor three phase phasor, which is symmetrical and balanced. Therefore, the sum is equal to 0. Same thing for I c I c is equal to I 0 plus a I 1 plus a square I 2. This again comes out to be 1 plus a plus a square into I 1 this term again is a balanced unit phasor. So, this is 0. So, this we get I b is equal to I c, which is 0. This is we had seen earlier also when we described condition in phase variables for a single line to ground faults.

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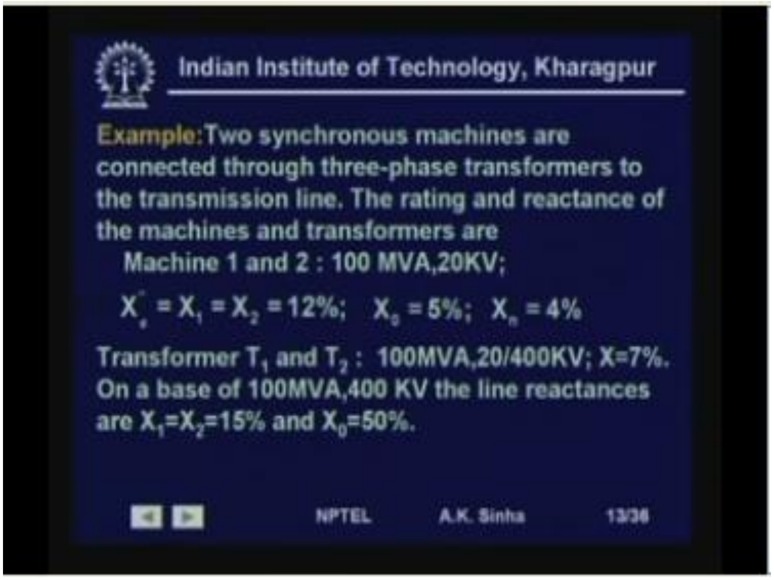

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Example: Two synchronous machines are connected through three-phase transformers to the transmission line. The rating and reactance of the machines and transformers are

Machine 1 and 2 : 100 MVA,20KV;

$X_d'' = X_1 = X_2 = 12\%$; $X_0 = 5\%$; $X_n = 4\%$

Transformer T_1 and T_2 : 100MVA,20/400KV; X=7%. On a base of 100MVA,400 KV the line reactances are $X_1 = X_2 = 15\%$ and $X_0 = 50\%$.

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Now, let us take a small example to see how this works. We have two synchronous machines connected through a three phase transformers to the transmission line. That is the two machines are connected to each other by means of transformers and a transmission line as shown in the figure.

The rating and the reactances of the machines and the transformers are machine one and machine two are rated at 100 MVA, 20 KV. And thus direct thus direct axis sub-transient reactance is equal to X 1. That is a positive sequence reactances is equal to negative sequence reactance is equal to 12 percent on the base machine base.

At zero, the zero sequence reactances is 5 percent and the machine is connected it is neutral is grounded through a reactance of 4 percent. Transformer T 1 and T 2 are again rated at same 100 MVA 20 KV to 400 KV that is the lines side voltages 400 KV, whereas generators had voltages 20 KV.

The reactance of the transformer is 7 percent on the base of 100 MVA 400 KV. That is on the high voltage side, it will be same on the low voltage side, because we are using per unit system. The line reactances are X 1 X 2 is equal to 15 percent and X 0 is equal to 50 percent on 100 MVA 400 KV base. So, these reactances again, since the transformer is 20 KV to 400 KV. So, these are also again on the same base.

So, we do not need to convert them to different base. If the values are given at different basis we need to convert them to the same base.

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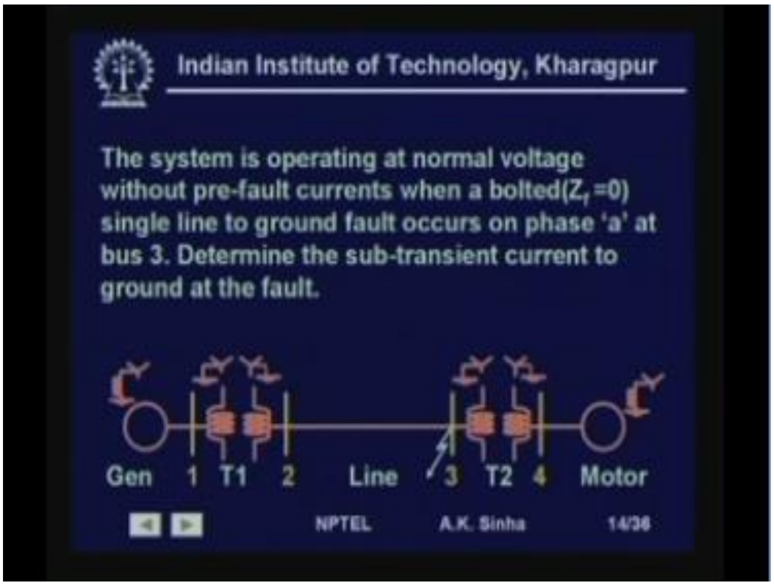

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The system is operating at normal voltage without pre-fault currents when a bolted(Z_f =0) single line to ground fault occurs on phase 'a' at bus 3. Determine the sub-transient current to ground at the fault.

The system is operating at normal voltage without pre-fault currents. That is we are assuming the system to be unloaded before the fault. That is pre-fault currents are assumed to be 0 and the voltages are 1 per unit.

When a bolted that is Z f is equal to 0 single line-to-ground fault occurs on phase a at bus 3. Determine the sub-transient current to ground at the fault. So, we have the system this is a generator. These are this is the transformer T 1, this is a transmission line, this is another transformer T 2 and this is the motor connected.

These are all having start grounded system. Whereas, the motor and the generators are grounded through an a reactance. Now, the problem says a fault occurs on bus 3 on phase a that is single line to ground fault is occurring at this point. We need to find out the fault current.

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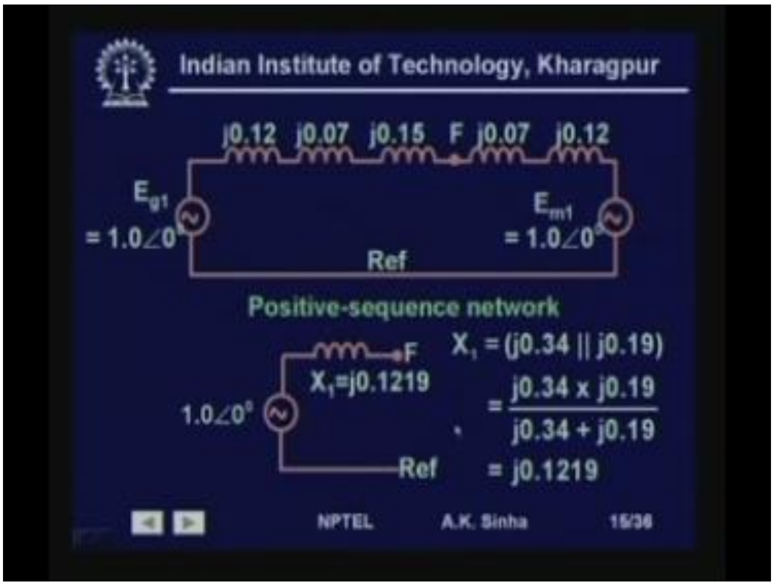

Positive-sequence network

$$X_1 = (j0.34 \parallel j0.19) = \frac{j0.34 \times j0.19}{j0.34 + j0.19} = j0.1219$$

Now, first what we need to do is create the positive negative and zero sequence network for the system and find out the reduced network at the fault point. So, if we take the positive sequence network then we are assuming the normal voltage which is 1 per unit for the generator and same is for the motor.

The reactance of the generator is 12 percent. So, j 0 point 1 2 the reactance of the transformer is 7 percent that is j 0.07. The transmission line positive sequence reactances is given as 0.15 percent that is j 0.15. The fault has occurred at this point that is at the bus which connects the transmission line and the transformer on the motor side. So, this is the fault point and we have this transformer reactance having 7 percent that is j 0 this is the sub-transient reactance after motor. So, this is j 0.1 to 12 percent.

The voltage is given as 1 per unit since there was no current flowing initially. So, the voltage angles are also assumed to be 1 per unit as 0 degrees. So, this is our positive sequence network that we have. Now, what we need to do is find out the impedance between this F and the reference.

