Power System Protection
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Lecture 14
Introduction to Directional Relaying

Welcome to NPTEL Power System Protection course. In module four, we will talk on directional relaying.

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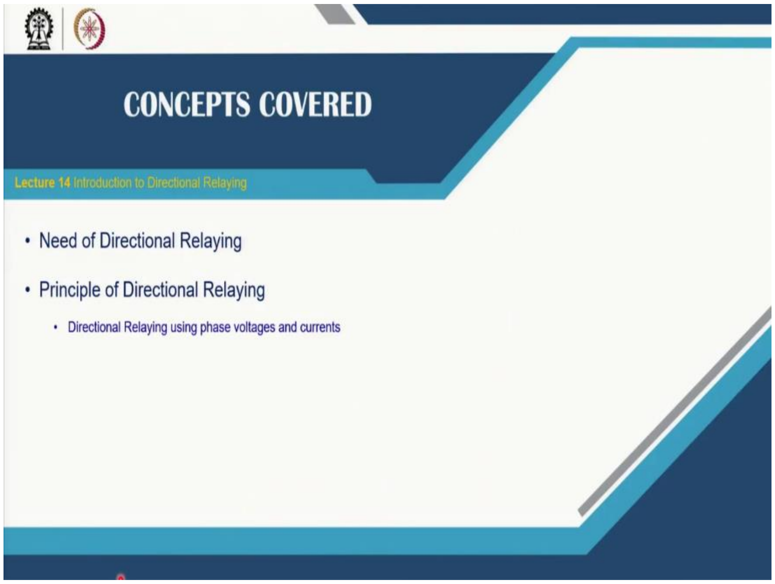

In this lecture we will see how directional relaying is being applied in different protection schemes. The basic protection philosophy for directional relaying and there are different ways to address the directional relaying perspective. We will go one by one. Today we will talk about the phase quantity-based direction relaying principle.

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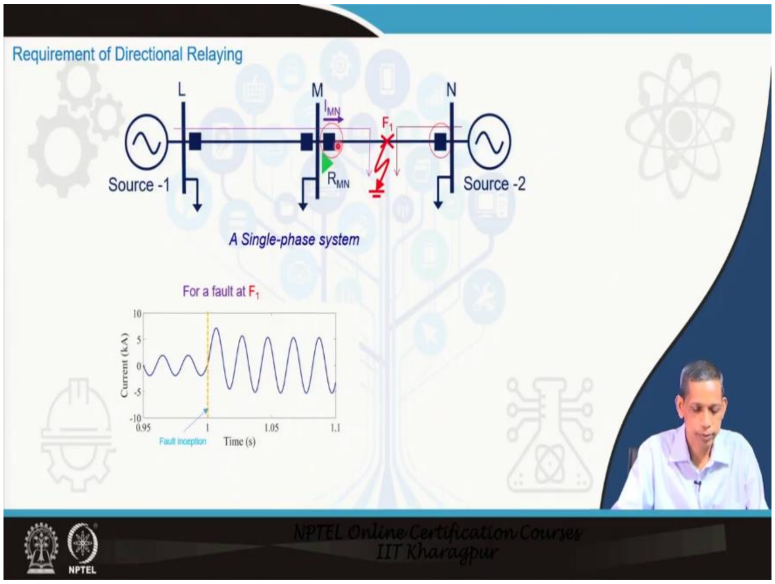

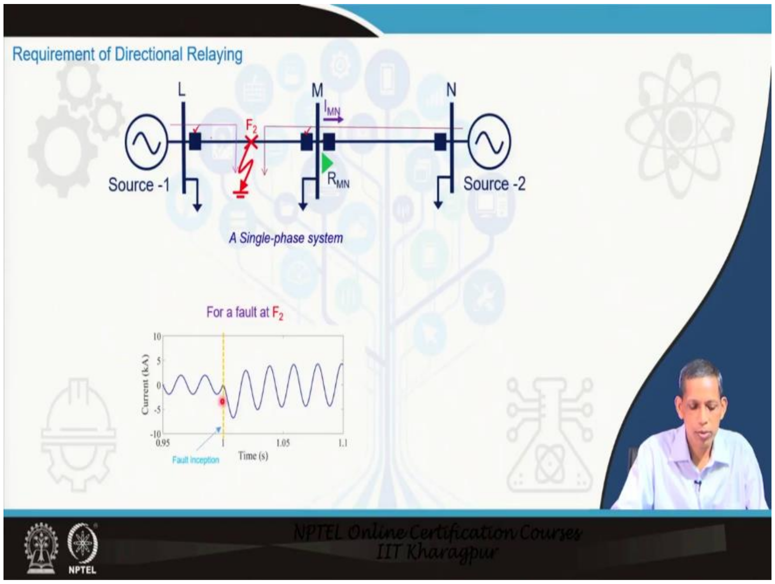

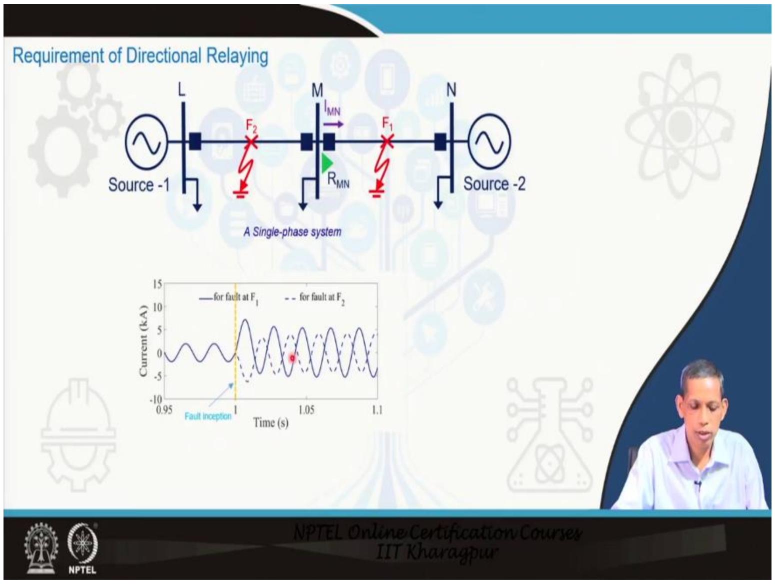

Before going to the directional relaying, we will see the need of directional relaying. How does it help in protection schemes? So, if we see this simple system. Now, as compared to earlier cases, we have sources at both the sides, so this is a no more radial. So, power can flow from left to right or right to left, we can think about a tie-line connection at transmission level also.

