Power Network Analysis

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Week - 10

Lecture-48

Hello everyone, welcome to lecture 3 of week 10 of the course Power Network Analysis, in which we continue with our second-to-last module on fault analysis. In this discussion, we will take up the analysis behind understanding the impact of two categories of unbalanced or asymmetric faults: line-to-ground fault, also known as phase-to-ground fault, and double line-to-line or phase-to-phase fault. In the notion of faults, these line-to-line or phase-to-phase they pertain; they are analogous terms. The last category of unsymmetrical faults, which is double line-ground or phase-to-phase to ground, will be discussed in the next discussion. So in the previous lecture, we discussed Fortescue's theorem and the implications of Fortescue's theorem in decomposing an n-phase system, which is assumed to be unbalanced. This can be categorized or decomposed into n balanced systems.

By balanced, I mean that the corresponding phasors, be it voltage or current, for a three-phase system n would be equal to n. The voltage magnitudes or the current magnitudes, basically the magnitudes, would be equal to each other, and the corresponding phase angles would also have equal phase angle differences between these phasors. So for an n-phase system, there can be certain combinations of possibilities. One equal phase angle is, by default, 0 degrees or 0 radians.

And the other possibility for an n-phase system is. . . 360 degrees divided by n . For n equal to 3 , this angle turns out to be 120 degrees.

So basically, we can create corresponding balance systems: one with a 0 -degree phase angle and two others with 120 -degree phase angle differences between the phasors, either in the clockwise or anticlockwise direction. For n equal to 2 , the possibilities here would be either 0 degrees or 180 degrees. So we can have a zero-sequence component present for a two-phase system, and the other sequence component, with some name, would have these two phases in opposing fashion to each other. For n equal to 4 in a 4 -phase system, the number of possibilities that can exist would be either 0 degrees or 90 degrees. With 0 degrees, we would have one parallel set of phasors, and with 90 degrees, we can have three other combinations of phasor diagrams in which the four balanced systems can exist.

So we had discussed that n is equal to 3 specifically for the three-phase network applying the application of Fortescue's theorem, which essentially decomposes the phase components into three balanced systems, and that's how we came up with the notion of sequence voltages or currents. We had also discussed sequence impedances, whose notion is a bit different compared to sequence components of voltage and currents because these impedances pertain to the impedances offered by the corresponding sequence currents in a particular sequence circuit. And we had discussed the sequence impedances for transmission lines and the three-phase transformers under different possible configurations. So I request the viewers to please revisit the previous lecture, which would provide a good premise of what the sequence components will be. Today's discussion will start with sequence networks and components for a synchronous generator.

To be specific, we would take the case of both loaded and unloaded conditions. In case the network or generator is unloaded, that would mean that the corresponding currents would all be zero in an unloaded scenario, which would mean that whatever the internal EMF generated by this synchronous generator is, the same voltages appear as the phase voltages of v_a, v_b, and v_c, respectively. In case the generator is loaded, these currents won't be zero and consequently the corresponding phase voltages at the terminal won't be the same as the internal EMFs. With that premise, we assume our three-phase synchronous generator is loaded. For the unloaded condition, the current would simply become zero.

We have a three-phase synchronous generator that is inherently producing a balanced internal voltage. So basically, if E_a is a phasor in the frequency domain defined as E_a at an angle of zero degrees, then E_b is E_a at an angle of minus 120 degrees, and E_c would be E_a at an angle of 120 degrees. The reason for this combination of voltages is that synchronous generators inherently produce positive sequence voltage by design, and that is why this sort of voltage arrangement would come in. For more details, please revisit our discussion on synchronous generators, where you would have a better understanding of why the stator voltages inherently tend to be positive sequence voltages. So by balanced term here, I mean that the internal EMFs are inherently positive sequence voltages, and the neutral of this generator is grounded through a neutral impedance Z_n.

