**Power Network Analysis**

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**Week - 10**

**Lecture-50**

Hello everyone, welcome to Lecture 5 of Week 10 of the course Power Network Analysis. This lecture is going to be the second-to-last lecture of the module on fault analysis, in which we will take up two numeric examples in order to have a better understanding of the different aspects regarding fault analysis that we discussed in the previous lecture. So, until the previous lecture, we had theoretically analyzed the application of Thevenin's theorem and Fortescue's theorem to understand or evaluate the worst-case fault current that can occur for asymmetric faults, which can be categorized as single line-to-ground fault, double line-to-line fault, and double line-toground fault. In all this analysis, our preliminary assumption, or the most critical assumption, was that the pre-fault power network in which these faults could occur could also happen for the three-phase balanced fault. The pre-fault power network is assumed to be a balanced network, and that is a big bottom line or assumption behind the application of Fortescue's or Thevenin's theorem. The situation might be different, or the analysis might be different if this preliminary understanding of having pre-fault balanced power network operation is not valid.

So, given that for high voltage transmission level power networks, things are usually balanced, at least on the transmission end. The analysis that we have had would very well be applicable. So let's understand more about the numeric aspect of how this Thevenin analysis, Fortescue's theorem, how they are applicable. So what I have here is shown in this particular slide: I have a three-bus power network where the buses are numbered in the square boxes that I'm drawing.

This is actually bus number three; I think this has been cut off because of the cropped image aspect. So bus numbers 1, 2, and 3 are the three buses that are interconnected through three transmission lines numbered 1 to 3,1 to 2 , and 2 to 3 . On each of these buses, there is a set of machines connected. They are essentially synchronous machines; to be specific, if I am not wrong, but that does not matter. These could be synchronous.

They are basically rotating machines that are connected to this power network. There might be a presence of load somewhere in the power network, but given the understanding that this network we are considering is going to experience some type of fault, even if the load consideration were to be taken into account, the pre-fault condition would mean that the load currents won't be that high compared to the fault current. Therefore, the presence of loads has not been considered in this network; we are assuming it to be an unloaded network. That is the bottom line reason. If it were to be even loaded, the normal load currents would be much smaller than the corresponding fault current that would appear, and hence their contribution is going to be very small.

So that's the reason why loads are not present: they are considering the aspect of unloaded operation. The network is balanced, and there are four machines that are connected to the different buses. So at bus 1 we have machine number 1 , at bus 2 machine number 2 , and at bus 3 we have two machines, bus number 3 and 4 . These machines are interconnected to the network through a set of four transformers: transformer T1, T2, T3, and T4. These are three-phase transformers in themselves, where, if we look at transformers T1 and T2, the LV side is delta connected and the HV side is star grounded.

The same is true for transformer T2; the LV side is delta connected, and the HV side is star grounded. How am I identifying LV and HV? LV is low voltage; HV is high voltage. Because essentially when I am looking at the transmission network, it is going to operate at higher voltages and that is where the necessity of these transformers comes in, where the power or voltage gets amplified. And if I look at transformers T3 and T4, the HV side connections are both star-grounded, but the LV side connections have a difference. Transformer T3 LV is only star-connected, whereas T4 is also star-grounded.

The reason I am emphasizing all this is that when we have to analyze some fault, whether balanced or unbalanced, in this three-phase balanced power network, the connections of these transformers are going to significantly affect the zero sequence network or the zero sequence diagram of the corresponding network. Also, the way the machines are connected is that machine 1's neutral is star grounded, machine 2's neutral is ungrounded, and it is star connected, whereas machines 3 and 4 are also star connected. But 4 is neutrally ungrounded, whereas 3 is grounded through some reactants Xn, whose value we will see in the next slide. So these aspects of how the grounding is there for the machines with respect to the neutral are also going to affect the zero sequence network. The respective line parameters are not given; what is given instead is that we directly know what the positive sequence admittance matrix of this network is.

$$Y_{bus}^{1}=\begin{bmatrix}-j29.9068 & j11.7045 & j14.6308\\ j11.7045 & -j29.6687 & j14.6308\\ j14.6308 & j14.6308 & -j33.3471\end{bmatrix}$$

