Power System Protection
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Lecture No. 23
Multi-Terminal Lines

Welcome to NPTEL course on Power System Protection. Today we will continue with distance relaying on multi-terminal lines.

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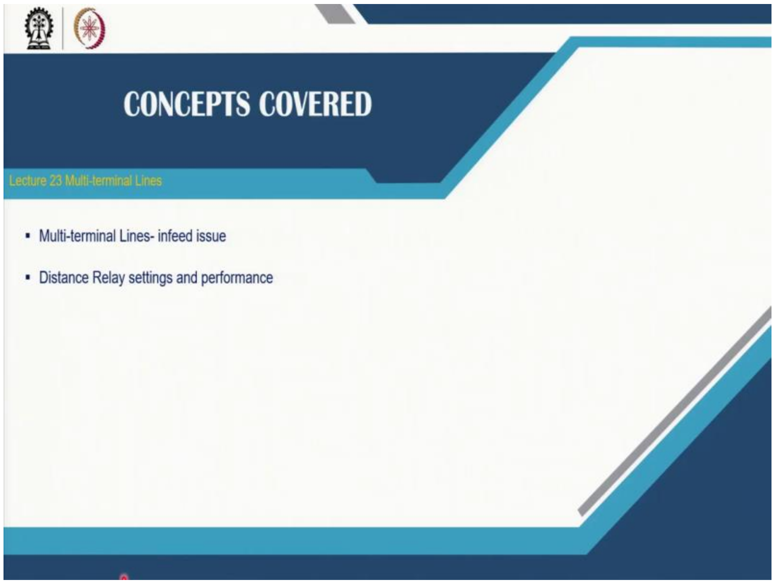

This lecture is on the issues with multi-terminal lines, the protection issues, and how the distance relay performs in such a configuration, we will see.

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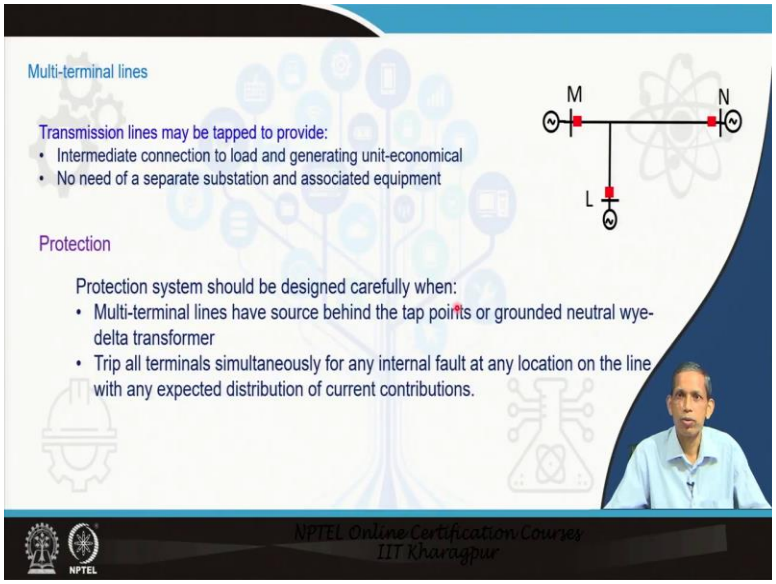

In, last lectures we discuss about two-terminal lines having multiple circuits. We discussed on the double circuit line, otherwise called parallel line also. But that, such a system can be also, we will find with having more number of parallel lines, quad circuits and so having 4 parallel lines also. So, we discuss on the zero sequence mutually impedance aspect with further discussing on that perspective on different configurations in transmission system this lecture is on multi-terminal lines.

If you see this, we have a 3-terminal configuration here. But such terminals can be more in number also. But in power systems, in the multi-terminal configuration, 3-terminal lines are more common. In such a situation it has economical advantage as at the tap point we do not need any substation or the associated equipment. So, whenever a load center or the generating point comes out, instead of connecting this, say this this center directly having a different line to the end bus, which requires right of way and so, this L bus can be connected to a nearby line and which can dispatch power to the N side or any other side.

So, this advantage leads to the existence of the need of multi-terminal lines but it has operational and also these protection setting issues. So, we will discuss on the protection perspective. Now, what happens when you have a source or a star-grounded delta transformer connected here then, in any case, a fault happens to be any of the three sections here, all the three sources participate in that fault say fault will be here, so this generator participates, so also these, and so also the N side generator participates in that fault.

So, that leads to a different scenario on apparent impedance seen by the distance relay, and so with the associated protection issues. And note here that, anywhere in these 3 sections a fault happens to be there, then all the 3 breakers associated all the 3 buses must trip otherwise the fault will be felt from the untripped circuit breaker side. So, that is what the basic need of protection we will see the problem and, the issues, and then we will go to the different setting perspective for distance relay.