Since the generator is feeding in some three-phase load, that's how the notion or orientation of phase currents has been shown. And if I apply KCL at this neutral point, then the corresponding neutral current has to be an incoming current because the phase currents are all outgoing currents; they are feeding some load. So, if we try to sort of understand what the sequence network or component or corresponding impedance for a loaded synchronous generator would be, the way we did it for a three-phase balanced load yesterday, that is, we started with the phasor equations and then applied

Fortescue's theorem transformation. On similar lines, let us do the same for this three-phase synchronous generator. So if we apply KVL between the ground point and go all the way to the positive terminal of v_a, what we would observe is that v_a, or basically let me rewrite it again, E_a would be equal to, or the other way round, v_a would be equal to the internal EMF minus the voltage drop across the armature impedance, let me mark it as Z_s, which is the synchronous impedance, minus I_n into Z_n, where $I_n Z_n$ is the voltage drop across the neutral impedance and I_n is nothing but the sum of the corresponding phase currents as per KCL on the neutral point.

Similarly, we would also have equations for phase b and phase c correspondingly. So $E_b E_c$ minus $I_b Z_s I_c Z_s$ minus $I_n Z_n$ where we can expand I_n in terms of individual phases. So if we compactly represent this in vector form. This is what that vector form looks like.

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} - \begin{bmatrix} Z_s + Z_n & Z_n & Z_n \\ Z_n & Z_s + Z_n & Z_n \\ Z_n & Z_n & Z_s + Z_n \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

And remember or recollect that $v_a v_b v_c$ was essentially equal to a times V^{a012}, assuming phase a as the reference for sequence components. So basically we have a reference in the phasor domain, and we also have a reference of phase in defining which sequence component we are trying to represent. So we are assuming that the inherent phase of a sequence of components uniquely represents all other phase quantities. And on similar lines, this three-phase vector is also a multiple of I^{a012}, again assuming phase a as a reference for sequence components. So what I'm trying to do, the way we did it for the sequence impedances of a three-phase balanced load, is apply the same logic here with the underline or bottom part that E_b, since E_a, E_b, and E_c are positive sequence voltages, E_b is a^2 times E_a and E_c is a times E_a, where a is our complex operator which is one at an angle of 120 degrees.

So, the dimensionless quantity is all in per units. So, a is the same operator that is appearing in this term. So if we do that mathematical rearrangement, try to shift a from the LHS of V^{a012} to the RHS, we can get the corresponding equations as shown here, and that's what I mentioned internally: that internally, EMFs are assumed to be balanced; by balanced, I mean in terms of positive sequence voltages. So KVL equations, by rearranging the terms, would give us an A^{-1} term here, A^{-1}, and A. If we include those multiplications as per the A matrix which we saw in the previous lecture, essentially this is one unique, beautiful equation that we get, which in terms of sequence components states that V^{a0}, as per this equation, is equal to minus Z_0.

Internal emfs are assumed to be balanced, hence let

$$E_a = E^{a1}, E_b = a^2 E^{a1}, E_c = aE^{a1}$$

The KVL equations in seq. components form are

$$\begin{bmatrix} V^{a0} \\ V^{a1} \\ V^{a2} \end{bmatrix} = A^{-1} \begin{bmatrix} E^{a1} \\ a^2 E^{a1} \\ aE^{a1} \end{bmatrix} - A^{-1} \begin{bmatrix} Z_s + Z_n & Z_n & Z_n \\ Z_n & Z_s + Z_n & Z_n \\ Z_n & Z_n & Z_s + Z_n \end{bmatrix} A \begin{bmatrix} I^{a0} \\ I^{a1} \\ I^{a2} \end{bmatrix}$$

$$\Rightarrow V^{a012} = \begin{bmatrix} 0 \\ E^{a1} \\ 0 \end{bmatrix} - \begin{bmatrix} Z_s + 3Z_n & 0 & 0 \\ 0 & Z_s & 0 \\ 0 & 0 & Z_s \end{bmatrix} I^{a012}$$