So, what we do is we will short these two voltage sources and then find the impedance between these two points. So, that will show that this 0.19 is in parallel with 0.34. So, this is what we have written X 1 is equal to j 0.34 in parallel with j 0.19. This comes out to be this is equal to j 0.34 into j 0.19 divided by j 0.34 plus j 0.19. That gives the reactance to be 0.1219 between fault point and the reference. And the voltage source is one and with 0 degree. So, this is the reduced positive sequence network at the fault point.

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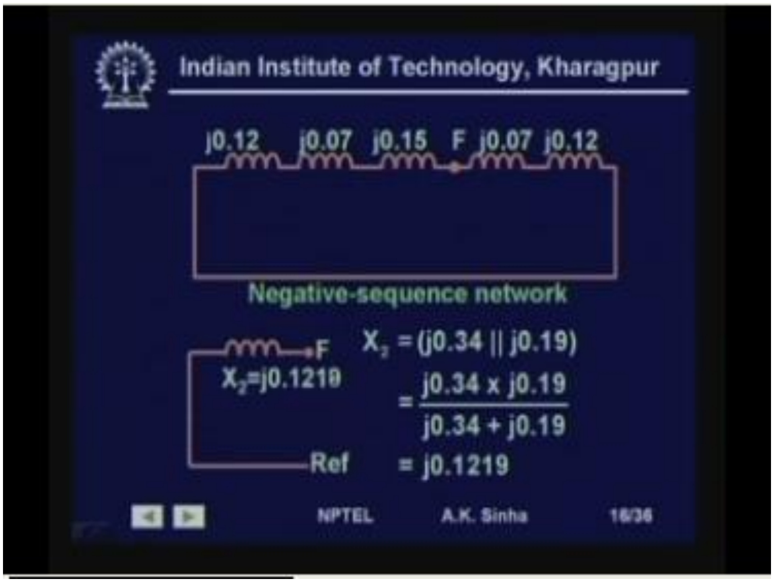

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Negative-sequence network

$$X_2 = (j0.34 \parallel j0.19) = \frac{j0.34 \times j0.19}{j0.34 + j0.19} = j0.1219$$

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Similarly, we can draw the negative sequence network there everything is same except that there is no voltage sources for the generator or motor, because there are no negative sequence generating sources. So, this is the dead network and between this fault point and the reference point we can again find out the reactance or the impedance for the negative sequence network this again comes out to be same thing.

J is 0.34 in parallel with j 0.19 which gives us j 0.1219. So, this is the reduced negative sequence that were for the system with with respect to the fault point. Now, for zero sequence network what we have is negative zero sequence reactance of the generator is 5 percent which is j 0.05 and the grounding reactance is 4 percent. So, here we will get 3 times X n. So, we have got j 0.1 to 3 times 0.04.

So, this will be the reactance here for the transformer positive negative and zero sequence reactances are same. So, j 0.07, the transmission line zero sequence reactance is much higher and in the problem it is given that this is equal to 0.50. This is the fault point F, then the transformer reactance which is again 7 percent j 0.07. The machine or the motor reactance again is j 0.05 and this is the grounding reactance 3 times the grounding reactance to j 0.12.

Again between fault point and reference, we can reduce this network. This comes out to be X 0 is equal to j 0.74 in parallel with j 0.24 this comes out to be equal to j 0.1812. So, this is going to be the zero sequence reduced zero sequence network for the system.

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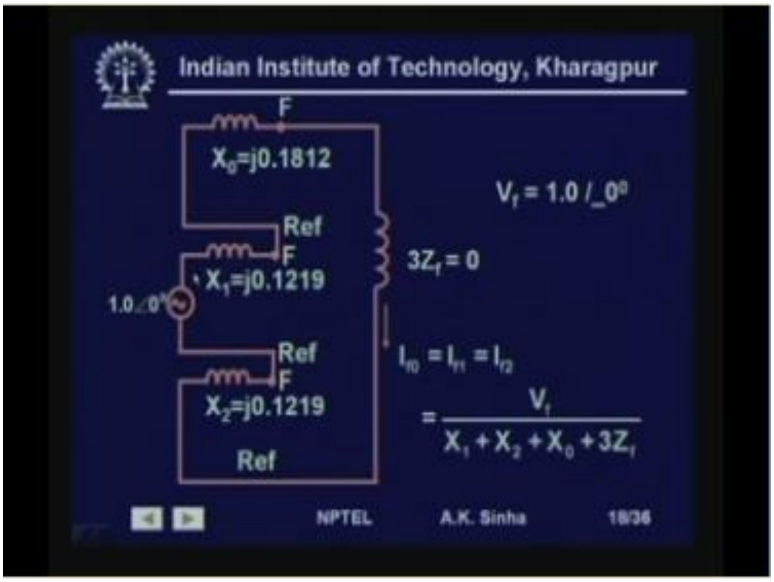

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$V_f = 1.0\angle 0^0$

$$I_{f0} = I_{f1} = I_{f2} = \frac{V_f}{X_1 + X_2 + X_0 + 3Z_f}$$

NPTEL A.K. Sinha 18/36

So, now what we have is for a single line to ground fault as we have seen. We have the three networks in series. So, this is the positive sequence network this voltage source and the positive sequence reactance zero sequence network no source. And the zero sequence reactance. The negative sequence network with the negative sequence reactance have no source. So, all these are connected in series.

Now, this 3 Z f is here, but here Z f is equal to 0, because the fault is a bolted fault. So, this is 0. So, what we need to do is calculate the fault current. So, first we will calculate the sequence current I 0, I 1, I 2 all will be equal. So, I f 0 I f 1 and I f 2, which is the fault current zero sequence, positive sequence, negative sequence, this is equal to V f this is 1 angle 0 divided by X 1 plus X 2 plus X 0 plus 3 Z f this is 0. So, we substitute the values. So, I f 1 is equal to 190 degrees, this should be 0 degree 1 0 degree this is the voltage source. So, 1.0 angle 0 degree, this is that divided by X 1 plus X 2 plus X 0.

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$$I_{f1} = \frac{1\angle 90}{j(.1219 + .1219 + .1812)}$$

$$= -j2.353$$

total fault current is $I_f = 3I_{f0} = -j7.059\text{p.u.}$

NPTEL A.K. Sinha 19/36

So, j 0.1219 plus j 0.1219 plus j 0.1812, so this comes out to be equal to j 2.353. So, this is the positive sequence current, this is same as the negative sequence current, this is same as the zero sequence current. The total fault current I f will be equal to 3 times I f 0 or I f 1. So, this is equal to j minus j 7.059 that is 3 times this value. So, what we see is 7 per unit current flows in the fault, when a single line to ground fault occurs at bus 3 of this system.

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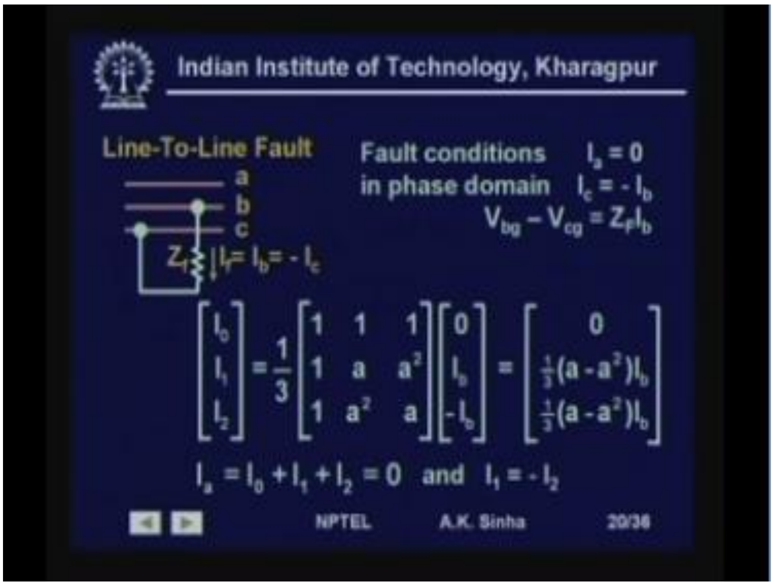

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Line-To-Line Fault

Fault conditions in phase domain $I_a = 0$

$I_c = -I_b$

$V_{bg} - V_{cg} = Z_f I_b$

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} 0 \\ I_b \\ -I_b \end{bmatrix} = \begin{bmatrix} 0 \\ \frac{1}{3}(a - a^2)I_b \\ \frac{1}{3}(a - a^2)I_b \end{bmatrix}$$

$I_a = I_0 + I_1 + I_2 = 0$ and $I_1 = -I_2$

NPTEL A.K. Sinha 20/36

Now, let us take another kind of fault that is line to line fault. Now, for line to line fault we have the fault occurring at any bus, where between bus b phase b and c are faulted through an impedance Z f. So, now since we have assumed no pre fault currents which means I a is equal to 0. So, fault conditions in phase domain are I a is equal to 0, I b is flowing like this, I c is flowing like this. So, I b is equal to minus I c. So, I c is equal to minus I b.