But first, consider a single-phase system for understanding. We will extend this idea to generic three phase system. Let us consider a fault happens to be there at F_1 positions between M and N line. So, at that time, current will flow from source one like this and also current flows from source two to the fall point like this. So, this current as you know becomes also very high and at that time, the objective of the protections scheme is that the breaker at this and breaker at these at the end must be open.

So, the fault is clear from both the ends otherwise current will flow and that is not desirable. Now one may say that we will trip this breaker here from this side also that means that the load at this also will be hampered. So, from selectivity point of view, part F1 fault here, we essentially say that the breaker at M bus, this breaker and this breaker should trip, that is the desirable things for the protection scheme.

However, in case of a failure of the breaker at this point, the backup against that breaker here should operate. Now, on this perspective you can say that if the relay for the corresponding breaker at this point designated at R_{MN}, the current during this fault as seen by the relay for a fault at 1s inception then the current becomes like this and the current becomes higher following through a transient decaying DC component and so.

So, this is what for the single-phase system or fault at F_1 the current which will be observed by the relay at bus M, the R_{MN} relay which is being assigned we can say that for this breaker. Now, let us come to this another fault, fault at F_2 in line MN in the same single phase system, now current flows to this fault F_2 like this from left hand source and from the right hand source. At this point the desirable thing is that the breaker, this one and this one should be open.

Now, how does this relay at M, same relay what we have earlier discussed, how does it see, so now the current which will be seen, you see here now flows from right to left for this relay and that is what is shown here, that the current now changes in different way for a fault F_2 as compared to F_1. So, this is what you can say that for the two fault cases, one in F_1 this side and one in F_2.

Now, if you mark this to consideration, assuming that you can say that the corresponding both the faults happen at the same fault inception point 1s here. This is some simulated data for understanding purpose. So then if you plot the two currents, fault currents become like this, the solid line for the F_1 fault and the dotted line for the F_2 fault and both the currents are observed by the relay R_{MN}.

So, we observe that you can say that for R_{MN} for F_2 fault the current become reverse as compared to for the fault for F_1. That is what if you see these two currents that there is a phase separation between two currents F_1 fault and F_2 fault. This is what we observe from this simulation plots for the two currents.

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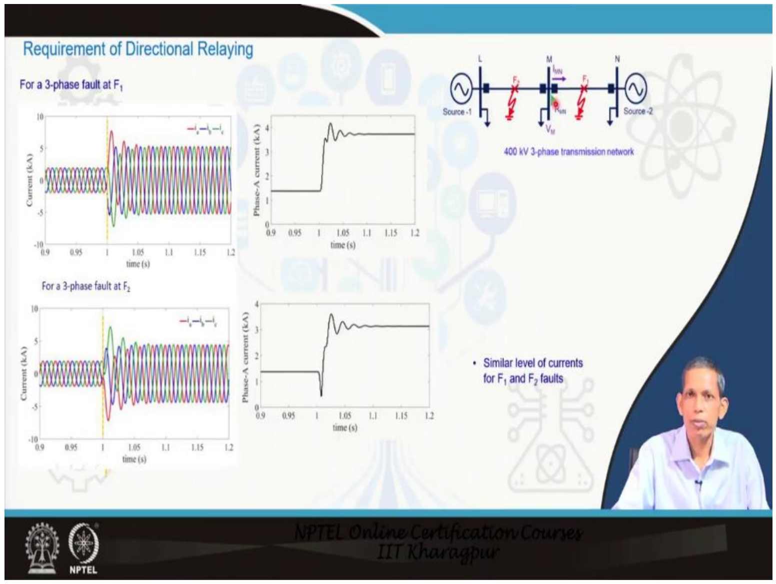

Now, we can extend this idea to the three-phase system. So, this is 400 kV three phase transmission network, part of the big network, and this interconnection one, so source one and source two, similar to what we have discussed earlier in the single-phase case. There are two faults F_1 and F_2 and we are observing the R_{MN} relay.

So, if we see that same, the corresponding fault we can say that is being created at 1s and then we see that the corresponding three phase faults are there at F_1 and F_2 site and we see you can say that the corresponding current magnitude for both the faults to be very high. So, what we say from the earlier discussion that in both cases for F_1 fault F_2 fault, whether it is single phase or three phase the current magnitude becomes significant. Therefore, the relay R_{MN} only trip this breaker in case of F_1 not for in case of F_2 from selectivity point of view. The relay R_{MN} cannot distinguish from magnitude of fault current. So, we have learnt till now, discrimination of faults in different sections using current over current principle.

Now, what you see that the overall current is full of limitations here that this relay has to discriminate whether the fault is this side or the fault in this side simply a fault in F_1 direction or in F_2 direction. Accordingly, this has to trip or not to tip the corresponding breaker. So, for that we conclude from this discussion that only current magnitude based over current relay cannot distinguish that, and that is what we like to say that for such discrimination directional relaying is required, direction what we mean here is that direction of fault.