Let me see what the notion of Z_0 is; then we have V^{a1} equal to E^{a1} minus $Z_1 I^{a1}$, and lastly, V^{a2} is equal to minus $Z_2 I^{a2}$. What are E^{a1}, Z_0, Z_1, and Z_2 ? Z_0, Z_1, Z_2 are the respective positive and negative sequence impedances of this loaded synchronous generator. So in terms of self-impedance and neutral impedance, Z_0 is Z_s plus 3 times Z_n. The neutral grounding aspect influences the zero sequence impedance, as was also the case for transmission lines and transformers. Z_1 is equal to Z_2, which is nothing but the synchronous impedance for fault analysis; Z_s would typically be the sub-transient direct access reactance of the synchronous generator, with negligible resistance R being 0 . Z_s refers to essentially j times X_d'', which is a sub-transient direct axis reactance in the context of fault analysis. So that defines our sequence impedances, and E^{a1} is nothing but the internal EMF positive sequence voltage, which is being generated in terms of phase a. Again, remember when I talk about a three-phase system: if it is generating, or if it is exactly equivalent to positive sequence voltage, then it is imperative that in this sort of a three-phase voltage arrangement, negative sequence and zero sequence components won't exist at all; V^{a0} and V^{a2} would all be zero because inherently the generator is producing positive sequence voltage, so only the positive sequence component would come in. So in that context, since E^{a1} is positive sequence voltage, that is the reason why there is no voltage source appearing in the zero-sequence and the negative-sequence circuit. So if we were to redraw these or sort of represent these equations in terms of some fictitious circuit, those three circuits would look like what is shown in this particular slide, slide number 5.

The positive sequence circuit essentially consists of only the internal EMF, which is equal to E^{a1}. With a voltage drop across the positive sequence impedance and remaining negative sequence and zero sequence circuits, they are always passive circuits for a balanced three-phase synchronous generator, and these circuits, as can be seen, are all essentially independent of each other once we know the positive sequence impedance, negative sequence, and zero sequence impedance, which are functions of the machine's synchronous impedances and neutral impedances. The resulting sequence circuits become completely independent, and that is where the beauty of Fortescue's theorem comes in.

Each of these circuits can be analyzed according to KVL and KCL independently, without negative sequence current interfering with positive sequence or negative sequence voltage. Only the positive sequence network here has a voltage source; it is an active circuit, while the negative and zero sequence circuits are passive.

If we focus on this particular positive sequence circuit, we have already seen such a circuit for a three-phase balanced cylindrical pole synchronous generator, which was being represented by its analogous equivalent singlephase diagram. If the machine operates under balanced conditions, the same circuit is also used to analyze its steady-state performance. The difference in that circuit would be that instead of direct access to sub-transient reactants, you would be using the steady state reactants. For positive and negative sequence circuits, the reference with which these terminal voltages are being measured is always the neutral point, whereas for the zero sequence circuit, the zero sequence voltage is being measured with respect to ground. So, in case the neutral and ground are not connected to each other, what would happen if neutral and ground are not connected? Let me go back to the circuit here.

That means if there is a break between the neutral and ground points, it is analogous to having neutral impedance as infinity. If neutral impedance is infinity, the zero sequence impedance would also be extremely high, and that is the reason why there would not be any flow of zero sequence current for the zero sequence network or circuit if neutral and ground are not connected. And that's the reason why, for the zero sequence network, ground acts as a reference for the measurement of potential, specifically the zero sequence voltage, whereas for the positive and negative sequences, neutral is the reference for measuring the voltages. If neutral and ground are unconnected, there is no flow of zero-sequence current, because in that condition, Z_0 tends to be infinity, which would indicate that no matter what the voltage source is, the corresponding current would always be zero. So that is the big difference in terms of sequence networks or components for synchronous generators.

I hope all my viewers are comfortable so far with the understanding that we have developed. In case there is any confusion, please revisit the previous lecture slides that we have discussed. The next set of slides, as I mentioned at the beginning of today's discussion, will start with our first unbalanced fault, which is also known as SLG fault in its full form. It is a single line to ground fault, also called a phase to ground fault. So, we will take up these unbalanced faults one by one, and to keep the discussion simple, we will focus only on generators per se.

We won't be discussing the occurrence of these faults on the actual power network, although there is no necessity for these faults to always occur near the generator; faults can occur elsewhere in the network as well. So in the next lecture, hopefully, I'll be able to convince all my viewers of how to understand these unbalanced fault occurrences elsewhere in the network, which is where the Thevenin theorem's application would come in. So the first single line to ground fault that we focus on is the phase A to ground fault, which has occurred at the terminal of the generator-the same synchronous generator that we discussed in the previous few slides. There can also be other possibilities of faults, such as a single line to ground fault. It can happen between phase A and ground.