And we have V b g, that is voltage from this point to ground minus V c g, that is V b c will be equal to Z f into I b Z f into I b the current flowing in this direction. So, this is what is the condition for the line to line fault in the system, when the line to line fault occurs on phase b and c

Of course a, b, c are only given bias it can be phase b or c i can always rename it as c b a or whatever we like. So, it basically means any two phases. So, generally we put this fault on phase b and c. So, this is the condition. Now, we would like to transform these conditions into sequence domain.

So, we have sequence currents I 0, I 1, I 2 is equal to 1 by 3 into 1 1 1 1 a a squared 1 a squared a. This is the a inverse matrix 1 by 3 into this. And here the condition is I a is 0, I b we have and I c is equal to minus I b. So, if we do this multiplication what we find is this is I 0 I 0 then we have I 1 is equal to 1 by 3 a minus a square I b. And I 2 is equal to 1 by 3 a minus a squared I b this should be minus here. Minus 1 by 3 a minus a square I b or it can be 1 by 3 a square minus a I b. If you see from here I 2 is equal to 1 by 3 1 into 0 and then a square into I b and minus a into I b So, this should be a square minus a into I b or minus 1 by 3 a minus a square I b, this is a mistake here it should be minus here. So, and we have I a is equal to I 0 plus I 1 plus I 2, which is equal to 0. And I 1 is equal to minus I 2. So, this is one condition that we get that is I 1 is equal to minus I 2.

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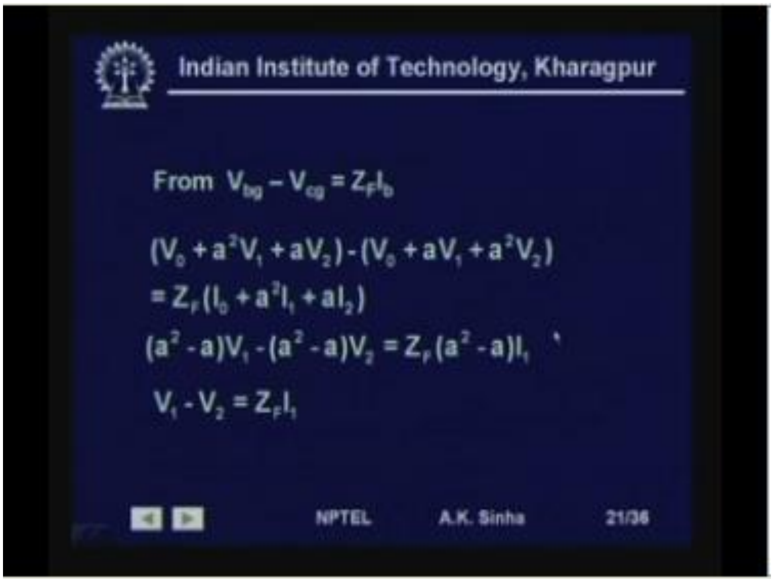

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From $V_{bg} - V_{cg} = Z_F I_b$

$$(V_0 + a^2V_1 + aV_2) - (V_0 + aV_1 + a^2V_2)$$
$$= Z_F(I_0 + a^2I_1 + aI_2)$$
$$(a^2 - a)V_1 - (a^2 - a)V_2 = Z_F(a^2 - a)I_1$$
$$V_1 - V_2 = Z_F I_1$$

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Now, from V b g minus V c g is equal to Z f into I b. We can substitute the value. So, V b we are substituting here in terms of sequence voltages. And V c we are substituting here in terms of sequence voltages. So, V b minus V c is equal to Z f into I b.

And once we organize this equation then we get a square a into V 1 minus a squared minus a into V 2 is equal to Z f a square minus a into I 1. So, this a square minus a will cancel out in all of them. So, V 1 minus V 2 is equal to Z f into I 1. So, this is the other condition, that we have V 1 minus V 2 is equal to Z f into I.

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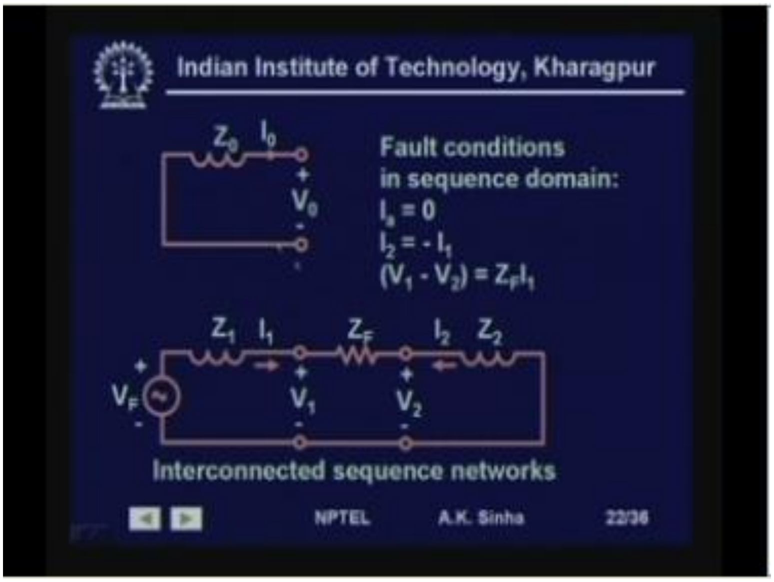

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Fault conditions
in sequence domain:
$I_a = 0$
$I_2 = - I_1$
$(V_1 - V_2) = Z_F I_1$

Interconnected sequence networks

NPTEL A.K. Sinha 22/36

So, we see that I 0 is equal to 0; that means, the zero sequence network is open. And since there is this network there is no voltage source. So, this V 0 has no meaning. So, this network is a dead network as such.

We have I 2 is equal to minus I 1. So, this is the positive sequence network and this is the negative sequence network and this current I 2 is flowing in this direction and I 1 is flowing in this direction. So, I 2 is equal to minus I 1 or I 1 is equal to minus I 2. And also we have this is the voltage V 1 here and this is the voltage V 2 here V 1 minus V 2 is equal to Z f into I 1. V 1 minus V 2 is equal to Z f into I 1 current flowing here, so Z f into I 1. So, this is the sequence network connection that we get. That is positive and negative sequence network are connected across each other through an impedance Z f.

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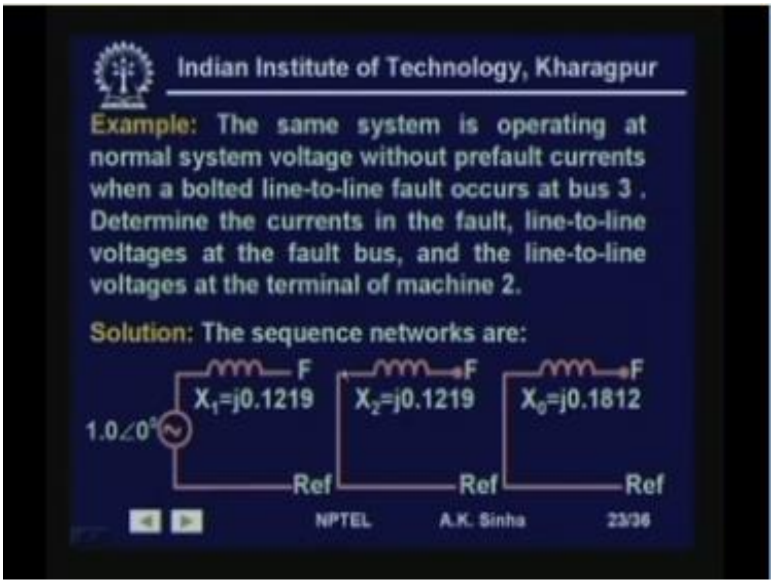

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Example: The same system is operating at normal system voltage without prefault currents when a bolted line-to-line fault occurs at bus 3 . Determine the currents in the fault, line-to-line voltages at the fault bus, and the line-to-line voltages at the terminal of machine 2.

