Power System Protection
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Lecture – 16
Negative and Zero Sequence Directional Relay

Welcome to NPTEL Power System Protection course module 4 on direction relaying lecture 16 on negative and zero sequence directional relay.

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In this lecture, we will explain negative sequence and zero sequence component based directional relaying principle, how they can be useful for identifying the direction of fault.

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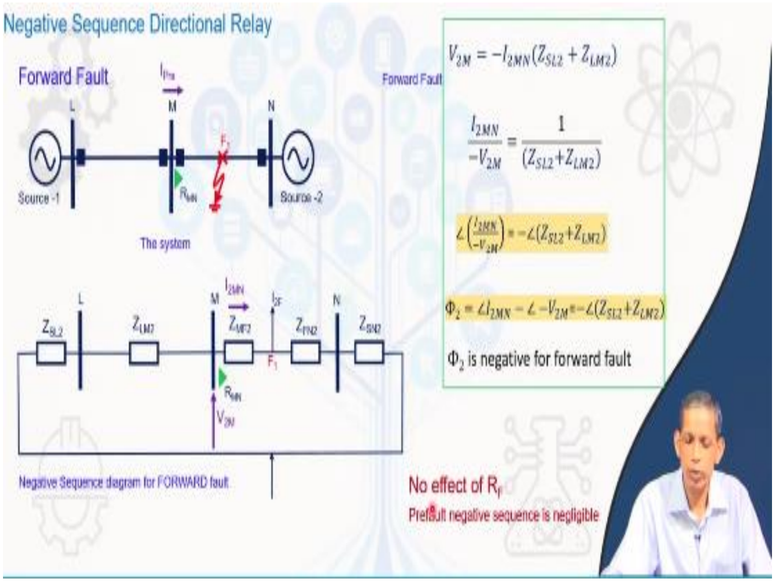

By this time we know how positive sequence component can be useful for direction of fault. What is the limitation of positive sequence component? Now we will see how we can explore advantage using negative sequence and zero sequence. So, see this negative sequence directional relaying first and then we will go to the zero sequence. Let us consider the system same 3-bus system for F_1 for relay R_{MN}.

For all unbalanced faults negative sequence component is available. So this is the negative sequence network for such a situation any unbalanced fault line-to-ground, line-to-line or double line-to-ground fault except the three phase fault. So let us I_{2F} is flowing through the fault point negative sequence component. These current will be divided by into two parts. There is a forward fault F_1. So through this relay a component will flow and another component will flow from the right side. So, what we see that the corresponding I_{2F} flowing through the fault will be divided in terms of the corresponding impedance of this source line and so. For this sequence diagram, for this forward fault in this network we have only negative sequence no positive sequence, no zero sequence in this portion.

For this network we can write down the relay bus negative sequence component of voltage as

$$V_{2M} = -I_{2MN}(Z_{SL2} + Z_{LM2})$$

I_{2MN} is the current flowing through relay; Z_{SL2} , Z_{LM2} are the impedances for the source and line section respectively.

Now from the above relation we can write

$$\frac{I_{2MN}}{-V_{2M}} = (Z_{SL2} + Z_{LM2})$$

$$\angle\left(\frac{I_{2MN}}{-V_{2M}}\right) = -\angle(Z_{SL2} + Z_{LM2})$$

So angle of the ratio between the negative sequence current and voltage seen by the relay gives the negative sequence impedance behind the relay bus. So, we say that if we represent this $\angle\left(\frac{I_{2MN}}{-V_{2M}}\right)$ as ϕ_2 for negative sequence directional relay we have the mentioned relation to be as

$$\varphi_2 = \angle I_{2MN} - \angle -V_{2M} = -\angle(Z_{SL2} + Z_{LM2})$$

ϕ_2 equals to negative of the angle of the impedance behind the relay, but this impedance if we see line impedance for this source impedance there will be large angle for that more than 80^0 kind of thing. So, therefore we say that the ϕ_2 will be negative for this situation and this situation is forward fault.

So ϕ_2 becomes negative for this forward fault. This is clearly evident from this sequence network for negative sequence and based on this voltage current relationship. So what do you see from this that this network do not have any Z_F for R_F. So these relations which we have narrated here is independent of R_F. So, the conclusion that the ϕ_2 negative sequence angle that angle we have defined here angle of negative sequence current that is seen by the relay minus negative angle of negative sequence voltage seen by the relay.