And remember, when this positive sequence admittance matrix is evaluated specifically for fault analysis, then the bottom line for this evaluation-I mean, one could think: does it mean that Y bus 1 corresponds only to the parameters of transmission lines, which is the usual case in power flow analysis? No. For steady state analysis, we focus only on the lines, but when we consider fault analysis, the machine's internal reactance, which is represented by Xd dash values, as well as the transformer's leakage reactance, has also been considered while specifically evaluating these diagonal terms. That's the reason you would see that if only the transmission lines were considered, the off-diagonal terms should add up or negate the diagonal terms, which is not the case in any of these three diagonal elements. The reason is that the machines Xd dash or Xd double dash, to be precise, as well as transformers' leakage reactants, in all cases have been incorporated into this bus admittance diagonal dumps. Zero sequence network negative sequence admittance is given to be the same as the positive sequence admittance matrix, and the zero sequence admittance matrix is also given, wherein this negative zero sequence admittance matrix significantly depends on how these neutral connections are and how the transformers are connected at each of the three buses.

$$Y_{bus}^{0} = \begin{bmatrix} -j19.7538 & j3.9015 & j5.8527 \\ j3.9015 & -j19.7538 & j5.8527 \\ j5.8527 & j5.8527 & -j11.7045 \end{bmatrix}$$

And that is essentially the reason why you would see that again in the zero sequence admittance matrix: the off-diagonal terms don't add up and negate the diagonal entry, which otherwise would have been the case if we had only three lines whose conductances were not considered. So directly, the positive and negative sequence, zero sequence, negative sequence, and positive sequence admittance matrix have been given, and now comes the statement that the neutral of machine 1 is solidly grounded, as I have mentioned in the previous slide. Machines 2 and 4 are neutrally ungrounded, as shown here through the star connection. The neutral of machine 3 is grounded through a neutral reactor Xn , whose value is not known. During a fault at bus number 3, which is the bus marked over here, a fault has occurred, and after that fault occurrence, the post-fault phase voltage at bus 1 in per unit is given as Va1.

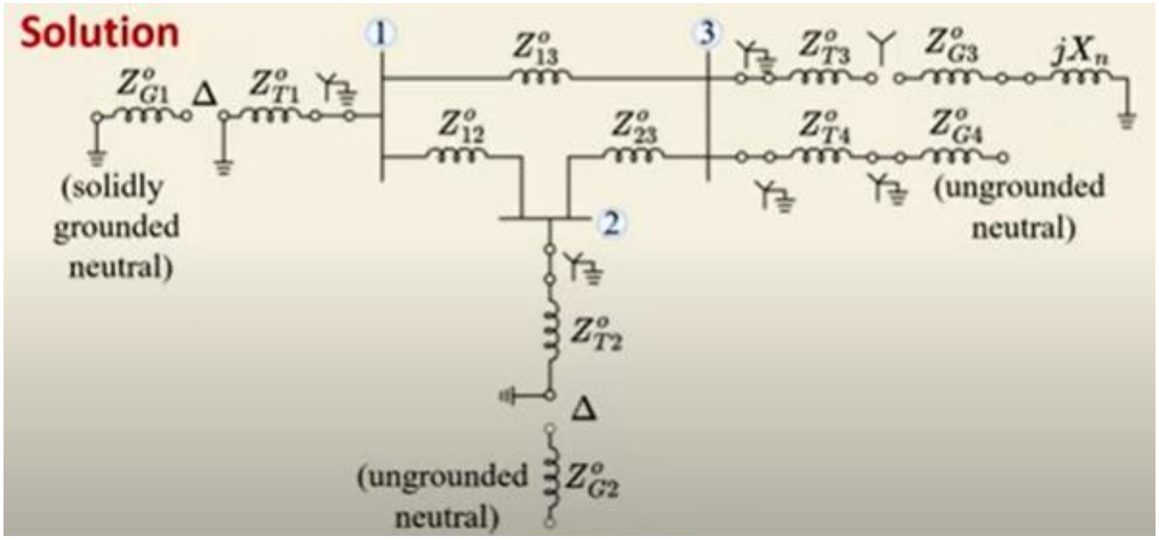
Here, Va refers to the phase, whereas 1 refers to the bus number. The post-fault phase voltages of bus 1 are given as mentioned in this question, and it is also stated that if we have to do a sequence analysis using Fortescue's theorem application, we should use phase a as a reference for sequence components. So essentially we have the information of the network in terms of $Y$ bus $1, Y$ bus $2, Y$ bus $0$ . The neutral connections and the way they are connected are also mentioned. And there is some fault at bus $3$ , for which these are the phase voltages at bus $1$ .

$$V_{abc}^{1} = \begin{bmatrix} 0.9657 \\ 0.4390\angle-157.5938° \\ 0.4390\angle157.5938° \end{bmatrix} \Rightarrow V_{012}^{1} = \begin{bmatrix} 0.051328 \\ 0.553796 \\ 0.360576 \end{bmatrix}$$

And you have to choose phase A as a reference for sequence components. So, let's see what the next bit of the question is. The first bit of the question says, "Draw the zero-sequence impedance diagram of the system with all impedances." We do not have to mark their corresponding numbers or values of the impedances because, essentially, that information is not known to us. What you otherwise know is the admittance matrix elements.