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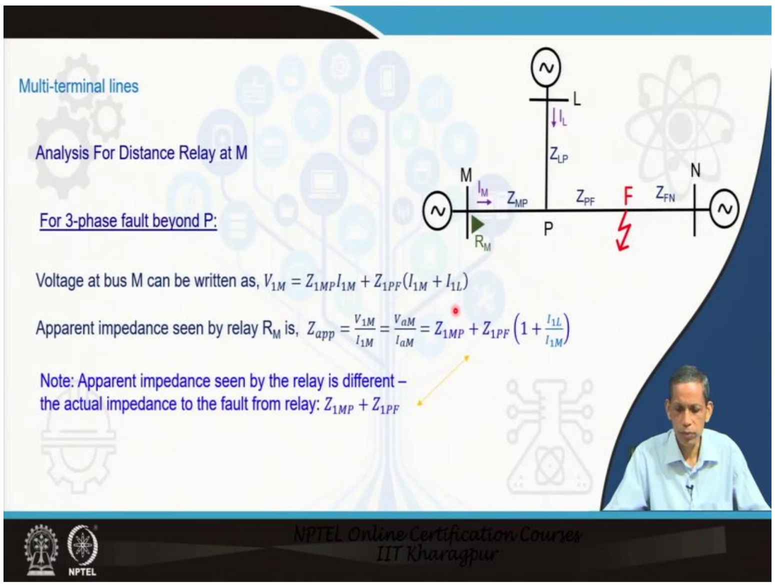

So, this is the 3-terminal line and we have the tap position P where a source is being connected to, bus L, we have MN line, we are observing the relay at R_M. Similarly, you can consider the relay at L and N also. These line sections have their impedances P the tap point. So, impedance between M and P is Z_{MP}, impedance between P and N is, F being a fault point here, (Z_{PF} + Z_{FN}), and impedance from P to L is Z_{LP}. They have their associated positive sequence impedance, negative sequence impedance, and zero sequence impedance for each line section.

For easy assessment, we consider that each line section is having same conductor. There were and the tower structure, thereby, the per kilometer impedances remain the same. Now, let us consider this distance relay data, the R_M, distance relay at bus M, we considered first 3-phase fault in the line, let us consider a 3-phase fault at F. So in the section P to N and how this relay at M sees.

Voltage at bus M will be this corresponding drop from here till P and from P to M. So we say if we consider the positive sequence current which is the only component of current flows during the 3-phase fault.

So we say that the corresponding current in this part, ZPF part, if we see from this side current from bus M flows and also current from bus L flows. So, these two generator participate feeding current through these path. So, the common path is P to F, and from P to M for relay R_M is only the I_M current flows. This I_M current is the current through the relay R_M but from P to F, the corresponding current becomes (I_M +I_L), the I_L component of current is not associated with the relay R_M.

So with that difference, if we see the drop from F to P, from the 3-phase. So, that becomes equals to $V_{1M} = Z_{1MP} . I_{1M} + Z_{1PF} (I_{1M} + I_{1L})$. So, that is the voltage of the V_{1M} for the 3-phase fault. But we know that the positive sequence voltage and current is same as the phase component of voltage and current also for each phase. The apparent impedance seen by relay RM for this 3-phase fault equals to $V_{1M}/I_{1M} = V_{aM}/I_{aM}$ as you know.

So that equals to, if we divide, you can see that this I_{1M} here or the same as I_M, so that becomes $Z_{app} = \frac{V_{1M}}{I_{1M}} = \frac{V_{aM}}{I_{aM}} = Z_{1MP} + Z_{1PF}(1 + \frac{I_{1L}}{I_{1M}})$. We are dividing by I1M but we have a term now, I1L. But the fault point from the relay bus the positive sequence impedance between these two points is (Z_{1MP} + Z_{1PF}). So, the actual positive sequence impedance up to the fault point from the relay bus is (Z_{1MP} +Z_{1PF}). But what the relay will see now in this scenario, because of these I_L current, we will see $Z_{app} = Z_{1MP} + Z_{1PF}(1 + \frac{I_{1L}}{I_{1M}})$.

So these ratio difference, the additional term, the Z_{1PF} (I_{1L} / I_{1M}) is the additional component in the apparent impedance calculation. So, that is the difference we notice from the actual impedance, positive sequence impedance up to fault point versus the apparent impedance seen by the relay for the three-phase fault case.

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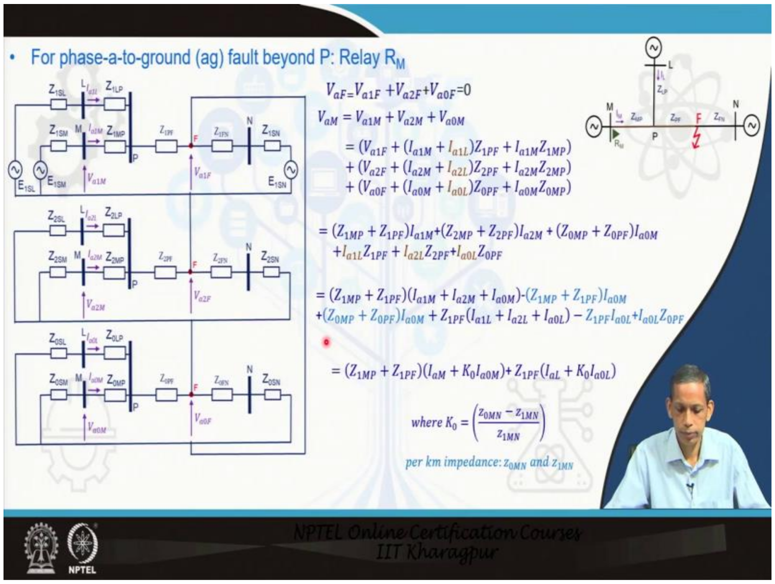