Solution: The sequence networks are:

NPTEL A.K. Sinha 23/36

So, now again we can work out for a line to line fault for the same system with the fault occurring at the same point that is at bus 3. So, we take the same example the positive sequence network reduced to the fault point is the same one negative and zero sequence network, which we have already done in the earlier example.

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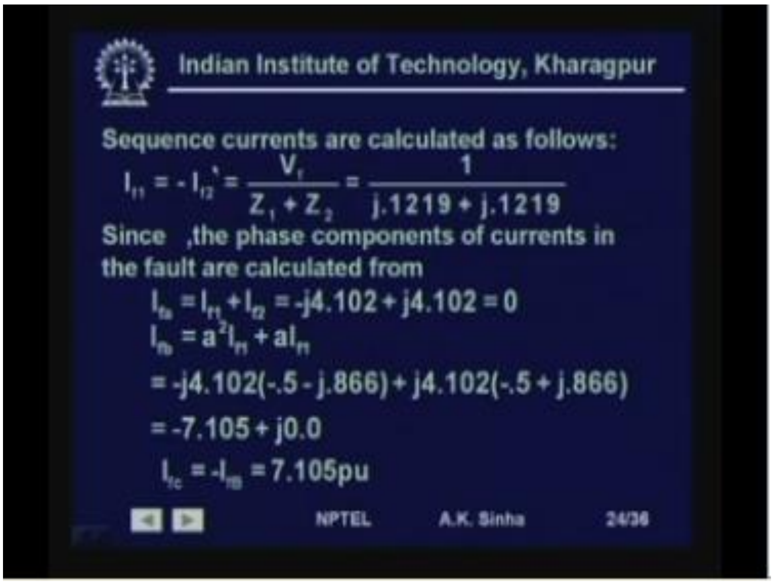

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Sequence currents are calculated as follows:

$$I_{f1} = -I_{f2} = \frac{V_f}{Z_1 + Z_2} = \frac{1}{j.1219 + j.1219}$$

Since ,the phase components of currents in the fault are calculated from

$$I_{fa} = I_{f1} + I_{f2} = -j4.102 + j4.102 = 0$$

$$I_{fb} = a^2 I_{f1} + a I_{f1}$$

$$= -j4.102(-.5 - j.866) + j4.102(-.5 + j.866)$$

$$= -7.105 + j0.0$$

$$I_{fc} = -I_{fb} = 7.105pu$$

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So, now the sequence currents can be calculated as follows. I f 1 is equal to minus I f 2 and this will be equal to 1. If we see here this is V f. So, V f divided by Z 1 plus Z f plus Z 2. And since Z f is equal to 0. So, we have I f 1 is equal to minus I f is equal to minus I f 2 is equal to V f by Z 1 plus Z 2 which is 1 angle a 0 divided by j 0.1219 plus j 0.1219, which comes out to be equal to I f 1 will come out to be equal to j minus j 4.102 and if we see what is the current I f a. I f a is equal to If 1 plus If 2 plus If 0 since If 0 is equal to 0.

Therefore I f a that is fault current in phase a is equal to this plus this. If we see this then this comes out to be zero, because this is the value that we will get for I f 1 and I f 2 is negative of that, So this is equal to 0. I f b is equal to a square I f 1 plus a I f 1 plus a I f 2 plus I f 0 I f 0 is 0. Therefore, this is equal to minus j 4.102 minus 0.5 minus j 0.866 this is a squared. And then this is a into I f 2 this is I f 2. So, this is equal to this. So, when we do add this up we will get this as equal to minus 7.105 plus j 0.0.

And since I f c is equal to minus I f b. Therefore, this is equal to 7.105 per unit. So, we can calculate the phase currents in phase a b and c for the fault line to line fault which has occurred between phase b and c. The fault currents as we see here are 7.105 per unit or 7 times the rated current on this system.

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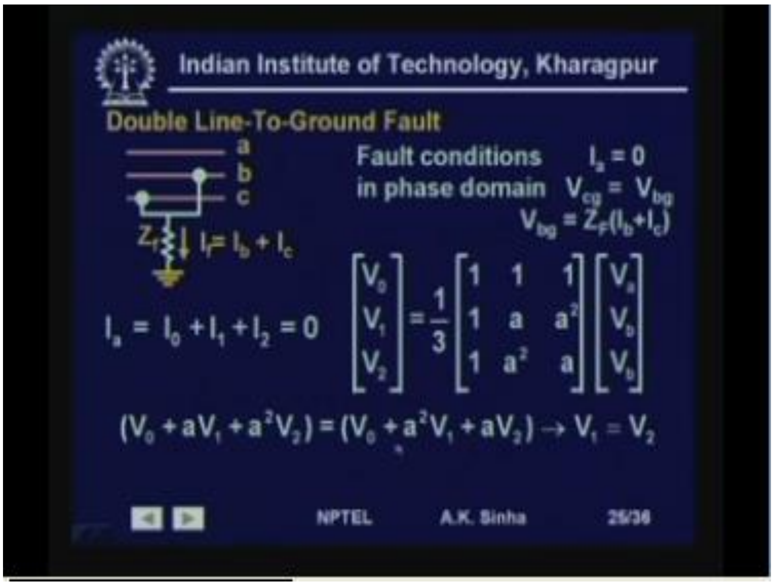
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Double Line-To-Ground Fault

Fault conditions in phase domain $I_a = 0$, $V_{cg} = V_{bg}$

$V_{bg} = Z_f(I_b+I_c)$

$I_a = I_0 + I_1 + I_2 = 0$

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_b \end{bmatrix}$$

$$(V_0 + aV_1 + a^2V_2) = (V_0 + a^2V_1 + aV_2) \rightarrow V_1 = V_2$$

NPTEL A.K. Sinha 25/36

Next we will take double line to ground fault. Now, here what the conditions are again very similar to the line to line fault that we had. Except that these two lines are faulted to the ground through an impedance set off. Now, again here pre fault conditions the currents are pre fault currents are 0. So, I a is equal to 0. Now, V b is equal to V c because these are shorted and this will be equal to Z f into I f. And what will be I f? I f will be this current I b and this current I c. So, the current here is going to be sum of these two currents. So, I f is equal to I b plus I c.

So, fault conditions in phase domain I a is equal to 0, V c g is equal to V b g and V c is equal to V b, and V b g is equal to Z f into I b plus I c. So, this voltage V b or V c is equal to Z f into I b plus I c, which is same as I f. Now, again saying I a is equal to 0, means I 0 plus I 1 plus I 1 is equal to 0. These we this condition that we get, the other one for the voltage we can write V 0 V 1 V 2 is equal to this is a inverse into V a V b V c.

Now, V c is equal to V b. So, we have substituted it like this. Now, from here we get V 0 plus a V 1 plus a square V 2 is equal to V 0 plus a square V 1 plus a V 2, which tells us that V 1 is equal to V 2.