It can also happen between phase B and ground. It can also happen between phase C and ground. Whatever we discuss for phase A to ground, a similar analogy would be applicable for the other two single line to ground faults as well. That is point number one. Point number two: since the fault has occurred at the generator terminal between phase A and ground, for simplicity, we are assuming the mutual impedance between the synchronous impedances of the per-phase synchronous impedances of the synchronous generator to be 0 .

However, if you consider mutual impedance as non-zero, what would happen? The circuit analogy would remain the same; only the values of Z_0, Z_1, and Z_2 would change. Change in what context? Along similar lines, the way mutually coupled three-phase balanced load sequence impedances were obtained in the previous lecture was discussed. So Z_m is equal to zero for the time being, but you can consider Z_m to be non-zero as well; the circuit analogy will remain the same. And to start with, we are assuming the generator is unloaded in an unloaded sequence, so basically in the unloaded sense, the phase currents are all zero. The internal EMF appears at the phase voltage itself. Z_f is the fault impedance, and since a fault has occurred between phase A to ground, if I apply KVL across this fault impedance, I would have v_a equal to $I_a Z_f$, and I_a itself is the fault current. So, I_f represents the fault current, and since the generator is unloaded, the other phase currents do not exist. So the obvious question would be, what would the situation be in case the phase currents are not zero, in case the generator is loaded? The answer to this we have indirectly discussed already in the balanced fault example that we discussed, that typically the impact of a fault always has a signature in which the current tends to go up much larger compared to normal load current. So even if the generator is loaded, the increase in fault current would be so great that, compared to the fault current in phase A, I_b and I_c would be very, very small. So even if the generator is loaded due to a fault, the current in phase A will be several times larger-maybe 4,5 , or 10 times larger-than the currents in the other phases because of the low impedance path offered across Z_f, and hence it makes sense for the currents in the other phases to be zero even during the loaded condition.

So, with these two as our equations of understanding or importance, what is the purpose of understanding or analyzing this single line-to-ground fault? The purpose remains the same; our objective is to find the fault current in terms of the known quantities. Now, what are these known quantities? They are the synchronous impedance of the generator, fault impedance, terminal voltage, and so on. But we also have to see that, okay, for a single line-toground fault, one could argue that if v_a is known and the fault impedance is known, then the analysis is nothing; it's just a simple KVL application. But then the corresponding analysis, when it is done from the Thevenin's theorem perspective, becomes completely different, and that's where I gave a word of caution that at the outset this understanding may appear to be very simple; but if the same fault were to occur in another position in the network, like at a transformer terminal or a bus terminal where these quantities may or may not be known, then the understanding becomes very difficult, and hence the Thevenin's application would come in. So our objective, as I repeat, is to find I_f in terms of certain known quantities.

So let's apply Fortescue's theorem, and for phase a to ground fault specifically, I will choose phase a as the reference for the sequence component. You could question or again argue why not phase B, why not phase c. Please have patience; I will come back to this point in the next few minutes, probably. So I am choosing phase a as my reference for sequence components, and if I recollect the phase b and phase c currents in terms of the sequence components, what do you need to remember? You just have to remember the sequence of phasors for positive sequence: if I^{a1} is, let's say, the reference, then I^{b1} is 120 degrees lagging phase a and I^{c1} is leading by 120 degrees I^{a1}. This is I120 degrees; this is for positive sequence.

So the orientation here is abc in a clockwise fashion. For negative sequence, the same sequence, I mean the same phasors with similar magnitudes or maybe different magnitudes can exist. But the sequence here is different. Here I have I^{a2}, I^{c2}, and I^{b2}.

This is 120 ; this is also 120 . The sequence $\mathrm{a, c, b}$ in a clockwise fashion is a negative sequence, and for the zero sequence, all the phasors are parallel to each other: I^{a0}, I^{b0}, and I^{c0} with the same magnitude. Here the magnitudes are the same; they will be different in different systems. So if I just remember this, then I can always rewrite I_b as I^{b0} plus I^{b1} plus I^{b2}. And since I have chosen phase A as a reference for sequence components, I need to represent I^{b1} in terms of I^{a1}, I^{b2} in terms of I^{a2}, and I^{b0} in terms of I^{a0}. For zero sequence components, the quantums are the same, so there is no need for that operator.