Now we will see for the same system, same fault point, we will see now the what happens for the phase a to ground fault, its analysis. We know for phase a to ground fault, the fault point voltage $V_{aF}=V_{a1F}+V_{a2F}+V_{a0F}=0$. Now, we see here, this V_{aM}, the relay bus voltage during the line to ground fault will be available from this calculation related to this sequence component analysis.

So, what we see here that we have these 3 components $V_{aM}=V_{a1M}+V_{a2M}+V_{a0M}$, similar to what we have analyzed in earlier discussions also. So, if you see this V_{a1M}, this is the corresponding sequence network for this system, if you see here, you can see that for this fault, for this relay, the corresponding current in the PF section is contributed where these two generators, so they are in parallel.

So, what we have done here, this should be fault point to the left, this is the section here common section from bus P, and then consider the two parallel parts contributed by the two sources, the sources at M and L. And then, like these, this is for positive sequence this negative sequence, this is for 0 sequence, and this is the fault point, so we connect it for R_F equals to 0 like this and that you can see that is our, the sequence network diagram for the phase a to ground fault.

Now, to evaluate V_{aM}, $V_{a1M}=V_{a1F}+(I_{a1M}+I_{a1L})Z_{1PF}+I_{a1M}Z_{1MP}$. So, this is for positive sequence. Similarly, for the negative sequence also, diagram is same. So, you have to consider similar terms for the negative sequence component and also for zero sequence component. This is being phase a to ground fault, so all 3 components will be there.

What we see as compared to the earlier two-terminal derivation that we add another current now, for the Z_{1PF} portion, the common portions where the both current, both currents flow I_{a1L} ,I_{a2L} and I_{a0L} , the 0 sequence component and their associated impedance. Now, if you segregate the different components like we did for a two-terminal line, so we have $I_{a1M}(Z_{1MP}+Z_{1PF})$ that is this portion of impedance, positive sequence impedance. For I_{a2M} also negative sequence contributed with passing through the relay bus. This current for the line, this corresponding impedance, negative sequence plus zero sequence impedance also, I_{a0M}.

Now, we have another three-term associated with these. $I_{a1L}Z_{1PF}+I_{a2L}Z_{2PF}+I_{a0L}Z_{0PF}$. Now for these three-term, this is same as what we have discussed earlier. So, we can do the corresponding 0 sequence compensation factor aspect and so that will lead to occurrence of their $Z_{apparent}$ calculation perspective. So, (Z_{1MP} + Z_{1PF}) so these are the three components of current sequence component.

So to get that, we can see that we subtract this one because we have considered here (Z_{1MP} + Z_{1PF}) I_{a0M}, so subtract here and add the same component. (Z_{0MP} + Z_{0PF}).I_{a0M}, and then we have $Z_{1PF}(I_{a1L}+I_{a2L}+I_{a0L})$ this additional term will be there. So, for this also we did similar things and therefore, what we did here that we added – (Z_{1PF} .I_{a0L}) + (Z_{0PF} .I_{a0L}) of these two terms. So, we have added these two terms, addition, to what we have found here. This leads to $(Z_{1MP}+Z_{1PF})(I_{aM}+K_0I_{a0M})+Z_{1PF}(I_{aL}+K_0I_{a0L})$.

Note, we have already talked about the 0 sequence compensation factor and that is $\frac{Z_0-Z_1}{Z_1}$ of the line and we have considered that all sections are having similar per kilometer impedances for all sequences. So with this, if we substitute this, then we will get the corresponding relations to be like this.

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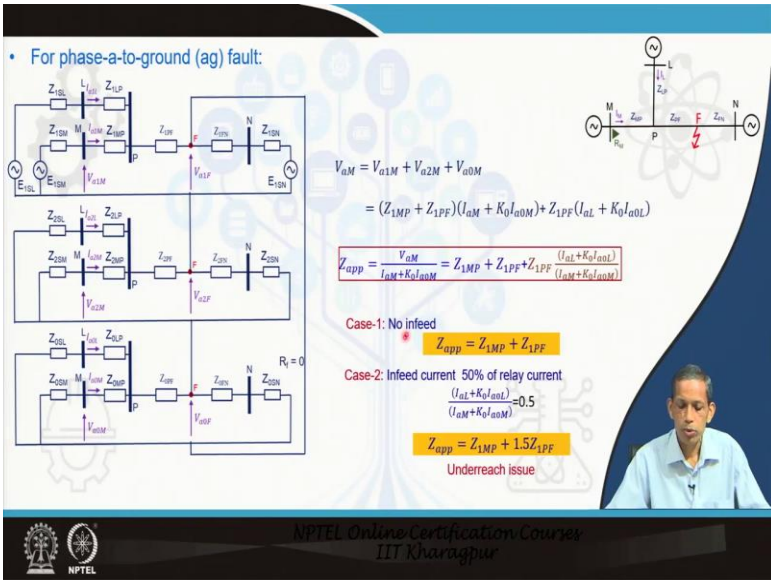