So I will probably explain one such interconnection, and then we will see what the other networks or impedances look like specifically from the zero sequence admittance perspective. So if you recollect that we had a star-delta and star-grounded transformer, which is the case for transformer T2 and transformer T1, and suppose the reactances of such a transformer are, let us say, Xt , the leakage reactance in the zero-sequence perspective. So, if we have a delta on the LV side and a grounded star on the HV side, which is LV and HV here, then if I denote the LV terminal and the HV terminal while drawing the zero sequence impedance diagram or circuit diagram, wherein ground acts as a reference, whereas for positive and negative sequence networks the neutral can act as a reference, there is a big difference between positive, negative, and zero sequence network connections. So, coming back to the zero-sequence representation of this transformer, with the HV side being stuck grounded and the LV side being delta connected, if we recollect or revisit our discussion where we have this jXt representing the zero-sequence leakage reactance of the transformer, then how should this connection look? Remember, in delta connection, the zero-sequence current can never escape out of the terminals; it can only rotate or pass, being present in a circulatory fashion within these three phases. So, in order to not have any zero-sequence current on the LV terminal, the only possibility for this connection of current to exist is on the LV side.

The jXT is grounded to the ground directly, whereas in the HV connection, where it is directly star grounded, we have the connection as shown above. So essentially, whatever zero-sequence current can be present on the HV side would also be present in the winding on the HV side, and instead of leaking out of the LV side where I0 is the zero-sequence current, it would pass through the ground and return back to the circuit. So if you recollect this particular discussion that we had about zero sequence impedances of transformers and lines, then the corresponding zero sequence impedance would look like this. So, for ZT2, I have specifically discussed this. The same would be true for ZT1.




For machines that are solidly grounded, like generator 1 , the corresponding reactance value will be directly connected to the ground, whereas for machines 2 and 4 , the neutrals are ungrounded, so there won't be any possibility of zero sequence current being present in this particular element as well as in this entire circuit because there is no path for zero sequence current to flow. Only for generator 3 is there a solid path from bus 3 to the ground for the zero-sequence current to flow either inward or outward. And for transmission lines, their corresponding reactances are as usual present. So we don't know what these Z values are, but it's just a symbolic representation. I hope this discussion is clear.

The next bit is which fault has occurred at bus 3 , because it was already given that a fault has occurred at bus 3 . Now we have to identify what that particular fault is. So, given the phase post-fall voltages of bus 1, they are given as a, b, c, and remember that phase a has been designated as the reference for sequence components. So if you recollect, Vabc is nothing but a capital A matrix times Va012. So, where A is the matrix that we discussed in Fortescue's theorem or the sequence network discussion.

So if you apply that capital A matrix, basically, if you want to find Va012, as shown over here for bus 1 with phase a as a reference, then you have to do A inverse of Vabc. So if you do that, you get this particular information. And since the sequence voltages at bus 1 are now known, it is imperative to get some information out of this using the corresponding impedance matrices.

So, since Y buses are given, we can take their inverses and get the corresponding impedance matrices. Why are these impedance matrices going to be important? So the first aspect is the application of Fortescue's theorem.

$$Z_{\text{bus}}^{1}=Z_{\text{bus}}^{2}=(Y_{\text{bus}}^{1})^{-1}=\begin{bmatrix} j0.10684 & j0.08329 & j0.08342 \\ j0.08329 & j0.10793 & j0.08389 \\ j0.08342 & j0.08389 & j0.10339 \end{bmatrix}$$

$$Z_{\text{bus}}^{0}=\left(Y_{\text{bus}}^{0}\right)^{-1}=\begin{bmatrix} j0.07114 & j0.02887 & j0.05 \\ j0.02887 & j0.07114 & j0.05 \\ j0.05 & j0.05 & j0.13545 \end{bmatrix}$$