This angle what the relay will see during fault if it happens to be negative there is a forward fault. So that is not affected by the R_F as evident from this diagram and these relations. Note that further that transmission system also, the amount of unbalance during normal operating condition is also very low. Negative sequence current during normal condition is pretty small. Unlike load voltage, load current they are the positive sequence component.

So, positive sequence current in a transmission system is significantly high during normal condition also. So that affects the positive sequence fault current that we have already observed through example. Now however in case of negative sequence component negligible in negative sequence current in a line that means that the negative sequence current here is not affected by the loading condition.

So that leads to another advantage that this approach using ϕ_2 is advantageous in terms of no affect by R_F and no affect by the prefault load condition or the load condition or the load current that is the advantage of the negative sequence over the positive sequence component we will see through different examples also. Now before going to that we will see through phasor diagrams how can you conclude the same logics.

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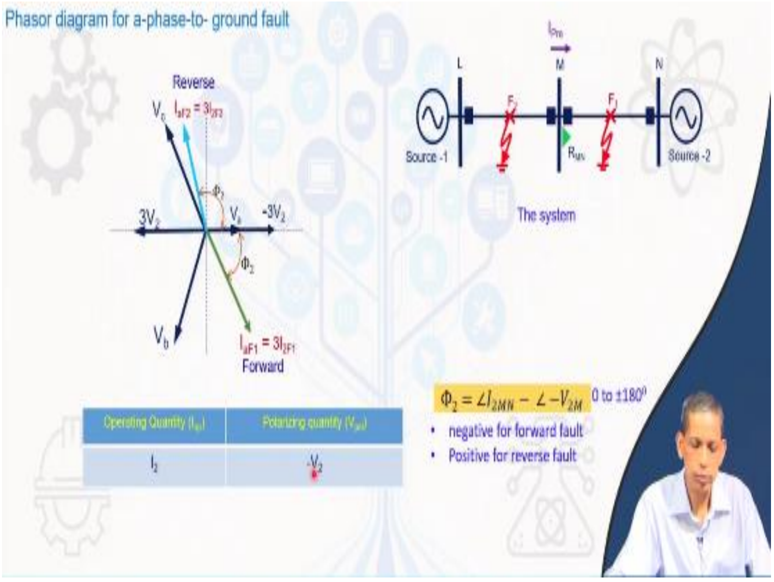

Let us say this is the system we will consider first the forward fault as seen by the relay R_{MN} and the corresponding phasor diagram and then we will go the reverse fault F_2. So, let us consider this is a phase *a*-to-ground fault at F_1 so V_a goes down V_b, V_c they remain intact almost at the relay bus. So V_b, V_c and V_a now you will have to compute the negative sequence component.

So $\alpha^2 V_b$, V_b 240^0 rotation αV_c , 120^0 rotation so V_c comes to V_b position and V_b goes to V_c position interchange. These two will be added plus the small value of V_a. Therefore the end result of these three phasors what we discuss will be coming in this direction and that is nothing, but $3V_2$. So we say V_2 equals to one third of V_a plus $\alpha^2 V_b$ plus αV_c so that means that this is $3V_2$.

Now in this situation of F_1 the forward fault the current direction through the relay will be like this. The corresponding current will lag the voltage. So to this V_a the corresponding current in the phase a I_{aF1}, F_1 means fault F_1 it will be this one, but this will be nothing but three times of this negative sequence current because for the line-to-ground fault I_{a1} equals to I_{a2} equals to I_{a0}.

Therefore, we say that this I_a current for this F_1 fault will be three times the negative sequence component. So this will be the negative sequence current direction and this will be the negative sequence voltage direction. Now if we invert intentionally to bring it to the V_a reference just like we did in case of phase component based approach even to the 90^0 approach, quadrature approach that is V_{bc} we shitted that 90^0 to bring it to the V_a axis.