And if you move more further, then the V_M expression, we got this in terms of this K_0. Now if we calculate the $Z_{apparent}$ for this relay, for this fault, phase a to ground fault, $\frac{V_{aM}}{I_{aM} + K_0 I_{a0M}}$, so that if we divide by this term, so this becomes equals to (Z_{1MP} + Z_{1PF}), this is the usual term we should get the (Z_{1MP} + Z_{1PF}), up to this point plus an additional term $Z_{app} = \frac{V_{aM}}{I_{aM} + K_0 I_{a0M}} = Z_{1MP} + Z_{1PF} + Z_{1PF}\frac{I_{aL} + K_0 I_{a0L}}{I_{aM} + K_0 I_{a0M}}$.

So this, we are dividing these if you consider by this perspective, this one. So there we have considered because we have additional term in terms of $(I_{aL} + K_0 I_{a0L})$, so this term is remaining this one and the Z_{1PF} is for this portion, the common portion for the current I_{aL} and I_{aM}. So, this leads to like the case of three-phase fault we saw. Now, only that additional term the rest you can compensation factor is coming here and for that, the two 0 sequence current and are also the associated are that the corresponding 0 sequence current at bus L also what is being flowing into this circuit. So that is also coming to picture in the Z apparent calculation.

So two situations, suppose at one instant there is no infeed, this sources out from operational perspective, then there will be I_{aL} current flowing in this. In that case, this component will be 0, this part. So, therefore, only these two components will be there. So, Z apparent at that time will be the (Z_{1MP} + Z_{1PF}) for the fault F, phase a to ground fault at F, so this will be this. Now, suppose another case with the L source present and let us say consider its contribution is 50 percent of what the corresponding relay current is being there at that time. So, if we consider this ratio to be 50 %, 0.5, then if we substitute this in the, in our derivation here, if this becomes 0.5, so then Z_{1PF} plus 0.5 Z_{1PF} gives us 1.5. Z_{1PF}. As compared to when the source L is not available.

So as compare to two-terminal equations and related Z apparent calculation, we saw that you can see that this impedance is now in the presence of the source at L that we call infeed current contribution. That infeed current you can see that it is 50% then the corresponding apparent impedance becomes ($Z_{app} = Z_{1MP} + 1.5\ Z_{1PF}$), so as compared to this apparent impedance this will be higher, that means that the relay at this will see an under reach issue. We will find it under reach issue or this kind of infeed, you can see that situation with a distance relay protection perspective.

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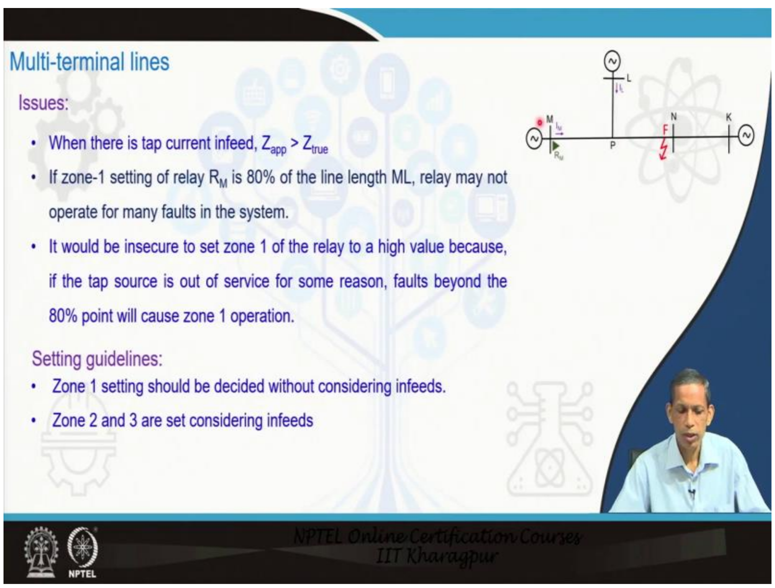

In moving further, we saw that you can see that when there is a tap current infeed, the Z apparent seen by the relay is greater than the actual Z, positive sequence impedance up to the fault point, from the earlier analysis, we saw. Now if you see, suppose the zone-1 setting is of 80% of the line ML or so, relay may not operate for many faults. So what will happen here, if we consider this line MN to be much longer and then if we to go for the zone-1 setting in terms of line from M to L, shortest distance, then many fault points in the system, because of this, under-reach issue will not be detected in the zone-1.