Here, small a is the a that we are seeing here. The small a is an angle of 120 degrees, and I^{b1}, it is. .. sort of lagging I^{a1} by 120 degrees. So, if a is one at an angle of 120 degrees, a^2 is one at an angle of 240 degrees, which is also equal to a conjugate, which is one at an angle of minus 120 degrees, and that is the reason why you have a^2 representing I^{b1}, and similarly, here this is representing I^{b2}, and the same goes for phase c current. So if I apply this coherency, I^{a0} gets canceled; a^2 is not equal to a, as shown over here. So the only possibility for this to happen is that the positive sequence current and the negative sequence currents are equal. Furthermore, I_b is zero, so if I apply the expansion of I_b in terms of phase currents, I also see that the zero sequence current happens to be the same as the positive and negative sequence currents. Now, under what condition do you expect this to be true, where three distinct currents pertaining to three distinct circuits are as shown here? Under what condition can these three currents be equal? This is possible only when these sequence circuits are connected in series, and that is the inference that comes from this: the sequence currents are equal, which is possible only when the associated positive, negative, and zero sequence components or circuits of this loaded/unloaded synchronous generator, at the terminal of which a phase A to ground fault has occurred, are connected in series.

So, in terms of fault current, if I know what the zero sequence current is, I can also find the corresponding fault current, and if I apply the second logic, which was the KVL voltage v_a in terms of $I_a Z_f$, since phase a is the reference, I can represent v_a as V^{a0}, V^{a1}, and V^{a2}. Remember, V^{a0} was the negative voltage drop across the zero sequence impedance, V^{a1} was this term as per the sequence network of the generator, and V^{a2} is this particular term, which is the negative sequence voltage drop with a negative sign. So if I put in those numbers and since all the sequence currents are equal, I can have an expression for fault current evaluation in terms of the internal EMF of the generator and the corresponding known quantities of the corresponding fault impedances. Now, if you recollect or compare, the basic KVL equation, which we started with, was v_a is equal to $I_a Z_f$, and the other expression of I_a, which we are getting in terms of fault impedance, is E^{a1} and functions of Z_0, Z_1, Z_2, and Z_f.

Fault current $I_f = I_a = I^{a0} + I^{a1} + I^{a2} = 3I^{a0}$

Further, $V_a = I_a Z_f \Rightarrow V^{a0} + V^{a1} + V^{a2} = 3I^{a0} Z_f$

$$\Rightarrow -Z_0 I^{a0} + E^{a1} - Z_1 I^{a1} - Z_2 I^{a2} = 3I^{a0} Z_f$$

As $I^{a0} = I^{a1} = I^{a2} \Rightarrow I^{a0} = \frac{I_f}{3} = \frac{E^{a1}}{Z_0 + Z_1 + Z_2 + 3Z_f}$

These two expressions are completely distinct. Reason? We are trying to find the worst-case fault current, not the steady-state current, and during faults, the maximum worst-case fault current would appear only in the subtransient period. In the sub-transient period, having information about v_a itself would be a big question mark. So essentially, that is the reason why you are representing generators as internal EMF sources with sub-transient direct access reactance, and that helps us evaluate what the worst-case fault current is in terms of the known quantities that are easily recognizable in fault analysis. So, with these two concepts, concept number one and the equation of current that we have obtained, if we combine these two concepts and try to represent them over a circuit, this is a circuit that would look like this: the $3Z_f$ representation is coming in because the $3Z_f$ term is coming in over here. So for a single line to ground fault, we need to understand the single line to ground fault, specifically phase A to ground fault, or faults occurring elsewhere in the network, which we will discuss again in the next lecture.

Instead of having Z_1, Z_2, and Z_0 for the generator, we'll make use of Thevenin's theorem to find the Thevenin impedances, and Z_1, Z_2, and Z_0 will be replaced by these Thevenin impedances, which we'll again see in the next lecture. In case the generator is ungrounded, as I mentioned, the neutral impedance would be infinite, and hence there would be no fault current at all. If Z_n is infinity, Z_0 is infinity, and you relook at this expression, the value of fault current is undefined. Because division by infinity is undefined, that means a single line-to-ground fault will have no effect in an ungrounded system. If the generator is grounded through some impedance, then in that condition only a single line-to-ground fault will have an implication.