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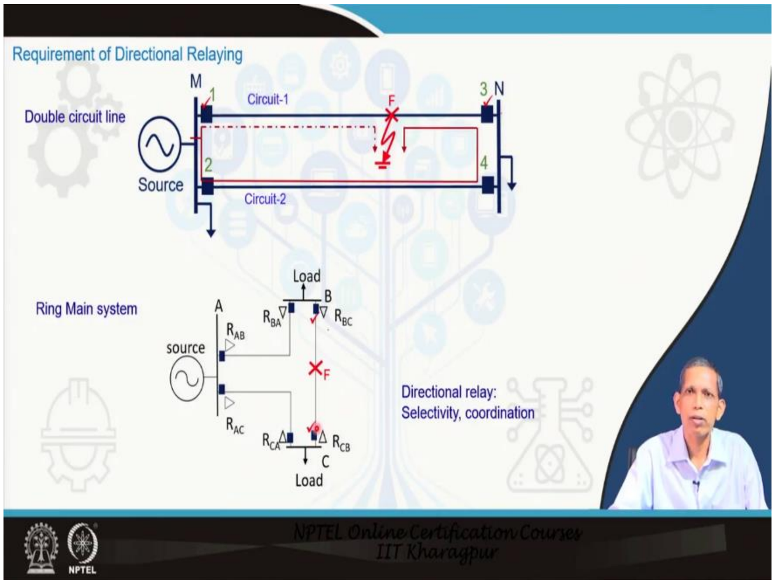

Let us see you can say that how these corresponding directional relaying is beneficial in discriminating practical systems. Consider a double circuit line and the source, substation side is this and the double circuit line and it is feeding to different loads for further section. So, we have four breakers here, the region behind then the fault happens to be there in any of the line let us say circuit one at F. So, this breaker 1 and this breaker 3 should open, so these lines will be out, the other lines still remain functional so that some of the loads here can still be supplied.

So, that is what the benefit of reliability from that perspective, we say that the breaker 1 and breaker 3 should be open for fault F in the circuit one. Now, see what happens during the fault condition. So, for fault F from this source, current flows like this and another path of current is from here to here. So, what you observed because this is a fault condition the current magnitude will be significantly high.

Therefore, relay at one, relay at two, relay at four and relay at three all will see large amount of current, so over current relay will see there is high level of current and it is go for decision depending upon the coordination but what you need in this case that for this fault only one and three should trip, not two and four. So, to resolve that, we can use your directional principle, we will have a directional relaying at bus three. So, what will happen here if in addition to over current relay, if you put a directional relay here then if we see here the normal flow of current direction for the relay at three is this but now whenever a fault happens to be in circuit one, the current direction is reversed. So, that is what a discriminating function perspective to know the direction of current, and that gives you the direction of fault. Furthermore, if we put a directional relay here, then that gets discriminated that the fault is in the line section or not. Thereby we can say that we can have a coordination at our current level between one and three. So, relay at bus three can trip fast and then you can say that once three opens here the breaker then no current from this side. So, this circuit does not have any current, and this current still may be flowing at a later time coordinated with three, this can be open.

Therefore, we see that in such a situation for the double circuit line or parallel line for the selectivity point of view directional relaying is a requirement. Now come to Ring main system, which we have already discussed in over current coordination, same system we have considered. So, we see you can say that there are different breakers. Now let us consider you can say a fault in this line B to C.

So, what will happen that current will flow from this side and also current will flow from this side but the objective from the protection perspective is that the breaker at here and breaker at here should open, not the any other breaker. That is the primary protection level. Therefore, relay at this and relay at this must see this fault. Note that all the relays should trip the breakers they will observe large amount of current. So, their overcurrent will trip and that is not desirable. So, only requirement is that relay at here and relay at here should be there and this discrimination can be achieved using directional principle. So, we will see you can say that more details. How we can you can say use the different directional principles to employ different nodes, different points for satisfying the different protection needs.

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Directional applications are quite wide. This is being widely used for the distribution and transmission system protections, supplementing overcurrent relay, high speed transmission protection at high voltage level to supervise distance relaying , will see more details on the distance relay, also used for earth fault protection when selectivity is required that also we will see along with the transformer protection and so.

The common IEEE standard numbers for the directional overcurrent relay in an alternating current system is 67, ground directional overcurrent relay is 67G and phase based directional overcurrent is 67P. They are to these 67 directional overcurrent relays that are other variance also we will see that later on.

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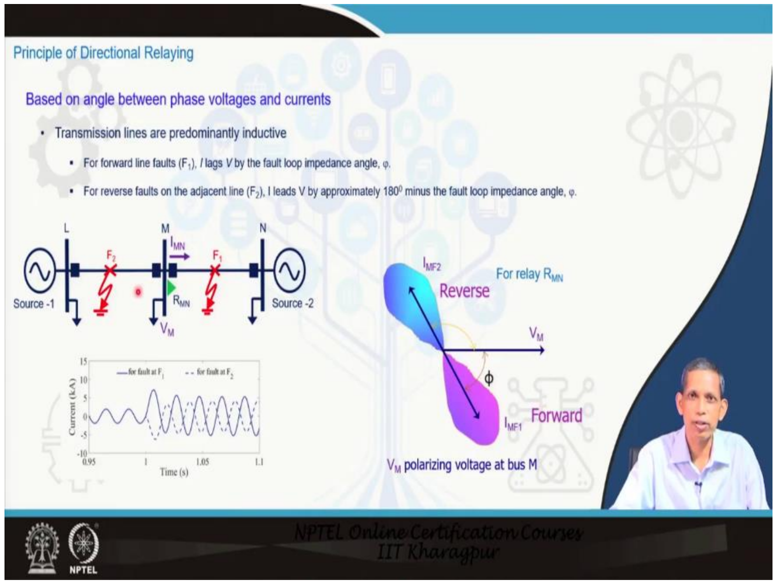

Now, we go to the principle one by one. So first we will go to we can say phase quantity based directional relaying principle. So, we know we can say that transmission lines are predominantly inductive R / X ratio is low and the angle impedance angle is pretty substantially high, 80^0 and above and so. Now, see this system we can say that as we have already seen, source-1 and source-2 we have already known that for these relays, for fault at F_1 and fault at F_2 the corresponding current patterns becomes like this. So, we like to know now how this corresponding relay at this will be able to discriminate whether the fault is F_1 side or F_2 side. That discrimination is nothing but here a two class problem for this is to be achieved using the voltage and the current signals available at the relay point. So, to achieve this let us see you can say that how we can go with that so first as I had mentioned we will go with phase quantity based approach and then we will extend this idea for other options also. So, we see here you can say that at V_M at the bus M, V_M that is reference, a fault happens to be in F_1 so current from left to right, this impedance path is highly inductive.