That means that if this zone-1 fault happens to be there towards the reach and with the infeed condition, then the zone-1 will not detect it. It means that will be detected by the other, like zone-2 or zone-3. So, the zone-2 or zone-3, they detect, then it will be delayed decision. So, that is one issue and furthermore, if you like, you can see that extend this zone-1 to further like 90%, 95%, or beyond that to address this infeed, then when these infeed is not there then that may consider to go beyond this line section MN and that may interfere to the corresponding protections at bus N.

So which is also not desirable from the system security perspective. So, based on this above observations, we say that there are some guidelines for the protections for the multi-terminal lines, simple guidelines. The zone-1 setting would be decided without considering infeed. From the above discussions, it is a general recommendation that zone-1 settings should be as usual without considering the infeed, so when you are considering the R_M then we do not consider the infeed of IL for the zone-1 setting. Zone-2 and Zone-3 settings need the consideration of the infeed. Zone-2 and zone-3 settings need the contribution of the infeed settings.

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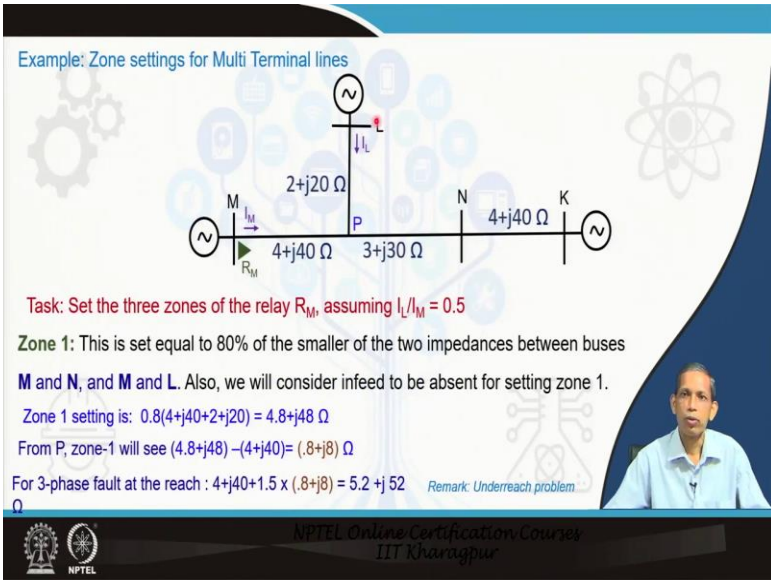

So now, we will go, you can see that guidelines are being applied for transmission system having multi terminals configuration. So, we have considered a system like this, the corresponding T point or the tap point it is P, one section here, the infeed section from L to P, and then the another section from P to N. Now for zone-3, we have considered another exam from N to K in an interconnected power system. But we see here, you can see that this is a multi-terminal line and so, from N also, for a fault here inside these 3 terminals, 3 sections, from N side also current can flow, from L side also, and from also M side.

So, the impedance is assigned, positive sequence impedance is available to us is in terms of 2 + j20, 4 + j40, and 3 + j30 Ω and we have another section NK, 4 + j40 Ω. This is for a simple example. The rest task is there to set the 3 zones for the relay R_M which is someone can extend, you can see that for the relay at L and N also. We will consider maximum the infeed amount is for this case, for this relay is I_L/I_M = 50 % , 0.5 . Now, first, we will consider zone-1.

So for zone-1 as in the guideline, we will consider no infeed issue and then we will go ahead. Now, this is set equal to 80% of the smaller of the two impedances between buses M and N, M and N, and M and L. So, what we will see that from this relay whatever, whichever length becomes smaller and 80% of that will be for zone-1 setting but without any infeed term which we have seen in the apparent impedance equation. So, for zone-1 setting, we say if you see this from this, for this relay from the tap point, this path is having smaller impedance, so our zone-1 setting will be 80% of (4 + j40) + (2 + j20) . 80% of that that becomes equals to (4.8 + j48)Ω.

So from P, the zone-1 will see, (4.8 + j48)- (4 + j40) Ω, this section. So, only (0.8 + j8) Ω additional impedance up to that portion you can see that from this side to this side, or this side to this side, it will able to see. For 3-phase fault at the reach, for 3-phase fault at the reach, let us say at this reach, this is the reach you can see that as per these setting. When I_L is providing a 50% as compared to this I_M side current, then as we have calculated for the 3-phase calculations that this will be (4 + j40), 1.5 of this portion, which portion? This section. So, 1.5(0.8 +j8) at the reach point; so that becomes equals to (5.2 + j52)Ω.

So, if we see that this is the setting of the reach, up to reach for the 80 %, but the, at the same reach point at 80% physical distance, the corresponding 3-phase fault give sequence here, (5.2 + j52). Here we have not considered any infeed. Here, by considering the infeed as in the 3-phase calculations, we saw that the corresponding impedance will be this small. So, this is higher than these, it means that this is will lead to under reach problem.