Whereas the impedance matrix evaluation would be an application of Thevenin's theorem, we have to find the corresponding Thevenin impedance between the fault point and the ground where the fault has occurred, or the neutral point where the fault has occurred. So essentially the reason for finding these Z buses is to look at or gauge bus 3 from the sequence voltages given for bus 1 . Similarly, Z bus 0 can be varied by its inverse, and since a fault has occurred at bus 3, in terms of changes in injection currents, the change in injection currents would only appear for bus 3 . This means that if I have to denote the I 0 vector for bus 1 , bus 2 , and bus 3 , then this vector, being a 3 by 1 vector for bus 1 , these quantities would be 0 , whereas for bus 3, this would be a non-zero quantity. So essentially, by using this method and since there is no change in sequence currents at bus 1 because the fault has not occurred at bus 1 or bus 2 .

So we can make use of the corresponding V01 expression in terms of the corresponding Thevenin impedances, which is what the element shown over here is. So Z 130 is the 1 , sorry, it is the 1.3 element, which is j 0.05 ; we will be using that particular expression. Trying to equate bus 1's zero sequence voltage to find the non-zero current, which I was talking about in terms of the zero sequence current at bus 3 .

$$V_0^1=-Z_{13}^0 I_0^3 \Rightarrow I_0^3=\frac{-V_0^1}{Z_{13}^0}=j1.02656$$

So by doing so, we can find the sequence currents that are non-zero at bus 3 because for the other buses, the fault has not occurred. So by using the corresponding zero sequence network and positive sequence network, which is an active network, there is no source present for the zero sequence. For the positive sequence network, we have an active source. Since the network is unloaded, V1 pre would be equal to 1 at an angle of 0 degrees. And similarly for V21, which is a negative sequence network, we have a passive network, so we can find I23, I13, and I03.

$$V_1^1=V_{pre}^1-Z_{13}^1 I_1^3 \Rightarrow I_1^3=\frac{V_{pre}^1-V_1^1}{Z_{13}^1}=-j5.34889$$

$$V_2^1=-Z_{13}^2 I_2^3 \Rightarrow I_2^3=\frac{-V_2^1}{Z_{13}^2}=j4.32242$$

Now when we look at these three currents, what appears is that the corresponding sum of these currents is zero. Now in which type of fault is the sum of these three currents zero? Definitely, there is an involvement of zero-sequence current because the zero-sequence component is not zero. So it is definitely going to be a ground fault. There are two possibilities of asymmetric ground faults: line-to-ground fault and double line-to-ground fault. In the case of a double line-to-ground fault, we have seen that the sum of these three sequence components is zero.

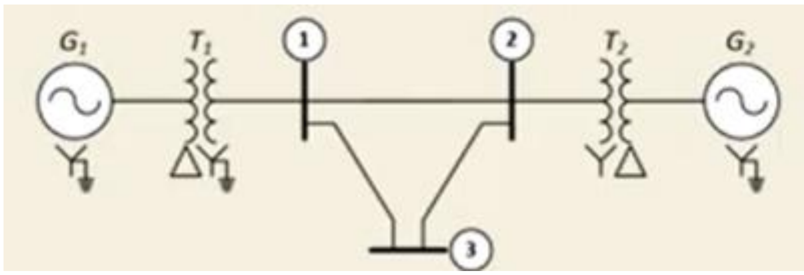
It's truly a case of phase-to-phase to ground fault. Now, which phases are involved? Since we have taken phase a as a reference, and typically when we choose phase a as a reference, this beautiful addition or equation is applicable for phase b to c to ground fault. The fault at bus 3 is a b to c to ground fault. That covers the second question. You can again cross-verify the statement that by adding some of the phase currents, the numbers do satisfy.

The next bit is: what are the fault current and impedance at bus 3 ? The fault is definitely a b to c to G fault at bus 3. Now we have to find the current and impedance. So from the solution of the previous bit, the fault is a phase b to c to ground fault, and the corresponding sequence network for the double line-to-ground fault we have seen. This part here is the positive sequence component; this part here is the zero sequence component; this part here is the negative sequence network or representation, and double line-toground fault; positive and negative are in parallel, and they are in anti-series to the zero sequence network. So we know this for sure; we can draw this circuit.