So therefore if you like to bring this to consider $3V_2$ to V_a axis then this becomes equals to -$3V_2$. Now, if you consider the corresponding angle between I_2 and V_2 then this give us ϕ_2. So, in earlier slide we saw that the angle of I_2 minus angle of minus V_2 and now also here this minus V_2 is coming and this angle of I_2. So

$$\varphi_2 = \angle I_{2MN} - \angle -V_{2M} \text{ 0 to } \pm 180^0$$

For the forward fault the corresponding ϕ_2 is lagging like we saw in the case of positive sequence method also. So the corresponding angle becomes negative for forward fault. Now we will see for F_2 the reverse fault. In case of reverse fault the current direction changes voltage a similar nature same V_a, V_b, V_c position $3V_2$. Current is reversed so current is upward now. In Phase *a* to ground fault this is we are considering. Therefore, I_2 direction becomes this one. So I_2 position in this in a similar way minus $3V_2$ becomes this.

So minus $3V_2$ and I_2 so we see that for F_2 fault which is reverse fault for this relay the angle becomes ϕ_2 becomes positive because I_2 is leading to - $3V_2$ similar to we observe in case of positive sequence approach. So, the conclusion is that the ϕ_2 becomes positive for reverse fault and how do we get the ϕ_2? Angle of I_2 minus angle of minus of V_2 that is seen by the relay that is computed by the relay. I_2 computed from the set of current measurement, V_2 computed from the set of voltage measurements V_a, V_b, V_c. So we say that the operating quantity for this relay negative sequence for relay is I_2 and the polarizing quantity is minus of V_2.

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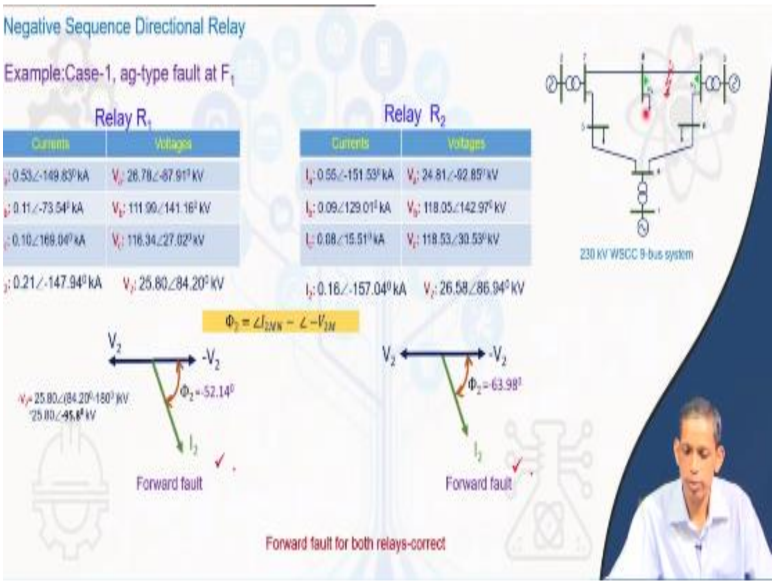

Let us see examples of this same 9-bus system, same two relays for 8 and 9, fault at F, forward fault for R_1, forward fault for R_2. Now let us see *ag*-fault, R_F is small here in this case one relay R_1 and relay R_2, set of measurement current and the voltage. From the current compute the I_2 one third of I_a plus $\alpha^2 I_b$ plus αI_c we get this corresponding I_2. Similarly from voltages you get the V_2 angles are important for us in computation.

So angle of I_2 is -147^0 and angle of V_2 is 84.40, but note that we require minus of V_2. Now what does minus of V_2 implies? If this is V_2 this is minus of V_2. So minus of V_2 means not simple of putting on the magnitude part negations, it is the angle rotation by 180^0. So we are talking about a phasor rotation of 180^0. So how to do that? So the angle part will be having a negation of 180^0.

So this minus V_2 becomes equals to $25.8\angle(84.2-180)^0$ kV that leads to a situation of -95.8^0 then we will compute this

$$\phi_2 = \angle I_{2MN} - \angle{-V_{2M}} = -147.94^0 + 95^0 = -52.14^0$$

Which implies it is a forward fault and which is correct for R_1. We know that this current I_2 lags the V_2 by certain angle lagging current means here in this case it is a forward fault. Similarly, using this R_2 data current we got the negative sequence current at the relay. Similarly for the voltage set consider we will get the negative sequence voltage. These negative sequence voltage has to be negated again like that what you did for this -180^0 case and then we compute the corresponding ϕ_2 based on this I_2 and minus of V_2 angle of that and then we got the corresponding phasor to be - 63.98^0. And this is negative angle means forward fault so for R_2 also this is negative angle which is correct. So both relays see the fault in the forward direction. This is correctly identified by this both relays.