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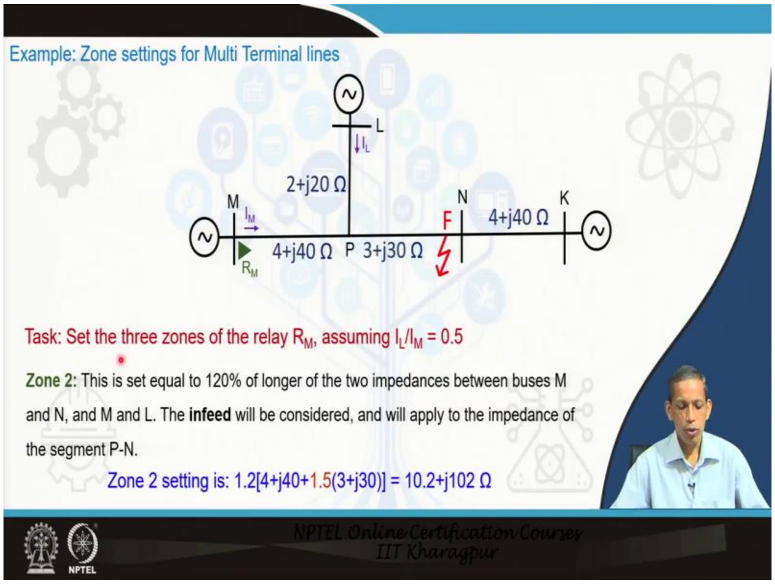

Now, next, we will go for consider the zone-2 setting. The zone-2 setting is 120 % or so. We know the two-terminal line of longer of the two impedances, in this case, multi-terminal line, it will be 120 percent of the longer the two impedances between buses, M and N, and M and L. So, we have from this relay bus, we will have two sections 1 and 2, and the other one you can see that is the, this one. So, whichever is the longer out of that, 120 % with the consideration of the infeed.

So for this, what we will do, the zone-3 setting equals to 120 %, so this is 1.2, 4 + j40, fine. And then have, we can see that longer is this part. So, infeed will be there from this side, so we will consider this infeed. So, in the Z apparent impedance, if you remember that becomes equals to the infeed part 1.5 now of all (3 + j30), and then that 120 % of that one. So, 1.2 (4 +j40), this part and with infeed considerations 1.5 (3+ j30). So, this becomes equal to (10.2 + j102) Ω for the zone-2 setting.

Note that in zone-2 setting, relay at R_M must address this part and also this part completely so that no fault in these two, in these two including these two sections can remain unidentified, otherwise, it will be a protection problem from the primary protection problem and the fault will continue you can see that from either the, from the M bus side for this design.

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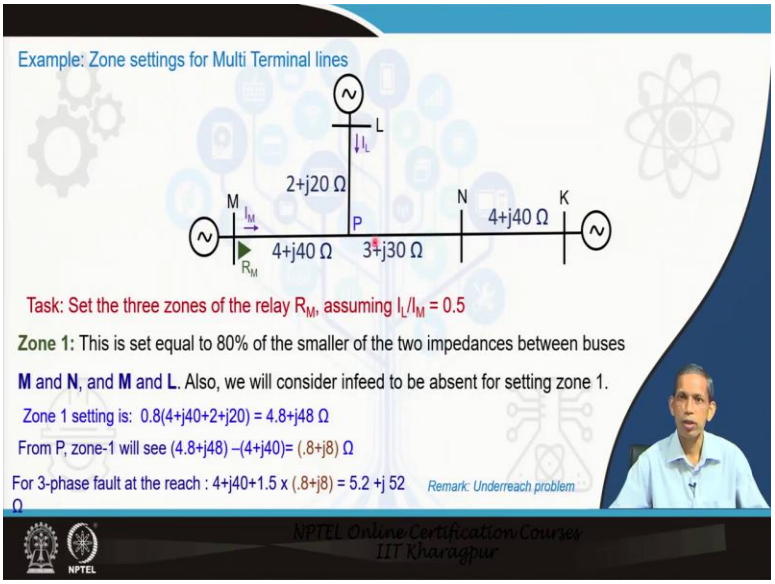

Now, we will go for the zone-3 setting for the system. In zone-3 setting, similar to the zone-2, what you do is that the apparent impedance of the M-N, M-N infeed is (4 + j40)+(1.53 + j30) up to this N section. So, this impedance plus considering the infeed (1.53 + j30) for zone-3 also we will go for the higher length distance. So, this becomes (8.5 + j85) Ω.

Now for this section also, because zone-3 has to wake up section N-K also. So, any fault here also the corresponding infeed current will flow. So, therefore, you can see that we will consider that the corresponding settings for you can see that (8.5+ j85) up to this endpoint from N-K, for N to K ,(4 + j40), 1.5 times with consideration of infeed. So that gives you can see that and 120 % of that, so if you get that, you can see that will come (17.4 + j170) Ω, 174 Ω.

So, that leads to situation that, we say the zone-3 should take care of this portion as well as this portion and should ensure that no fault is unidentified in this one, however, zone-3 is a delayed decision process.