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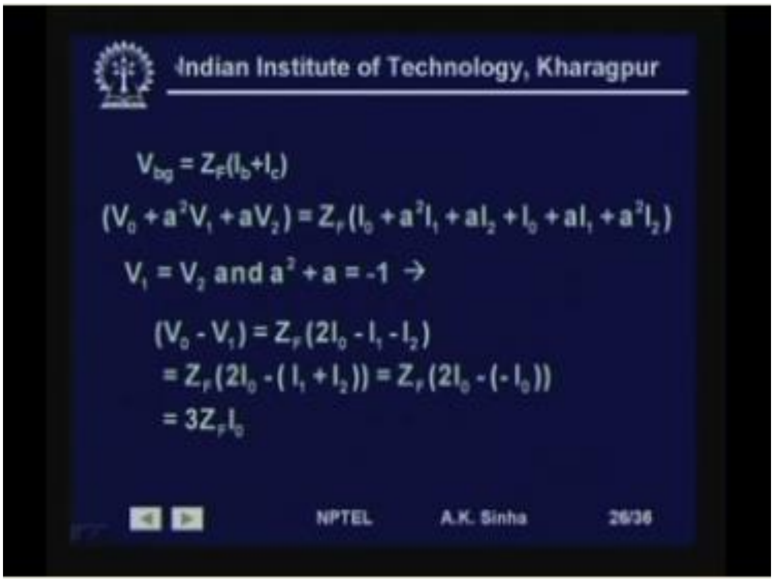

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$$V_{bg} = Z_F(I_b+I_c)$$

$$(V_0 + a^2V_1 + aV_2) = Z_F(I_0 + a^2I_1 + aI_2 + I_0 + aI_1 + a^2I_2)$$

$$V_1 = V_2 \text{ and } a^2 + a = -1 \rightarrow$$

$$(V_0 - V_1) = Z_F(2I_0 - I_1 - I_2)$$
$$= Z_F(2I_0 - (I_1 + I_2)) = Z_F(2I_0 - (-I_0))$$
$$= 3Z_FI_0$$

NPTEL A.K. Sinha 26/36

So, and V b is equal to Z f into I b plus I c. So, again substituting the values of V b we are writing plus Z f into I b plus I c. And then again taking help of V 1 is equal to V 2 and a square plus a is plus 1 is equal to 0 or a squared plus is equal to minus 1.

We will get finally, on organizing this all these terms and this as V 0 minus V 1 is equal to Z f into 2 I 0 minus I 1 minus I 2. And this we can write as Z f into 2 I 0 minus I 1 plus I 2, like here which is same as Z f into 2 I 0 minus I 0, because we have I 0 plus I 1 plus I 2 is equal to 0. So, I 1 plus I 2 is equal to minus I 0, this we get from here I 1 plus I 2 is equal to minus I 0. So, we have this comes out to be 3 Z f into I 0. So, V 0 minus v 1 is equal to 3 Z f into I 0. V 1 is equal to V 2 and I 0 plus I 1 plus I 2 is equal to 0.

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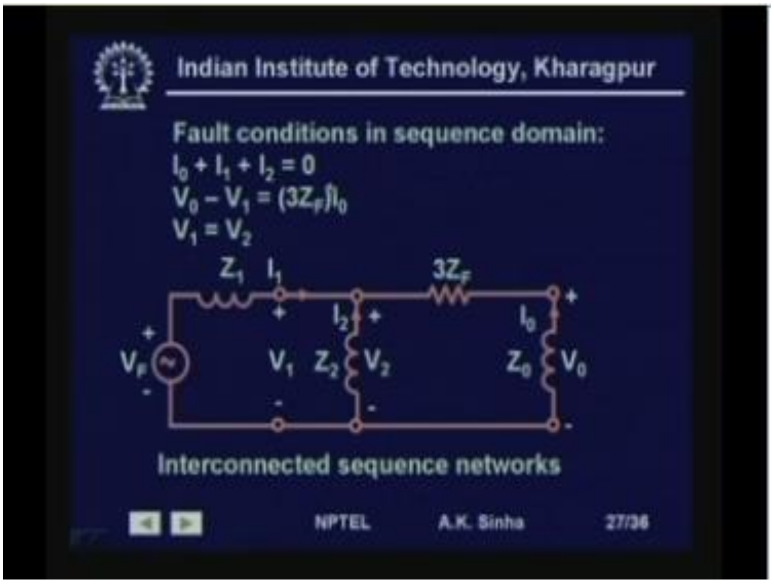

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Fault conditions in sequence domain:

$I_0 + I_1 + I_2 = 0$

$V_0 - V_1 = (3Z_F)I_0$

$V_1 = V_2$

Interconnected sequence networks

NPTEL A.K. Sinha 27/36

So, these are the conditions that we have got which tells us the sequence network connections are going to be like this. V 1 is this is the positive sequence network V f is the voltage source, Z 1 is the impedance and V 1 is the voltage between the fault point and the reference. We have the negative sequence network which is only having Z 2 no source. And the voltage across this is equal to V 2. So, V 1 is equal to V 2. So, this will be connected across this

And then we have this is the value V 1 V 1 V 0 minus V 1 is equal to 3 Z f into I 0 So, V 0 as this is Z 0 and the voltage across this is V zero. So, V 0 minus V 1 is equal to 3 Z f into I 0. So, 3 Zf into I 0. So, this is this current is flowing like this I 0. So, 3 Zf into I 0 is the drop here. So, V 0 minus V 1 is equal to 3 Z f I 0 this condition is put here. So, this is the final network that we get interconnected sequence network for double line to ground fault.

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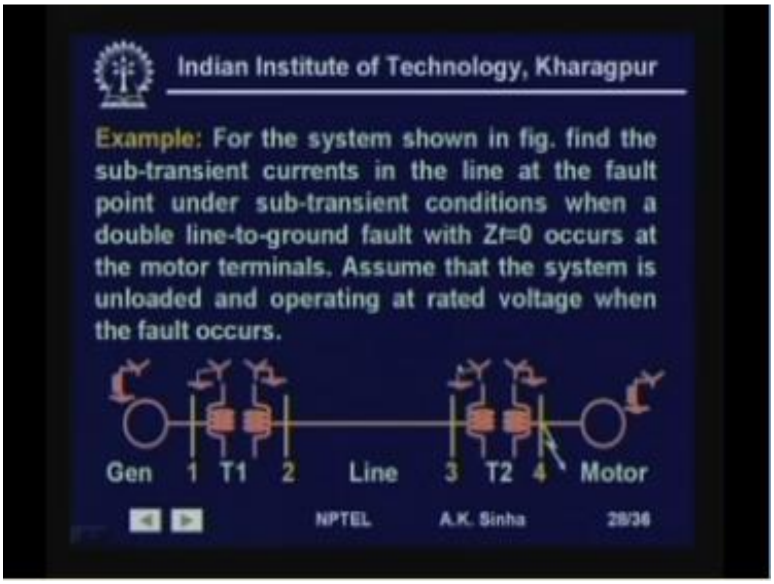

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Example: For the system shown in fig. find the sub-transient currents in the line at the fault point under sub-transient conditions when a double line-to-ground fault with Zf=0 occurs at the motor terminals. Assume that the system is unloaded and operating at rated voltage when the fault occurs.

Again we will take same example except that in this case we have taken the fault to occur at bus 4. So, again the fault is with Z f is equal to 0, a double line to ground fault at bus 4.

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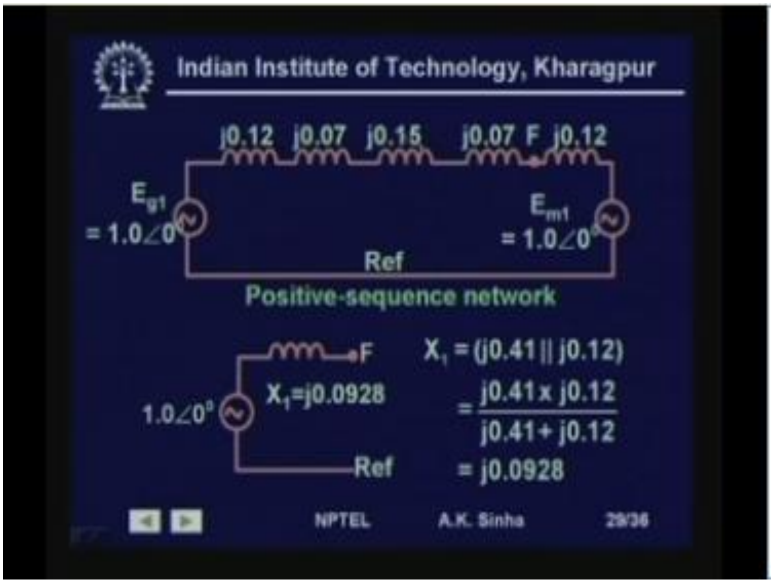

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Positive-sequence network

$$X_1 = (j0.41 \,||\, j0.12) = \frac{j0.41 \times j0.12}{j0.41 + j0.12} = j0.0928$$

So, what we need to do is. We need to compute the sequence network at the fault point So, we have drawn the positive sequence network which is same as what we have drawn earlier. Except that the fault point is here. So, now we need to find out the reduced network between fault and reference, which we if we do which comes out to be j 0.0928 because this part is this impedance is around j 0.41. This impedance j 0.12, they are in parallel. So, this on reduction finally, comes out to be this much.