Now, in this circuit, what is not known is the value of this fault impedance. Since we know the corresponding other quantities, we can evaluate this 3 Zf connection value using a simple KVL. So from the network, Zf is j0.1 pu, and for the fault current in a double line-to-ground fault, it is three times the zerosequence current. Since we know this value, we can find the corresponding fault current value.

$$V_0^3 = -Z_{33}^0 I_0^3 = 0.139048$$
$$V_1^3 = V_{pre}^3 - Z_{33}^1 I_1^3 = 0.44694$$
$$V_2^3 = -Z_{33}^2 I_2^3 = 0.44694$$
$$V_1^3 = -3Z_f I_0^3 + V_0^3 \Rightarrow Z_f = \frac{V_0^3 - V_1^3}{3I_0^3} = j0.1pu$$
$$I_f^3 = I_b^3 + I_c^3 = 3I_0^3 = j3.07968pu$$

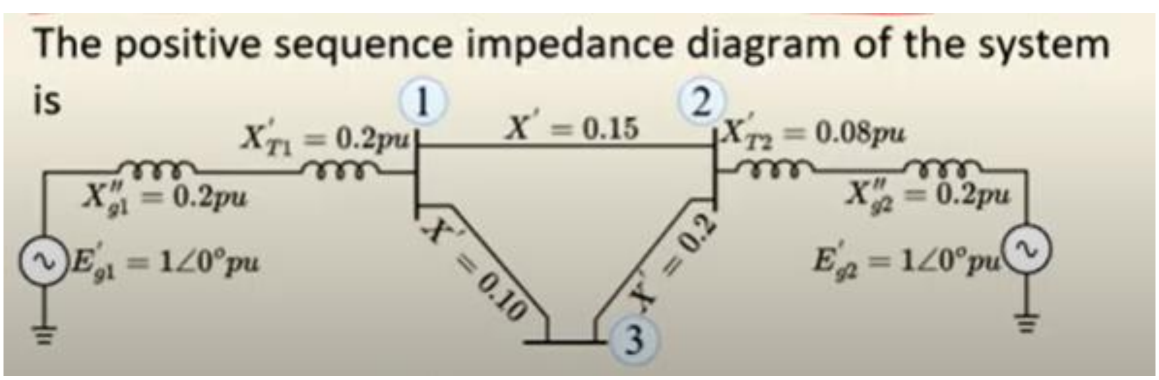
That covers question number one. Now I have another question, which is relatively simpler in terms of having just a three-phase balanced fault. Again, there are three buses, and across buses 1 and 2, two generators are connected. The transformers T1 and T2 have dissimilar configurations. Both machines are neutrally grounded, and the positive and negative sequence impedances of each of these elements, G1, T1, line 12,23,13, T2, and G 2 , are given over here on a common base. The neutral of the machines is grounded through a neutral reactor of 0 .05 per unit, the neutral of the HV side transformer is solidly grounded, the neutral of transformer T2 is ungrounded, and it is given that the system is operating at nominal rated voltage without pre-fault current, which means this is also an unloaded network condition. All resistances and capacitances are to be neglected.



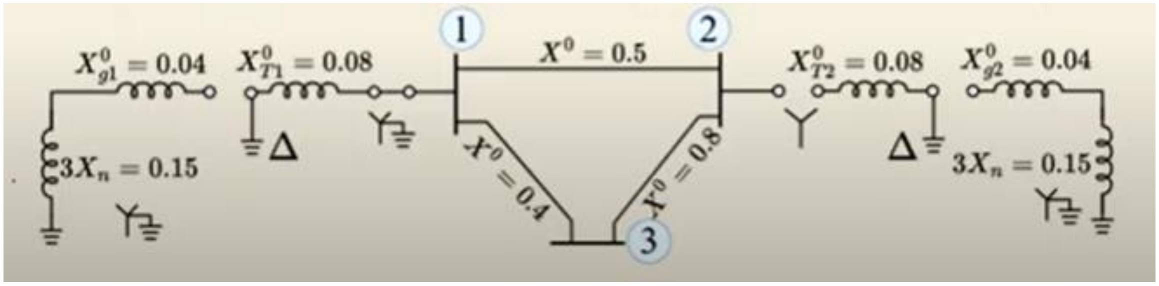

$$G_1: X_1 = X_2 = X_d' = 0.20pu, X_0 = 0.04pu$$

$$G_2: X_1 = X_2 = X_d' = 0.20pu, X_0 = 0.04pu$$
$$T_1: X_1 = X_2 = X_0 = 0.08pu$$
$$T_2: X_1 = X_2 = X_0 = 0.08pu$$
$$\text{Line }_{1-2}: X_1 = X_2 = 0.15pu, X_0 = 0.50pu$$
$$\text{Line }_{1-3}: X_1 = X_2 = 0.10pu, X_0 = 0.40pu$$
$$\text{Line }_{2-3}: X_1 = X_2 = 0.20pu, X_0 = 0.80pu$$

The question says to draw the positive, negative, and zero sequence impedance diagram with all impedances marked appropriately. So if you draw the positive sequence network, it is likely going to be the same as a negative sequence network, wherein each generator is represented by this internal EMF since the machine or network is unloaded. So, all voltages are at one at an angle of 0 degrees per unit, and the positive sequence impedance is the same as the sub-transient direct access transient reactance of the transformer.