Therefore, the current you can say that flowing through these, this relay I_{MN} for fault F_1, I_{MF1} at F_1 will be lagging to this voltage at this relay bus and that is what the lagging current is. Now, this is the solid line current we talk about. Now, in case of F_2 fault, same relay will now see a current flowing from right source to the fault point. Therefore, the relay can see the reversal of current with respect to the earlier case.

So, that is what a reversal of current we are noticing with the dotted line. Therefore, the reversal of current for F_2 becomes this I_{MF2}, and that is what with respect to V_M, this will be a leading current. This implies that the relay at here can discriminate this F_1 fault and F_2 fault using the phase current and the phase voltage and the associated angle. In case of F_1 the forward fault we call it as forward fault, forward looking relay for this line protection of MN. For this forward fault the corresponding current lags the voltage by certain angle and in case of reverse fault that is F_2 side fault the corresponding current noticed by this relay leads the voltage. That is what the conclusion we have from this slide.

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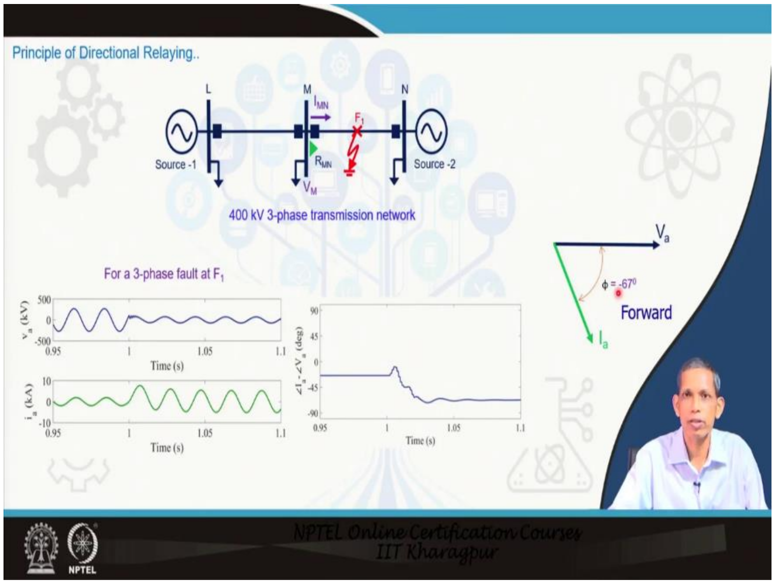

Now, going to a three-phase system if we see this corresponding three phase fault, so all faults are involved. So, this is V_a voltage signal. This is the current signal compute the phasors then you get the corresponding angle between current and voltage, angle of current minus angle of voltage because you are taking voltage as reference V_a where only concern now about the phase A voltage and current because we are trying to discriminate this direction of fault using phase voltage and phase current. So, with V_a as reference at bus M, the current here lags for this F_1 fault so the current here lags and for this situation if we see the corresponding current obtained you can say is 67^0. So, angle of I_a minus angle of V_a that comes out to be minus 67^0 that is what the ϕ angle.

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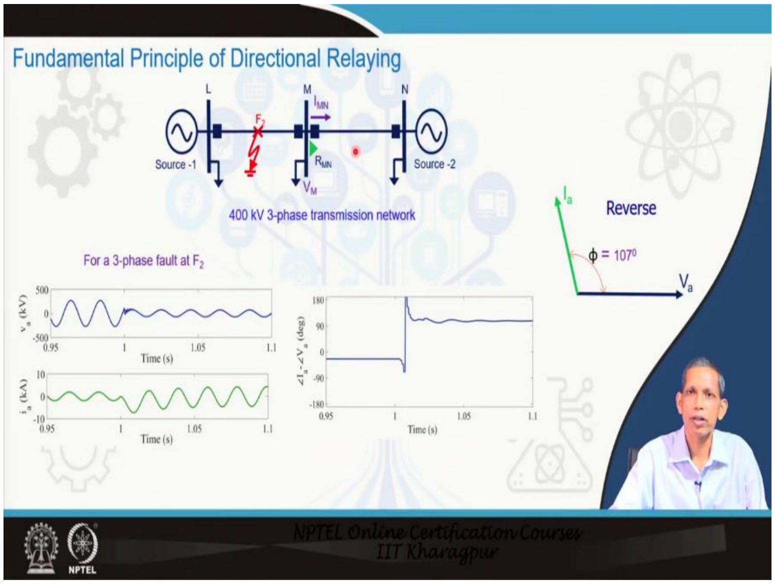

Now, when you go to F_2 fault for the same 400 kV system, fault now is in reverse direction so current flows from here to here. That is what notice from this current pattern with respect to this V_a, at bus M for this relay. So, the angle of I_a minus angle of V_a that it comes positive now as you have already seen. So, we have already done V_a the phasor, the phase fault is at bus M and the I_a is leading and the angle comes out to be 107^0 and this ϕ is a positive value. So, this is the reverse fault for this relay and that angle comes out to be positive.

The way we have computed here can be different options also for that perspective. The angle we have computed it angle of I_a minus angle of V_a whichever phase is involved with fault. Take that current phasor angle of that current phasor minus angle of that phase voltage will be indicative of the direction of fault. If that angle comes out to be positive, we say the fault is in reverse side for the relay. If that angle comes out to be negative, then we call the fault to be forward fault.