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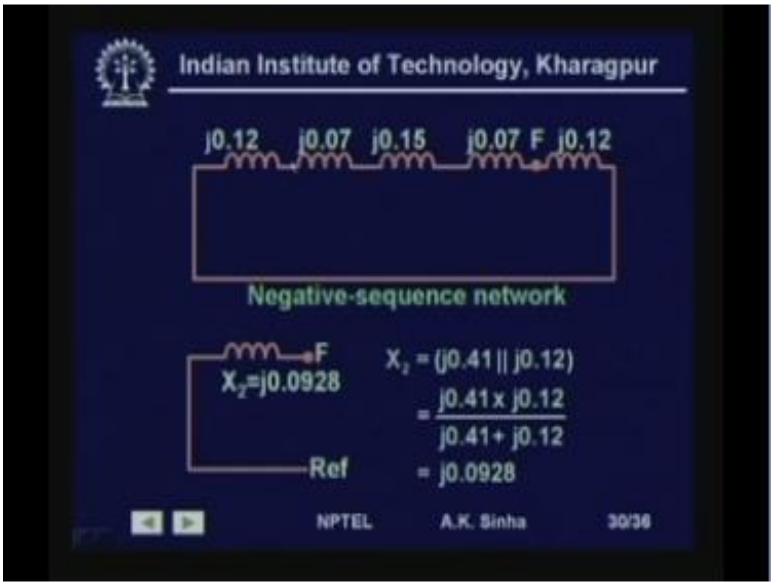

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Negative-sequence network

$$X_2 = (j0.41 \,||\, j0.12) = \frac{j0.41 \times j0.12}{j0.41 + j0.12} = j0.0928$$

NPTEL A.K. Sinha 30/36

Similarly, negative sequence network again since the impedances are same. So, the value of X 2 is also same that is j 0.0928.

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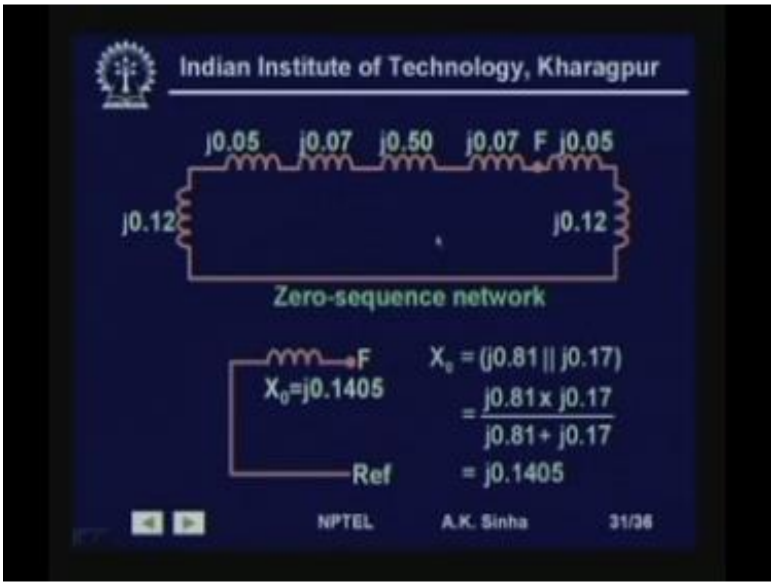

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Zero-sequence network

$$X_0 = (j0.81 \,||\, j0.17) = \frac{j0.81 \times j0.17}{j0.81 + j0.17} = j0.1405$$

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Now, for zero sequence again we can calculate the value here now this comes out to be the network is same; except that the fault point is here. So, we add these impedance this comes out to be 0.81. So, j 0.81 and this is 0.17. So, j 0.17 in parallel this comes out to be j14 05. So, this is the network here

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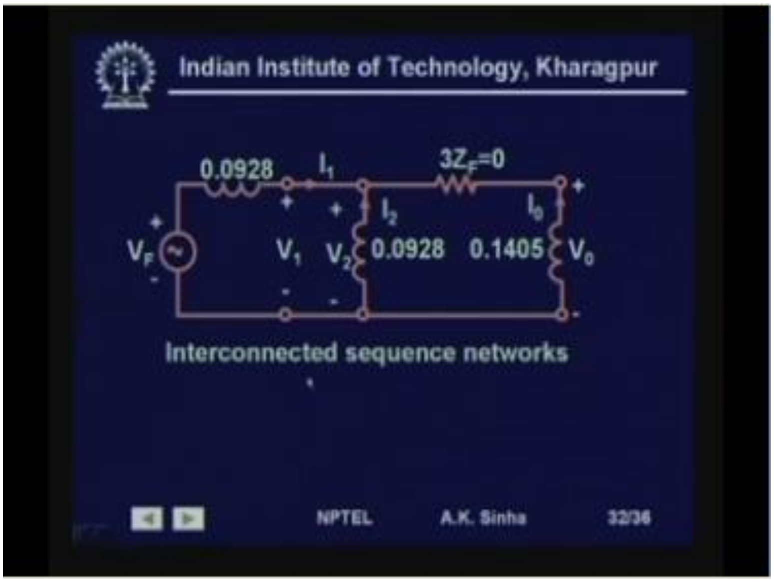

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Interconnected sequence networks

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Now, we connect these networks as we have shown V 1 V 2 in parallel and V 0 and that is Z 0 and 3 Z f is series connected in parallel with that. So, this what we get V f, this is the positive sequence impedance, this is the negative sequence impedance this is 3 Z f is Z f is 0. So, this is zero and this is the zero sequence impedance. So, interconnected sequence network will be like this.

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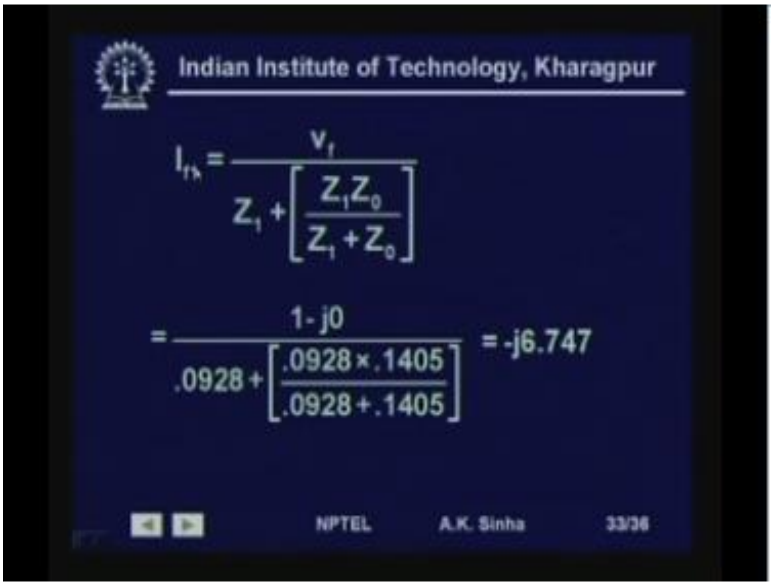

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$$I_{fa} = \frac{V_f}{Z_1 + \left[\frac{Z_1 Z_0}{Z_1 + Z_0}\right]}$$

$$= \frac{1 - j0}{.0928 + \left[\frac{.0928 \times .1405}{.0928 + .1405}\right]} = -j6.747$$

NPTEL A.K. Sinha 33/36

We can get the positive sequence current as if you see here this will be, this V f divided by the impedance this impedance plus these two impedances in parallel, So, that is what we have done Z 1 plus Z 1 Z 0 that is it should be Z 2 Z 0 Z 2 is same as Z 1. So, it is Z 2 Z 0 and Z 1 Z 0 divided by Z 1 plus Z 0. So, this is coming out to be equal to j minus j. 747