The positive sequence impedance network looks something like this. The generators are represented by their internal EMFs, which I was also talking about in the context of question number one. And the corresponding subtransient reactances are important. The leakage reactances of transformers, as they are given, will remain the same. And also, I'll have the line reactances as given in the data sheet.




The negative sequence impedance diagram will be exactly the same as the positive sequence impedance diagram. The only difference is that in the negative sequence impedance diagram, these sources won't be present, which is essentially what is marked over here. The generators and transient EMFs would be short-circuited. They won't be present at all. For the zero sequence impedance network, the discussion that we had for transformers with a similar configuration and the corresponding way the neutral is grounded for the machines will either have a flow of zero sequence current or no flow of zero sequence current.

So in this context, if I were to say there is no direct path in this circuit for zero-sequence current to flow. Nearby, there is a path for the zero sequence current to flow. So zero sequence current contribution from generators will never come into play if a ground fault occurs at buses 1,2 , and 3 in this particular network. The next step is to find the positive, negative, and zero sequence impedance matrices for the system buses. The positive sequence admittance matrix depends on the circuit that we have understood here.

$$y_{10} = \frac{1}{j\left(x^1_{g1} + x^1_{T1}\right)} = -j3.5714, y_{12} = -j\frac{20}{3}, y_{13} = -j10$$

$$y_{23} = -j5, y_{20} = \frac{1}{j\left(x^1_{T2} + x^1_{g2}\right)} = -j3.5714$$

$$Y^1_{bus} = \begin{bmatrix} -j20.2381 & j6.6667 & j10 \\ j6.6667 & -j15.2381 & j5 \\ j10 & j5 & -j15 \end{bmatrix}$$

We will be correspondingly evaluating the machines' internal reactances and leakage reactance to find Y10, Y12, and Y 13 ; they pertain to the line parameters. Y23 also pertains to line parameters, whereas Y20 is the connection of the machines' internal reactance, transformers' leakage reactance, as well as the ground with respect to the bus. So once we know these Y elements, the Y bus evaluation remains the same, which is as shown over here. The negative sequence admittance matrix will be the same as the positive sequence admittance matrix. The only difference is that in the network of the negative sequence matrix, sources won't be present.

The zero-sequence admittance matrix will depend on how the transformer connections are made and how the neutrals are connected. So if we look at the zero-sequence impedance on a network, bus 1 has some possibility of the flow of zero-sequence current not from the generator but through the transformer, so we will have to consider Y10, which is going to be the inverse of this element. Whereas if we look at Y20, the Y2 part is left hanging with respect to neutral, so Y20 won't exist for bus 3; there is no information given, and the load is considered to be unloaded. So only Y10 term would come in, and additionally, we will have Y12, Y23, and Y13 while evaluating the zero-sequence impedance matrix for the given network. That is the reason why only Y10 is given, whereas the other line parameters are given.

$$y_{10} = \frac{1}{jX_{T1}^0} = -j12.5, y_{12} = -j2, y_{13} = -j2.5, y_{23} = -j1.25, y_{20} = 0$$

$$Y_{\text{bus}}^0 = \begin{bmatrix} -j17 & j2 & j2.5 \\ j2 & -j3.25 & j1.25 \\ j2.5 & j1.25 & -j3.75 \end{bmatrix}$$

So once we get these Y values, the corresponding Y bus evaluation remains the same as discussed in power flow analysis or the way the corresponding Y bus 1 was evaluated. With this inverse, we can find the zero-sequence bus impedance matrix.

$$Z_{\text{bus}}^0 = \left(Y_{\text{bus}}^0\right)^{-1} = \begin{bmatrix} j0.08 & j0.08 & j0.08 \\ j0.08 & j0.4329 & j0.1976 \\ j0.08 & j0.1976 & j0.3859 \end{bmatrix}$$

The next bit is that at bus 3, a 3-phase bolted fault has occurred, and we have to find the LV side fault current contributions from generators G1 and G2. So if I go back and look at my circuit for a moment, what is given here is that in this network a 3-phase bolted fault has occurred, which means all three phases are equally getting shorted at bus 3 , and for this $3 - $ phase fault I have to find what the current contributions are from generators G1 and G2. Now, since this is a three-phase balanced fault, it is imperative that the negative and zero sequence networks won't play any role at all.