So, in a way, to restate it. It may go a little off bit, but then DC microgrids, which are alternative forms of small microgrids with DC sources and DC loads, have few underground or overhead cables mostly. DC microgrids are intentionally not grounded. They are intentionally not grounded to ensure that in case of a single line to ground fault, or a pole to ground fault, or a pole to pole fault, specifically. If it occurs in a DC microgrid, since the system is ungrounded, the single line-to-ground fault will have no fault current contribution because of this particular concept. And that's the reason why the first line to ground fault or single line to ground fault in the DC microgrid is not catastrophic.

But the moment the next single line-to-ground fault occurs, Z_n will no longer be infinity because there is already a ground reference available, and hence the fault currents would be very high. So some sort of interesting notion goes into the design aspects of a DC microgrid. Brings me to the end of a single line to ground fault. Now there was a question that I raised: why did I choose phase a as a reference for a ground fault? You can recalculate or redo this analysis by choosing phase b as a reference for symmetric components.

Sequence components or symmetric components. Please redo that and verify it. What you would observe is that phase b's choice as a sequence of reference for sequence components, as shown in concept number two, will still be applicable. But concept number 1 will not be physically realizable in the sense that if you choose phase b as a reference for sequence components, what you would observe is that I^{b0} would be a times I^{b1} and I^{b2} would be a^2 times I^{b1}. In the case of phase A as a reference for sequence components, we found that all the sequence currents were equal. If we choose phase b as a reference, we are still getting some correspondence between the sequence currents, but then the complex operator a appears in between. And that's the reason why concept number 1 won't be physically realizable. If concept number 1 is not physically realizable, representing this circuit won't be feasible or possible. That's the reason why there is a convention that goes by a single-ended ground fault. If a fault has occurred in phase a, please choose phase a as a reference.

If a phase b fault has occurred, choose phase b as a reference. And similarly, if a phase c to ground fault has occurred, please choose phase c as a reference. You would be able to physically realize this circuit and have concept 1 also be true. That is the reason. Please verify that. We will conclude this discussion with a double line-to-ground fault where we have chosen a similar generator, but now we choose phase b and phase c as our faulty phases shorted by impedance Z_f.

Phase a is healthy, so phase a current is almost zero because the load current is very, very small compared to the fault current, and if the generator is unloaded, phase a itself would be zero. By KVL across phase b and phase c, we have one equation, and the other equation is that the fault current is I_b or the negative of I_c. So we choose phase a as a reference again for sequence components for the phase b to c fault. If we apply phase a as a reference, we see that the zero sequence current is perfectly zero because I_a is zero and I_b is the negative of I_c.

So there is no zero sequence network involved. Phase sequence positive sequence currents and negative sequence currents are the negatives of each other. This is possible only when positive and negative sequence circuits are connected in an anti-series fashion, with zero sequence open-circuited. If we represent our phase currents in terms of sequence currents, this is the expression for the fault current, which we still have to find in terms of the internal EMF. So, if we apply the KVL equation now. We get our fault current as I^{a1} and I^{a2} in terms of this equation where I_a is 0 , and this is the physically realizable circuit that represents how a phase-to-phase fault circuit would look in sequence network impedances.

$$I^{a1} = \frac{I_a + aI_b + a^2 I_c}{3} = \frac{(a - a^2)I_b}{3}$$
$$I^{a2} = \frac{I_a + a^2 I_b + aI_c}{3} = \frac{(a^2 - a)I_b}{3} = -I^{a1}$$

In case the fault occurs elsewhere in the network, we would make use of

Thevenin impedances instead of Z_1 and Z_2. And since there is no ground appearing here, there is no notion of a zero-sequence circuit important here. So phase-to-phase faults don't get affected by grounding. The ground may be neutral, solidly grounded, or open.

So phase to phase faults will remain imperative, will remain unaffected. So, to summarize, for a phase b to c fault, the reference that you have to choose is phase a for sequence components. If you have a phase c to a fault, you should choose phase b as a reference. If you have a phase a to b fault, you have to choose phase c as a reference for sequence components. If you choose any other reference, this physical circuit representation of sequence networks won't be applicable; although the expression of currents would remain more or less similar. So the way we discussed for a single underground fault, the same logic applies here.

With this, I conclude today's discussion. In the next lecture, we will continue this with double-line to ground faults and understanding Thevenin's theorem for faults elsewhere in the network. Thank you.