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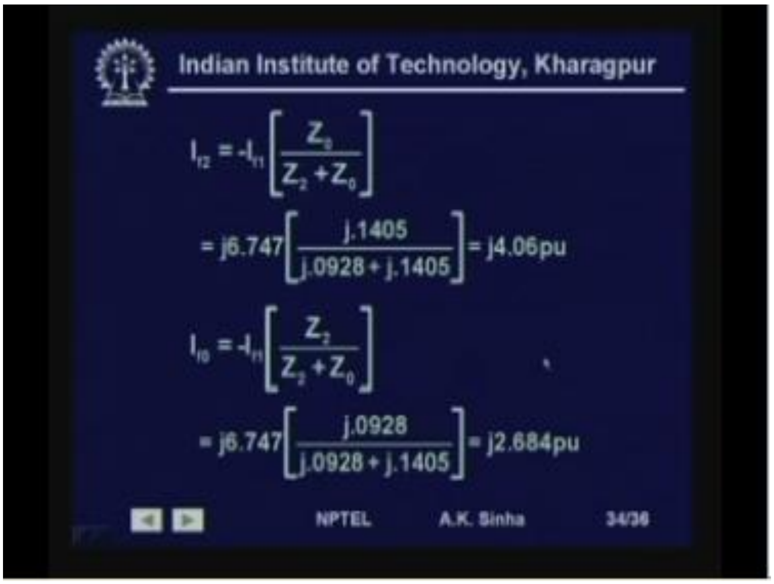

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$$I_{f2} = -I_{f1}\left[\frac{Z_0}{Z_2+Z_0}\right]$$

$$= j6.747\left[\frac{j.1405}{j.0928+j.1405}\right] = j4.06pu$$

$$I_{f0} = -I_{f1}\left[\frac{Z_2}{Z_2+Z_0}\right]$$

$$= j6.747\left[\frac{j.0928}{j.0928+j.1405}\right] = j2.684pu$$

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Similarly, we can calculate I f 2 which will be again if we look at this diagram.

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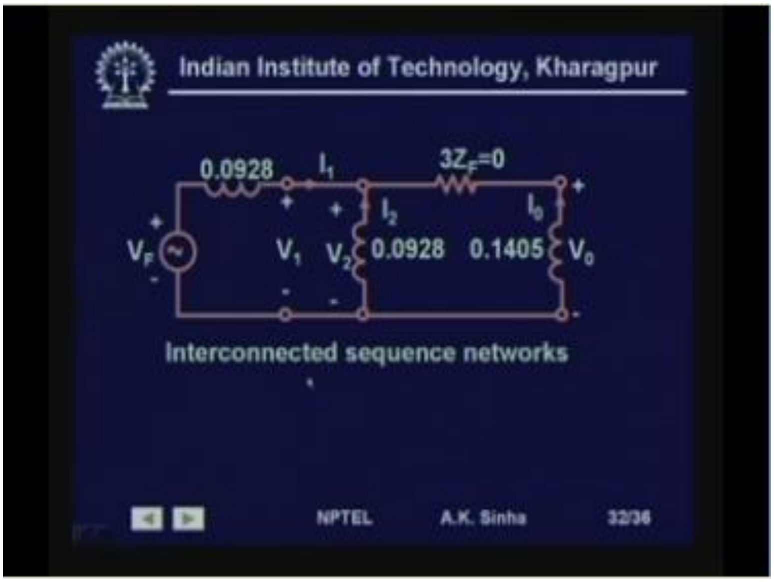

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Interconnected sequence networks

NPTEL A.K. Sinha 32/36

This is I 1 this gets divided into these two parts right and the part flowing in this is going to be inversely proportional to this impedance. And the sum of these two impedances. So, that is what we have got here.

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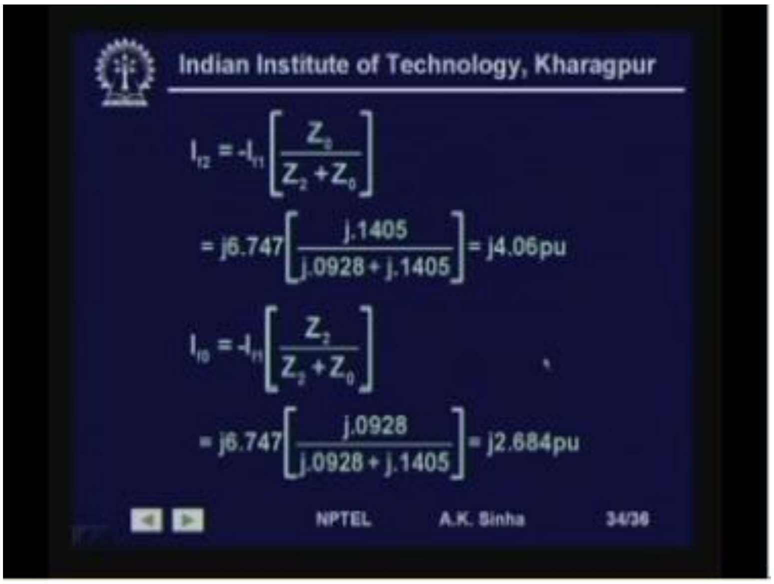

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$$I_{f2} = -I_{f1}\left[\frac{Z_0}{Z_2 + Z_0}\right]$$

$$= j6.747\left[\frac{j.1405}{j.0928 + j.1405}\right] = j4.06\text{pu}$$

$$I_{f0} = -I_{f1}\left[\frac{Z_2}{Z_2 + Z_0}\right]$$

$$= j6.747\left[\frac{j.0928}{j.0928 + j.1405}\right] = j2.684\text{pu}$$

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If 1 minus If 1 into Z 0 divided by Z 2 plus Z 0 when we do that we get this as j 4 point 0 6 per unit. Similarly, If 0 can be computed as minus If 1 into Z 2 by Z 2 plus Z zero So, substituting values this comes out to be j 2.684 per unit and once we have got these positive negative and zero sequence currents at the fault point.

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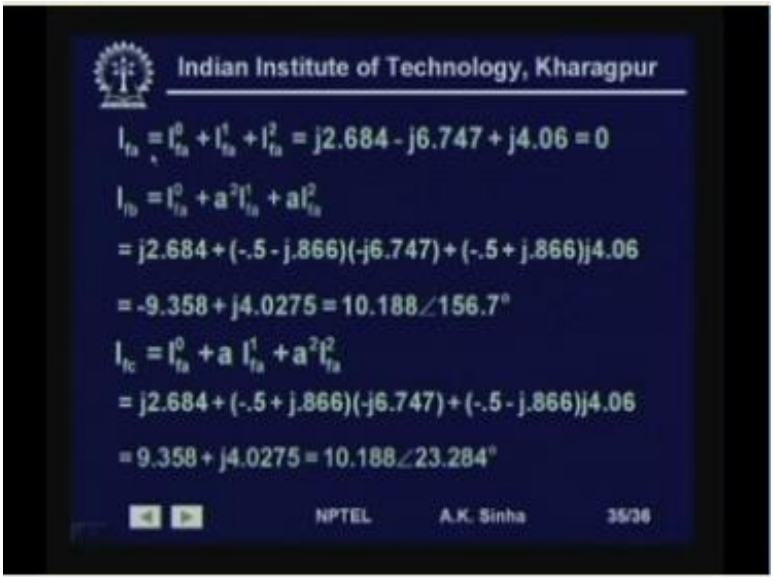

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$$I_{fa} = I_{fa}^0 + I_{fa}^1 + I_{fa}^2 = j2.684 - j6.747 + j4.06 = 0$$

$$I_{fb} = I_{fa}^0 + a^2 I_{fa}^1 + a I_{fa}^2$$

$$= j2.684 + (-.5 - j.866)(-j6.747) + (-.5 + j.866)j4.06$$

$$= -9.358 + j4.0275 = 10.188\angle 156.7^\circ$$

$$I_{fc} = I_{fa}^0 + a\, I_{fa}^1 + a^2 I_{fa}^2$$

$$= j2.684 + (-.5 + j.866)(-j6.747) + (-.5 - j.866)j4.06$$

$$= 9.358 + j4.0275 = 10.188\angle 23.284^\circ$$

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We can calculate the phase a current that is I 0 f a plus I 1 f a plus I 2 f a positive negative and zero sequence fault currents. This when we add up this comes out to be zero this is what we had seen in the very beginning that there is no current flowing through phase a. I f b again we substitute the values and then we calculate this comes out to be 10.188 with an angle of 56.7 degrees.

Similarly, I f c after substituting the values comes out to be again 10.188t with an angle of 23. 8 4 which shows the values for these 2 currents. So, we know the fault currents in all the three phases. So, with this we will stop today. And the next class we will talk about some other asymmetrical faults that is the open circuit faults and then we will take up some example and we will see how we do this fault analysis for large fault systems. What are the problems that we have to face when we work it out for large power systems

Thank you.