And that's the reason why only the positive sequence network comes into the picture for the pre-fault unloaded situation, where V3 is one at an angle of zero because that's the unloaded situation and Z331 is obtained from the corresponding positive sequence burst impedance matrix. We can find the corresponding fault current for a three-phase bolted fault, which is this number.

$$I_f = I_{a3}^1 = \frac{V_3^{pre}}{Z_{33}^1} = -j4.7847pu$$

And with this fault, we can now try to find the corresponding positive sequence voltages at all the buses: the first number is for bus 1 , the second is for bus 2 , and the third is for bus 3 . Since bus 3 is solidly grounded, its terminal positive sequence voltage is perfectly zero. The post-fault negative and zero sequence components are perfectly zero because these currents are zero; they don't exist for a balanced fault.

$$V_a^{1,\text{ post}} = V_a^{1,\text{ pre}} - Z_{\text{bus}}^1 \begin{bmatrix} 0 \\ 0 \\ I_{a3}^1 \end{bmatrix} = \begin{bmatrix} 0.2962 \\ 0.3641 \\ 0 \end{bmatrix} pu$$

$$V_a^{2,\text{ post}} = V_a^{0,\text{ post}} = 0 \text{ as } V_a^{2,\text{ pre}} = V_a^{0,\text{ pre}} = I_{a3}^0 = I_{a3}^2 = 0pu$$

Now, once we know these sequence voltages, we can convert them to the corresponding phase voltages. But before doing that, since we have to find the LV side current, it is always suggested to retain your evaluations in the sequence network or sequence component to the extent possible, because sequence components would be able to easily encounter the phase shift that would occur because of the similar transformer configurations. So we will evaluate the line currents using these sequence voltages only; we will not domain yet. So you find the corresponding positive sequence line currents Ia12, Ia13, and Ia23; other line components are perfectly zero.

$$\left[I_{a,12}^1\right] = \frac{V_{a,1}^{1,\text{ post}} - V_{a,2}^{1,\text{ post}}}{Z_{12}^1} = j0.4527 = -I_{a,21}^1$$

$$I_{a,13}^1 = \frac{V_{a,1}^{1,\text{ post}} - V_{a,3}^{1,\text{ post}}}{Z_{13}^1} = -j2.962$$

$$I_{a,23}^1 = \frac{V_{a,2}^{1,\text{ post}} - V_{a,3}^{1,\text{ post}}}{Z_{23}^1} = -j1.8205$$

Once we know the corresponding line currents and sequence currents on the HV side of the transformer where bus 1 is, what we have found is that if I have bus 1, 2, and 3, I have been able to find Ia13, the positive sequence current, and Ia12, which is the positive sequence current of bus 1 across line 12.

If these currents are flowing, then this is essentially the current present on the HV side of the transformer, which, by KCL, gives me this number. And hence, I have this as my generator HV side current; other sequence currents, since they don't exist, are perfectly zero. Similarly, for G2, I can apply KCL, where G2 is the current flowing over from here, and this is Ia231 and Ia211. So once I know my HV side current from the positive sequence perspective, other components are zero.

$$I^1_{a,G_1,HV} = I^1_{a,12} + I^1_{a,13} = -j2.5093$$
$$I^1_{a,G_2,HV} = I^1_{a,21} + I^1_{a,23} = -j2.2732$$

Now I should apply the corresponding phase shift because the transformers are delta and star, with star on the HV side and again here star and delta.

So the LV side is the delta component. And when we move from the HV side being star to the LV side delta, these currents will have a phase shift of an additional 30 degrees minus 30 . So the corresponding LV side currents are these components. Other sequence components don't exist because they never existed on the HV side of the transformer, either. And once I know these sequence components with zero other components, I can now transform them back to the phase network or phase component where Iabc for a given bus is a times Ia012.