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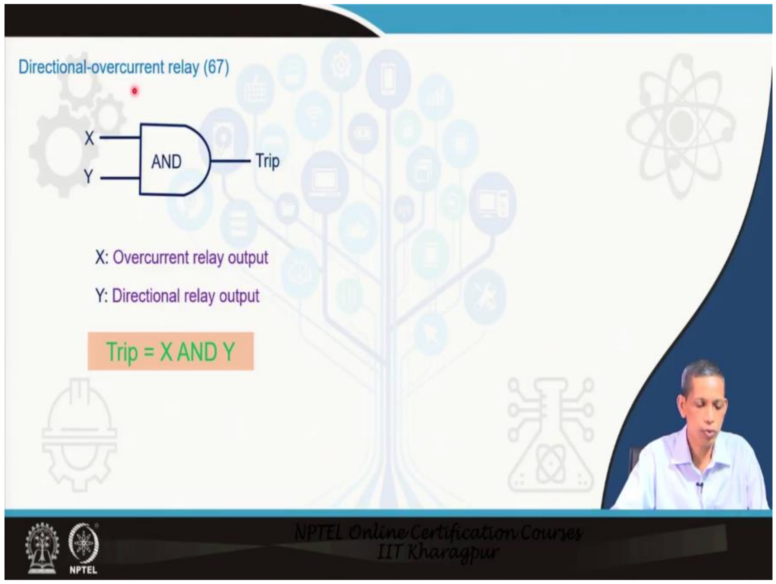

These kinds of principles in directional relaying is being widely used with overcurrent relays as I mentioned and that is designated by IEEE standard number 67. What is being done in directional overcurrent relay principle that the decision by the overcurrent and the decision by the directional we have a AND circuit and by and operation that we decide whether to trip the corresponding breaker or not. That is been that the trip decision is the decision by the X, the overcurrent and and the decision by the directional relaying. So that is what we talk about directional overcurrent relay while using in distribution and at transmission level.

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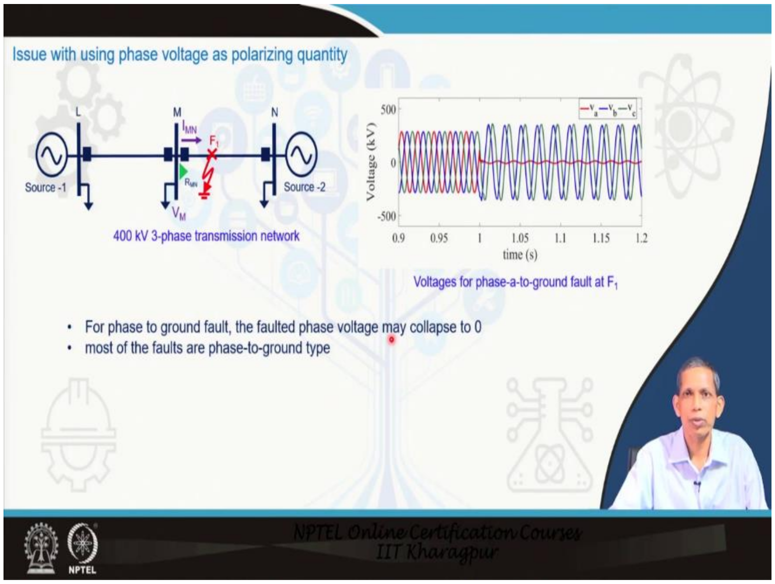

However, this phase voltage and phase current based relaying principle has certain problem. Let us observe this. So, for this three phase fault F_1 in this transmission system, if the faults comes out to be very closer to this one and this source is strong and this line is not long, then phase voltage here collapses and that may substantially having a lower value. That is what we observe here as compared to other phase voltages, the corresponding voltage is significantly low because of the fault being closer to the relay bus.

In that case the corresponding voltage being substantially low because of the other uncertainties and all these things. If phasor will not be reliable and therefore this corresponding associated angle of the phase voltage V_a and angle of V_a cannot be consider for reliable directional relaying principle. We know that most of the faults are line to ground faults. So, as already mentioned phase voltage and phase current can be used for directional relaying. If you use the corresponding phase voltage, for a line to ground fault the corresponding voltage may be substantially low and there may not be a reliable option for that one.

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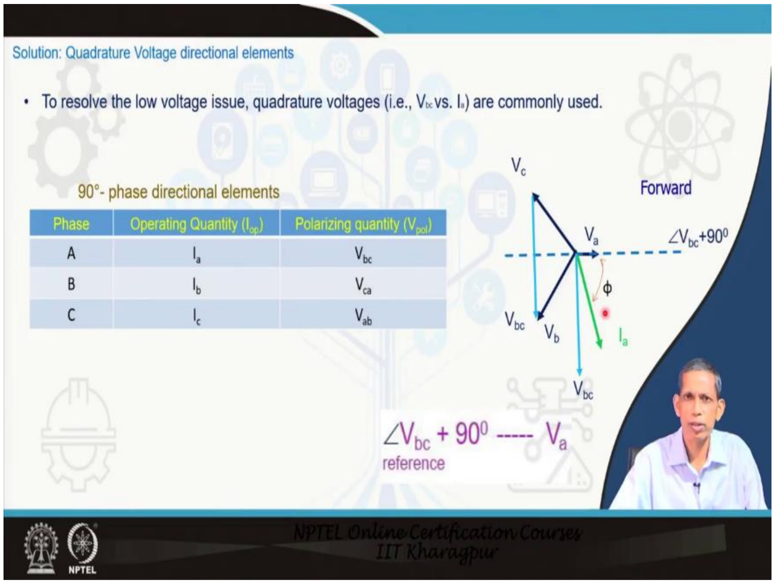

In that scenario, we have alternatives so for that what we do is that we use the quadrature voltage directional element. What do you mean quadrature here that because most of the faults are line to ground faults say AG fault phase A to ground fault. Then instead of taking V_a the *b* phase and *c* phase voltages are sound phases now. So, we can take V_{bc}, then we can get a more reliable we can say that directional relaying solution. So, what to do that to avoid that low voltage situation, the common practice is that for a phase *a* fault the corresponding operating quantities is I_a and polarizing quantity becomes V_{bc} instead of V_a. For b it is I_b current and V_{ca} not V_b.

For c phase it is this I_c current and V_{ab} not the V_c. I told you that most of the faults being line to ground faults we can overcome the problem of significantly small voltage for close in fault which are very close to the relay bus. In that case if you see this phasor diagram, so this is V_a line, this is V_b line and this is V_c line, 120^0 apart. Now let us say this is AG fault so V_a becomes smaller and the corresponding I_a current become significant and that will be lagging to V_a this is a forward fault case you have already seen in the circuit. So, this corresponding ϕ this is a lagging current. In this case, if you see this is V_b and V_c they remain intact. Therefore, you can say that the corresponding V_{bc} become this plot here you can say that at this point origin then this becomes V_{bc} become this. So, we see that now that this I_a and V_b, V_c then take this poison like this. When we realize what the, we can say that do if they suitably translate this you can say that V_{bc} to the again bring back this V_{bc} to this V_a reference for that you can say that 90^0 you can say that to the angle of V_{bc}.