Preview of Next Lecture

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Power System Analysis

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Lecture No. # 29

Unbalanced Fault Analysis (Cont.)

Welcome to lesson 29 on Power System Analysis. In this lesson we will continue with Unbalanced Fault Analysis. The symmetrical faults that we were considering in the previous lectures were the short circuits.

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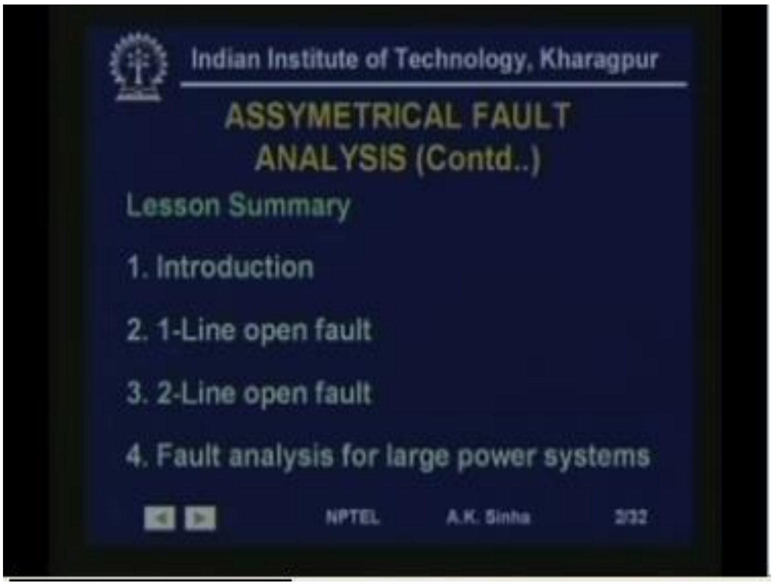

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ASSYMETRICAL FAULT ANALYSIS (Contd..)

Lesson Summary

1. Introduction
2. 1-Line open fault
3. 2-Line open fault
4. Fault analysis for large power systems

In this lecture we will consider the open circuit faults. So, here we will start with an introduction. Then we will discuss one line open fault and then two line open fault and after that we will discuss a little about fault analysis for large power systems.

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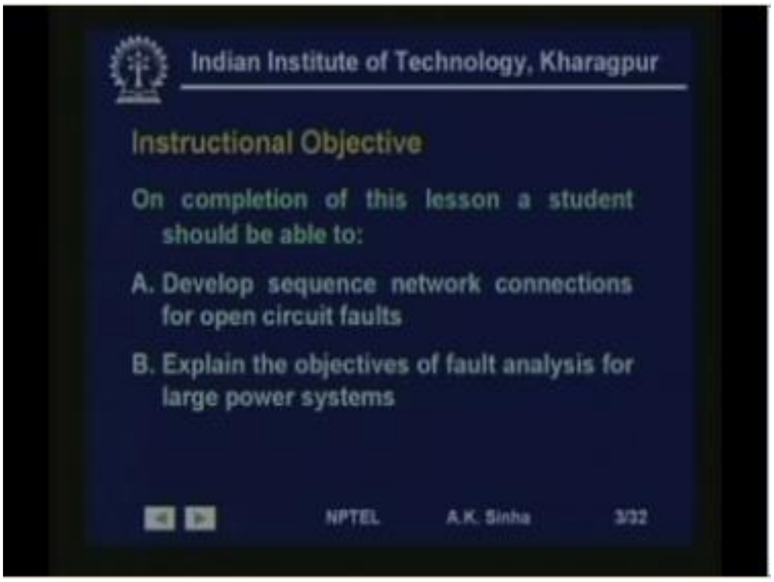

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Instructional Objective

On completion of this lesson a student should be able to:

A. Develop sequence network connections for open circuit faults
B. Explain the objectives of fault analysis for large power systems

Well on completion of this lesson you should be able to develop sequence network connections for open circuit faults. And you should be able to explain the objectives of fault analysis for large power systems.

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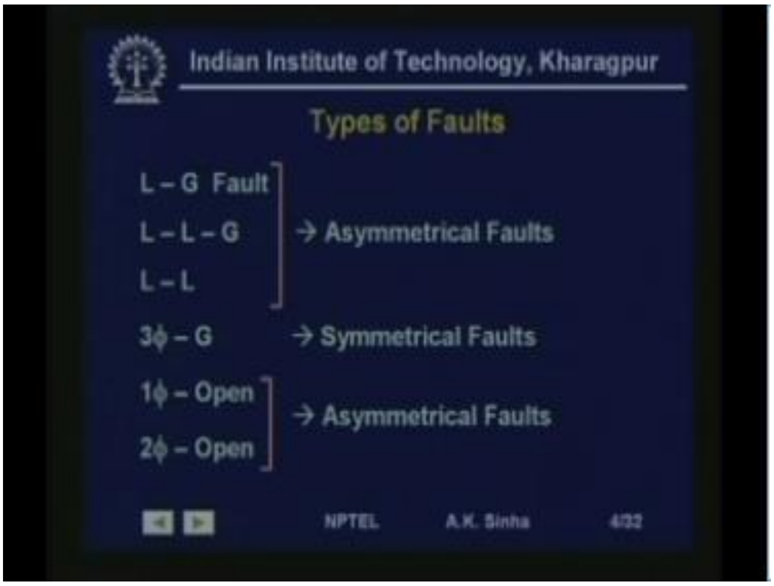

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Types of Faults

L – G Fault
L – L – G → Asymmetrical Faults
L – L

3ϕ – G → Symmetrical Faults

1ϕ – Open
2ϕ – Open → Asymmetrical Faults

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As we discussed in the previous lesson there are different kinds of faults which occur in power system such as line to ground fault or line to line to ground fault and line-to-line faults these are asymmetrical faults. Similarly, three phase to ground faults these are symmetrical faults. All these faults are basically short circuit faults.

Whereas, we have other types of faults which are basically open circuit faults like a single phase open. That is one line gets open or two line gets open. In both these cases the fault again is an asymmetrical fault, because the voltage and currents in all the three phases are not balanced or symmetrical.

Now, when we one question which comes to mind is we can understand studying the short circuit faults, because in case of short circuit heavy currents are going to flow in the circuit. And we need to protect our equipment from damage because of this heavy current. What happens in case of open circuit faults. Well open circuit faults in most of the cases will need to over voltages. And that is why we need to study them, because these over voltages can sometimes cause insulation failure and thereby resulting in a short circuit. So, we need to study these open circuit faults also to make sure that our system design for insulation can take care of the over voltages caused by the open circuit faults.

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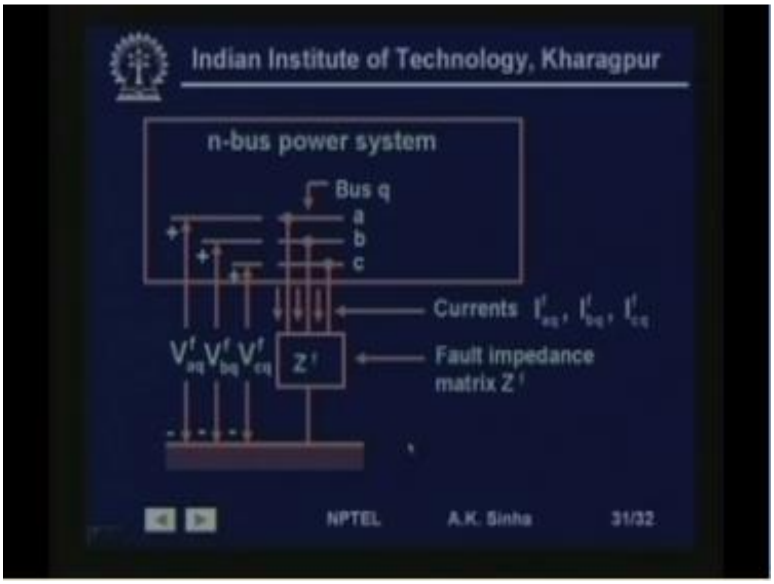

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So, that is if you see the system we can define this is a n-bus power system in which we have taken this bus q at which the fault has occurred. The fault impedance is Z f and the a b c phase voltages are shown here for the bus q. So, with this we end today. In the next lesson we will talk about how to develop an algorithm fault short circuit studies on large power systems.

Thank you very much.