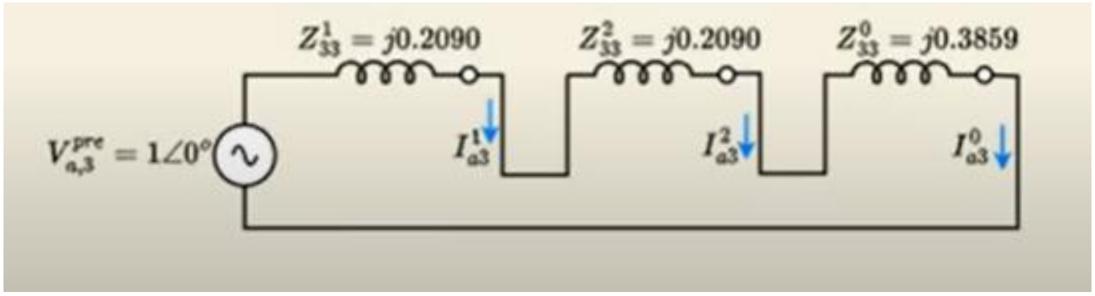
$$I^1_{a,G1,LV} = 2.5093\angle - 120°pu \text{ (Y} \rightarrow \Delta \text{ shift )}$$
$$I^1_{a,G2,LV} = 2.2732\angle - 120°pu$$

So a matrix is the same matrix that we discussed. So these are the corresponding current contributions from the LV side of the transformer.

What is a bit interesting to note here is that the fault has occurred on bus 3 , which is a balanced three-phase fault. And even though there is no physical flow of zero-sequence current from generators G1 and G2 on the network side, the three-phase currents still exist. And these three-phase currents are, in a way, balanced currents.

$$I_{a,G1,LV} = 2.5093\angle - 120°pu I_{a,G2,LV} = 2.2732\angle - 120°pu$$
$$I_{b,G1,LV} = 2.5093\angle 120°pu I_{b,G2,LV} = 2.2732\angle 120°pu$$
$$I_{c,G1,LV} = 2.5093\angle 0°pu I_{c,G2,LV} = 2.2732\angle 0°pu$$

So the last bit is that for a phase-to-ground fault at bus 3, we have to find the post-fault voltages at bus 1 , bus 2 , and bus 3 . It is just an enumerated combination that is given here. So, assuming phase a as a reference for a-to-ground fault, all the sequence networks or components would be in series. We know the impedances and the pre-fault voltage, so we can find the corresponding sequence currents. Once we know the sequence currents, we can apply Thevenin's theorem to find the sequence voltages. So this is the positive sequence voltage. Similarly, I have the negative sequence threephase voltage and the corresponding zero sequence voltage for all three buses that are present.




$$V_a^{1,\text{ post}} = V_a^{1,\text{ pre}} - Z_{\text{bus}}^1 \begin{bmatrix} 0 \\ 0 \\ I_{a3}^1 \end{bmatrix} = \begin{bmatrix} 0.8170 \\ 0.8347 \\ 0.7400 \end{bmatrix}$$

$$V_a^{2,\text{ post}} = -Z_{\text{bus}}^2 \begin{bmatrix} 0 \\ 0 \\ I_{a3}^2 \end{bmatrix} = \begin{bmatrix} -0.1830 \\ -0.1653 \\ -0.2600 \end{bmatrix}$$

$$V_a^{0,\text{ post}} = -Z_{\text{bus}}^0 \begin{bmatrix} 0 \\ 0 \\ I_{a3}^0 \end{bmatrix} = \begin{bmatrix} -0.09951 \\ -0.24579 \\ -0.4800 \end{bmatrix}$$

Once I know the voltages, I can then correspondingly apply the transformation back to phase voltages for bus 1 , where I have to find the phase a voltage. I will simply add the phase components or the sequence components because phase a itself has been chosen as a reference here, so I will add the positive sequence component, negative sequence component, and zero sequence component for the three buses given here, and I will be able to
obtain the phase a voltage. For phase b, I have the a operator coming in where a is at an angle of 120 degrees, and similarly for phase c. So that is all from my side regarding the discussion of the solved examples that we have discussed. Hopefully, this has given you enough understanding of how balanced faults and unbalanced faults are analyzed using Fortescue's theorem and Thevenin's theorem.

The next lecture is going to be the last lecture of the fault analysis module, where I'll briefly talk about the challenges that exist with a lot of renewable energy resources being integrated into the power network. By renewable energy resources, my focus is mostly on solar PV plants, wind generators, and all other possible inverter-based sources, which are sources that can be connected. So, inverter-based resources are all such sources that need to have this inverter connection in between before they can be connected to the AC grid. What challenges do they pose in terms of power network protection, where fault analysis is one such simple or small exercise that we do? So hopefully you will be able to gain some insight into what these challenges are. So that's all. Thank you. Thank you so much.