Then the corresponding reference we can say that voltage becomes in line with V_a and then similar we can say that positive value of ϕ, negative value of ϕ the concept which we have used for that reverse and forward fault can be applied. So, this for that once again I am telling that one of the way relay many relays do is that once you compute the $\angle V_{bc}$ add the corresponding angle you can say of the $\angle V_{bc} + 90^0$. Then again you can say that bring back the corresponding reference to the same reference as V_a and there we can say that you can apply this leading, lagging concept of this current which will decide you can say that the direction of the fault. We will see different examples for these kind of applications also.

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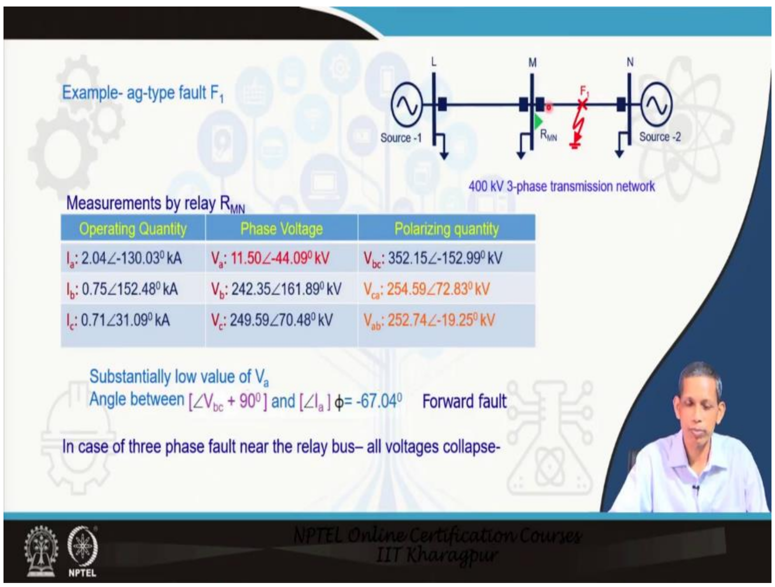

Now, let us you can say that come to the same 400 kV three phase systems and we have a forward fault F_1 and then this we are observing this relay which is assigned for this breaker. This is a forward fault and we are observing for this relay 400 kV transmission system. Now, let us say that for a fault this is the set of currents observed by the relay and set of voltages which is measured by the relay. So, if we see this current 2.04, 0.75, 0.71, so this clearly shows that this is *a* phase to ground fault and if we see this corresponding phasor become substantially low as compared to *b* and *c*. So, now the relay will make a judgment to this is acceptable for deciding on the relay or not, simple phase angle of V_a and I_a or it has to go for the polarizing quantity using what is that component that is V_{bc}.

Because this is phasor current, the fault is *ag* type phase *a* to ground fault. Therefore, what we say here that if the corresponding relay rejects that this is not acceptable then will be using V_{bc}, this is better option. So, then in that case what you do is that these V_{bc} whatever angle we have, we can say that you make a 90^0 with that and then you can say that you compare with I_a to compute the ϕ.

So, the ϕ angle is nothing but you can say that angle of I_a minus angle of this combinations then you get the angle to be - 67.04^0 and this angle is negative indicating this is a forward fault which is confirms to our simulation for F_1 fault. So, this sequence that we see that in case of *a* phase voltage is low significantly so the better option we can say that is quadrature component can be used.

So that is why we can say that this is very common. The instant of V_c in phase component of voltage the relay is generally take the option of quadrature component because most of the faults are line to ground faults. But still there is problem that in case of three phase fault this in case the closed by to this bus M that all the phase voltages may collapse, what is the solution. So, we will look into those kind of issues also later.

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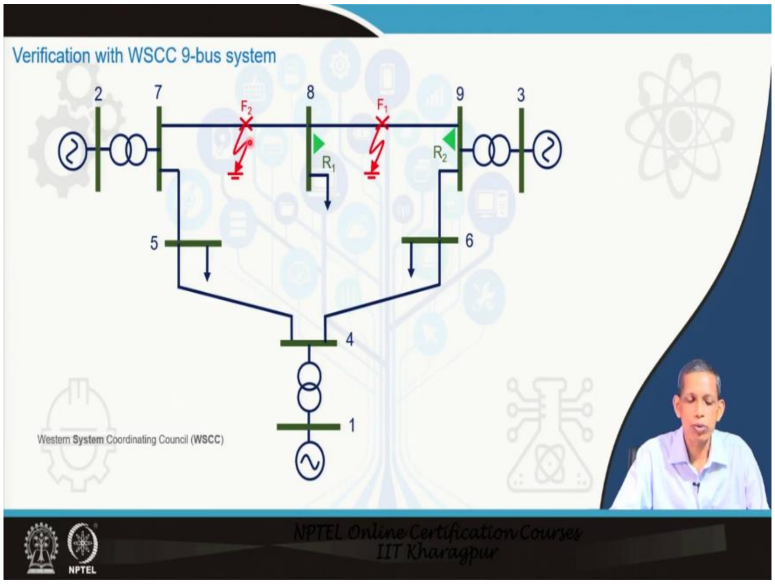

Now, let us we can say that whatever you have learn how to discriminate forward and reverse fault to obtain the direction of fault that is our directional relaying perspective which is being used in the different protection schemes. We will take a 9 bus WSCC system and we will check you can say that in this system, how we can say that the corresponding quadrature voltage approach is reliable will check.