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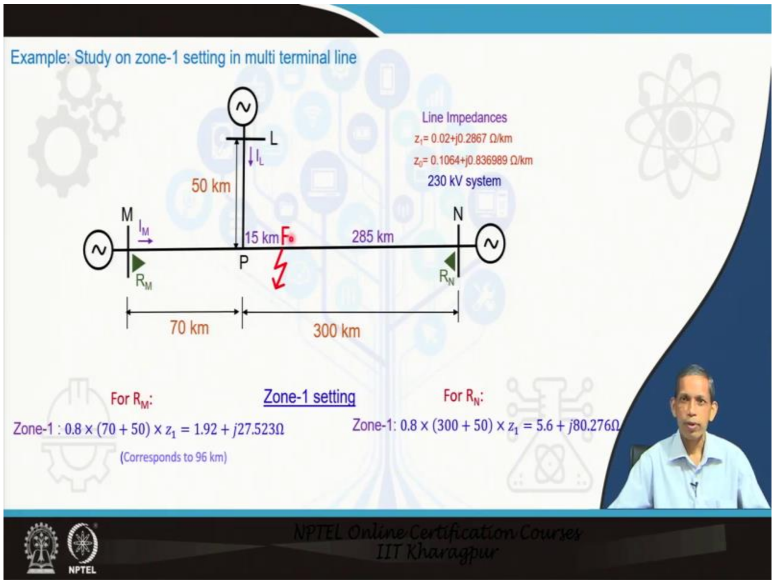

Now we will take a case example, simulated example how the zone-1 performs in a multi-terminal line. In a 230 kV system, we have considered the way we have done a 3-terminal line. So, it has a 50 kilometer here, 70 kilometer this section, and we have a 300-kilometer long line from P to N section. The 0-sequence and the positive sequence per kilometer impedances are available to us. Now we will see how the zone-1 setting will be there and then we will assess how good is the zone-1 setting.

So, the zone-1 setting for that as we have seen the guidelines and simple calculations earlier, for R_M relay, the zone-1 setting will be 80% we have considered. So, this is 70 kilometer plus 50 kilometers, shortest (70 + 50), this is the shorted path. So (70 + 50), 120 kilometer into the per kilometer positive sequence impedance. So, any two 0.8, that 80%; so that gives us (1.92 + j27.523) Ω. So, this corresponds to if we see (70 + 50), 120 kilometer; physical distance, 80 percent of that is 96 kilometer.

Similarly, for the zone-1 for L, for R-N, not L, for R-N with this infeed for R-N, the zone-1 setting becomes 0.8(300 + 50), minimum distance into the corresponding zone-1. That gives is (5.6 + j80.276) Ω.

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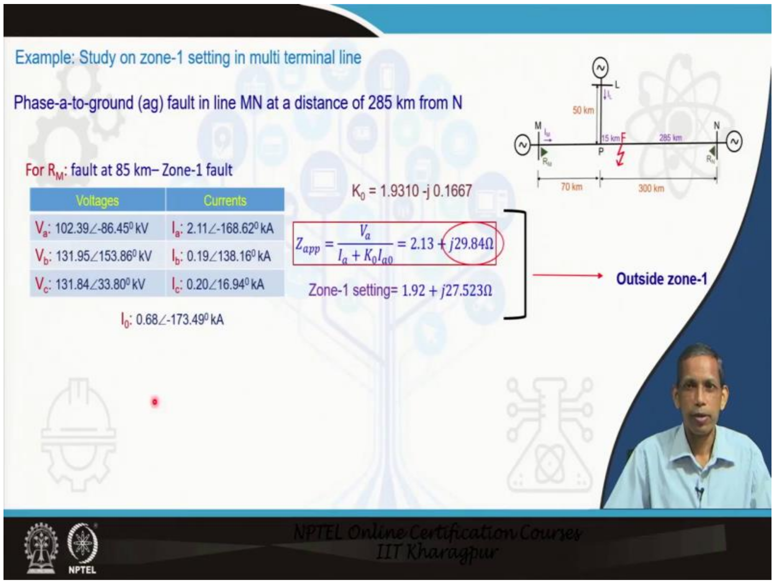

Now, we will see for a phase a to ground fault in the system the corresponding zone-1 is good enough or not. For this, in this system, if phase a to ground fault created at 85 kilometer from bus M which happens to be in zone- 1, as you have seen this setting, the zone-1 covers physical distance of 96 kilometer. So, therefore, this fault at F, which is only 15 kilometers from P, this part is 70 kilometer, happens to be in zone-1 fault for R_M.

By creating the phase a to ground fault, the corresponding phasor voltages and the phasor currents are noted here. So, we see here the corresponding phase a current is much higher than the other phases. Now, there will be infeed from this side during that moment. The K_0 for this situation is available from the Z_0 and Z_1, $(Z_0 - Z_1)/ Z_1$.