So, we will see you can say that see only this relay who takes care of breaker at here for the line section 8 -9 and also we can say that the other relay will check a R_2 at bus 9. So these two relay takes care this line, and how do they see this F_1 fault which is internal to this line and F_2 fault which is external to this line 8-9. So how do they see, now if you see this perspective as you understood, for R_1 this F_1 fault is a forward fault. For R_2 the F_1 fault is a forward fault, they take care of the corresponding breaker at this bus 9 and bus 8. For F_2 fault the relay at bus-9 R_2 will still see a forward direction but R_1 at bus 8 will see a reverse fault. So with this you can say that we will see how the corresponding relay will be able to distinguish this F_1 and F_2 fault as a forward or reverse fault.

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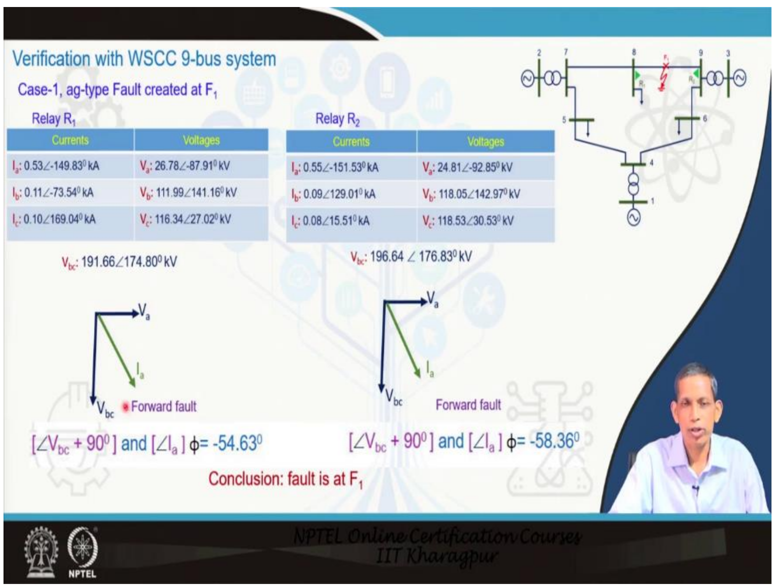

First case the fault is *ag* type phase a to ground called created at F_1 here, and now this relay R_1 and R_2 will have measurements for this fault. So, these are the set of measurements for R_1 current set I_a, I_b, I_c , V_a, V_b, V_c. Similarly, for R_2 we have current measurements and the voltage measurements from there we get the corresponding phasors using DFT, least square or so. Now, we see this perspective, if you see this phase *a* current is 0.53 kA phase B is 0.1 kA, phase C is 0.1 kA. This is phase *a* to ground fault. So, this clearly is being observed here.

The V_a is low, much lower than V_b and V_c. In this case also at bus 9 at relay R_2 the corresponding *a* phase voltage is substantially low that is what you observe. So now we can apply the corresponding quadrature voltage approach. One can use also the phase voltage approach also.

So, now if you compute the V_{bc} because fault is in phase *a*, compute the V_{bc} so V_b -V_c. So then only you get you can say that you get 191.66 $\angle$ 178.80 kV. So, these are all system level voltages without any sense also for our easy understanding. Similarly, for R_2 for the same F_1 fault, the V_{bc} is 196.64 $\angle$ 176.83 kV that is V_b - V_c.

Now, what we do is that we see for these cases, if we take the V_a as the reference, I will take the V_a as reference - 87.91^0. So, make it you can add that 87.91^0 in all the phasor quantity. So we shift it you can say that you rotate it anticlockwise, then we will get the corresponding V_a as reference. At that time so we will compensate for all you can say 87.91^0. At that time the corresponding V_a takes the position of this, you see here respect to -87.91^0 this is -149^0 so this current is lagging to V_a. Now we get the V_{bc} 90 ^{0} to that as such V_{bc} will be 90^0 to lagging to this V_a.

So, this is V_{bc} position but as far or you can say that quadrature principle what do we follow if that angle of V_{bc} plus 90^0 that again V_{bc} is being shifted to this V_a reference and then we compare the corresponding Ia position. So, angle of I_a minus that shifted angle of V_{bc} will compare that and get the ϕ and that comes out to be -54.63^0.

So, this shows that this minus angle so that this is a forward fault as observed by relay R_1 for this F_1, which is correct. Now, you go to this R_2 now. R_2 at this V_{bc} to be this and you draw the phasors. It comes out to same so R_2 the corresponding V_{bc} plus 90^0 whatever V_{bc} plus 90^0, angle I_a we know - 151.53^0.

So, angle of I_a minus angle of this shifted V_{bc} will give us ϕ and that comes out to be -58.36^0, that this minus angle shows again this is forward fault. So for R_2 also this is forward fault. So, the conclusion from these two we can say that R_1 and R_2 that both are forward and that means there is an internal fault and this also correctly identified by these two relays R_1 and R_2 using the quadrature voltage approach. We are able to identify the direction of fault properly. You can try also simple phase based approach.

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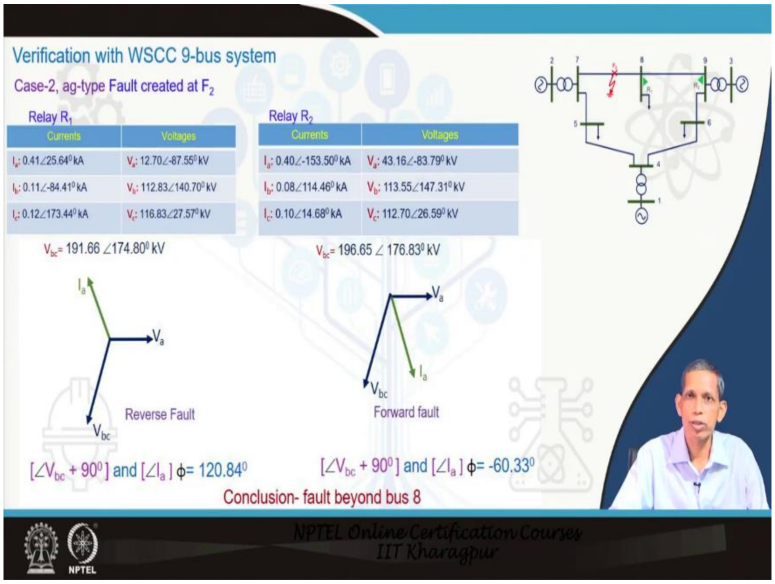

Now, I will go to the next with fault at F_2 as I already mentioned for fault at F_2 relay R_2 see forward direction what relay R_1 this is reverse direction. Let us see how they see through this calculation process. Relay R_1 has this set of current, these set of voltages. R_2 has this set of current and voltages.