This I_0, it is you can see, current for this situation is obtained from Ia, Ib, Ic; so we apply the normal Z apparent equals to Va /($I_a + K_0 I_0$) and we got the impedance to be (2.13 + j29.84) Ω whereas, our zone-1 setting for the 80 % of (M P + PL) because P to L is the minimum distance from P site. So, that gives you (1.92 + j27.523) Ω. Now, we see here, even though we have simulated at 85 kilometers, we happens to be in zone-1, the fault is seen outside zone-1. So, that is what we saw, mentioned earlier also is an issue of under reach, under reach for the zone-1 operation of distance relay.

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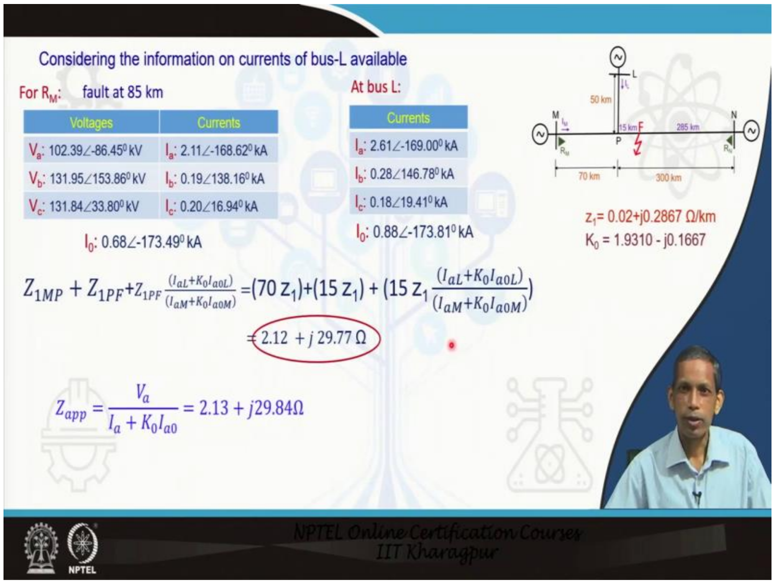

Now, we will see that the apparent impedance which you have derived for the phase a to ground fault, that is, that can be validated if you know the corresponding bus L, the infeed currents which we have noted here. 3 phases current at bus L, during that same fault corresponding zero sequence component of current. So, we have already derived these for the phase a to ground fault; $Z_{1MP} + Z_{1PF} + Z_{1PF}\frac{I_{aL} + K_0 I_{a0L}}{I_{aM} + K_0 I_{a0M}}$.

So in this relation, if it we substitute this current then, and the different impedances, then we have got the corresponding impedance to be (2.12 + j29.77) Ω. And that is what we got from the Z apparent impedance calculation Va /(I_a + K_0I_0). So this says, so is that our Z apparent impedance calculation is correct. So, what you found from this example is that for this case, that this zone-1 under reaches because of infeed issue and we cannot extend this zone-1 to larger also because when the infeed is not there, it may create problem to for the other bus relays and so, in the zone-1 point.

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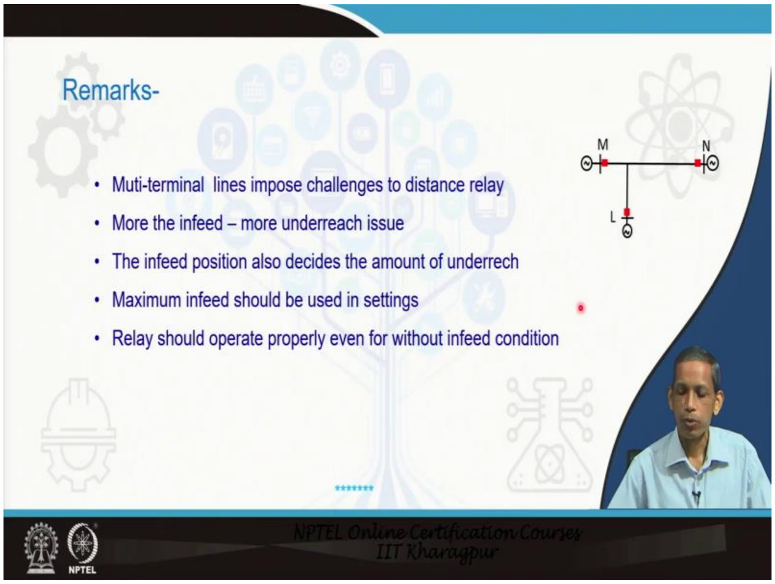

So in overall, we see that multi-terminal lines is a challenge for protection, particularly, for distances relay we saw here even through examples also. More infeed, more under reach, further the position of this infeed is also a factor in the amount of under reach issue, particularly for zone-1, of course, zone-2 and zone-3 also have also under reach issue.

While settings for different zone-2 and zone-3 particular, the maximum infeed should be considered, but note that there at an instant infeed may not be there, even at that time also the protection scheme should function properly. So in overall, we saw that the challenges are more as compared to the two-terminal line case for this configuration of transmission system of 3-terminal lines. Thank you.