So, current phase is high, current voltage in phase *a* is substantially low. Here also it is lower than *b* and *c*. You computed the V_{bc} from V_b - V_c here, now I got the corresponding V_{bc} , V_a and I_a position like this. And note that here for this case the I_a takes a position like this if we compensate you can say the corresponding V_a to be a reference - 87.55^0 add that 87.55^0 to all.

Then we will getting you can say that this I_a , 87.55^0, twenty five plus that. So, this gives you an angle like this. So this was that to with respect to V_a this is leading, when you come to know that this concludes that there is a reverse fault. Similar conclusion also from V_{bc}. V_{bc} takes a position like this 90^0 so again it comes out to be V_a reference with an angle of I_a.

So therefore, you can say that the I_a the corresponding ϕ happens to be 128.84^0. If that is so, there is a positive angle, 128.84^0. So, we conclude that this is a reverse fault. When you comes to R_2 and this set of measurements and then again V_{bc} becomes this. So, angle of V_{bc} plus 90^0 and then that we can say that the angle I_a. So, angle of I_a minus this angle you say ϕ is -60.33^0, negative angle indicates forward fault. So, we see that for R_2 this is forward fault and for R_1 this is reverse fault and this is correct as we have already mentioned for the F_2 fault. Therefore, these two relays we can say that are able to distinguish the corresponding fault in terms of the directionality successfully using the quadrature voltage component.

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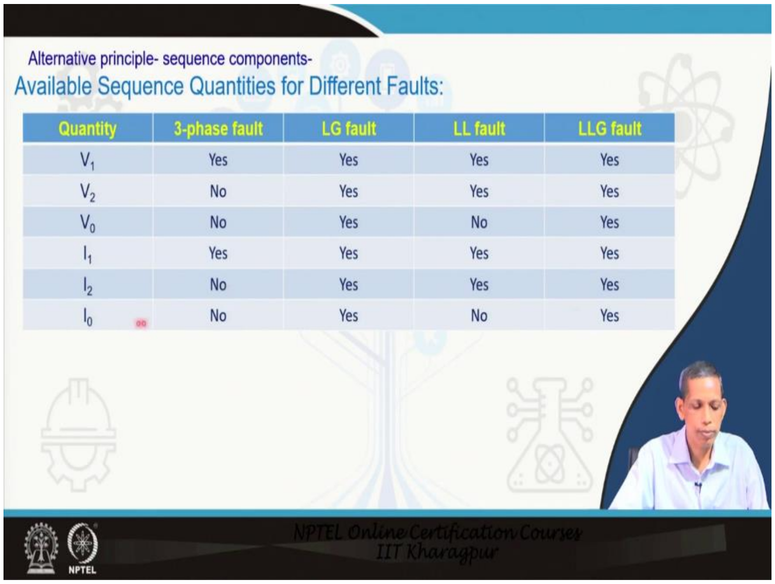

So, we see that quadrature voltage are simple phase voltages can be applied to that, but they have their own merits and demerits. There are alterative principles on sequence components based approach and so by different numerical relay. So, we will see you can say that, the how corresponding sequence components are able to distinguish the direction of the fault and how they can be applied in a better way for directional relay principle.

We will see more details on the next lecture, but have you can say see what happens there, the available sequence quantities for different faults. So, for three phase fault, V_1 is present, for line to ground fault V_1 is present, for line to line V_1 is present, for three phase fault V_1 is always present. Any measurements at any relay bus will give you the V_2 is present for all faults except three phase. V_0 is present only for you can say that fault involving ground LG and LLG. Similarly, I_1 for all, I_2 for unbalanced fault and I_0 for you can say that fault involving ground.

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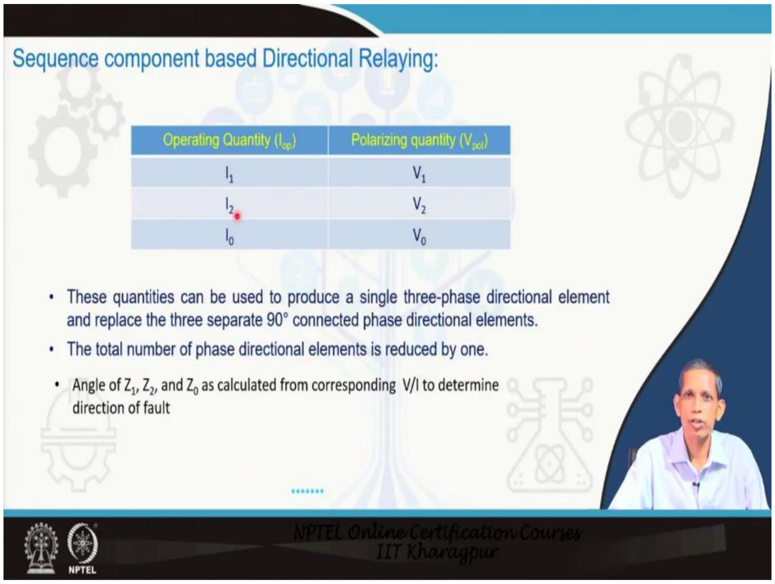

With this scenario so the sequence component based directional relaying principle are being applied. So there you can say having operating quantity is I_1 and polarizing quantity or reference quantity is V_1, I_2, V_2, I_0, V_0. These quantities can used to produce different relaying principles hopefully we will seek one by one. Because of the transformations from phase quantity to these sequence quantities, let us see for negative sequence. So, we are getting one pair only instead of Va, V_b ,V_c , and I_a ,I_b ,I_c. So that reduces the directionality computational perspective. Note that if V /I that is V_2/ I_2, V_1/ I_1 so that gives an impedance from, so we can use the impedance form and the angle of the impedance is indicative of direction that we will see in more details in the next class. Thank you.