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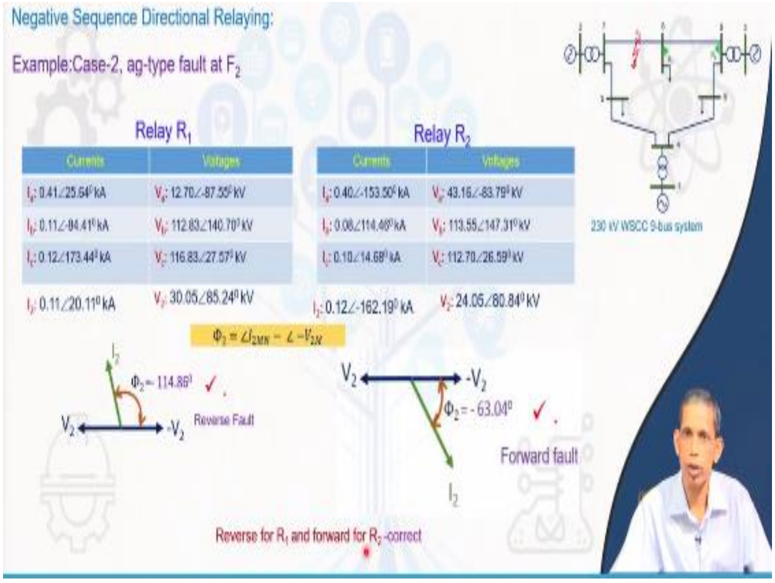

Now for a F_2 fault which is reverse fault for R1, but forward fault for R_2. Set of measurement I_2 and this is V_2 compute the ϕ_2 using $\angle I_2$ minus $\angle$-V_2. So we got this ϕ_2 to be -114.86^0 less than 180^0 acceptable. So this is minus angle means reverse fault for R_1 this is reverse fault so this is correct. Now I am coming to R_2 the corresponding data of current data of voltage I_2 by the relay R_2 and V_2 by the relay R_2. So we got the corresponding ϕ_2 computations like this and ϕ_2 from these two angles with a negation for this V_2 as mentioned then we got the corresponding ϕ_2 to be -63.64^0. So minus angle means for this, this is forward fault, this is forward fault. So that is what we got that this case for R_1 it is reverse and this case for R_2 it is forward which is correct as we see for the case.

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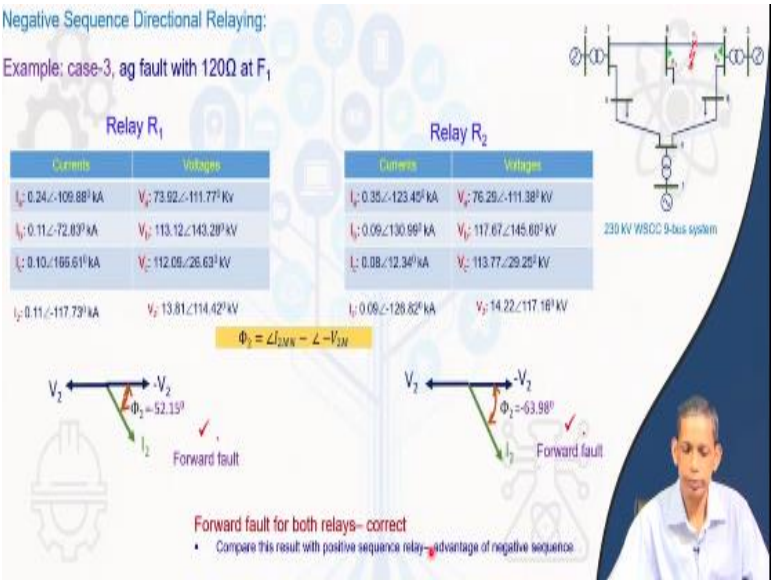

Now we go next to this with high R_F. Note that from the sequence diagram we have already discussed that R_F should not affect the negative sequence based relay. Let us see relay R_1, relay R_2 same forward fault increase value of R_F positive sequence was affected not properly identified in the case of positive sequence. Now we will see the corresponding set of measurement current voltage negative sequence computation.

Negative sequence voltage computation. Similarly for the relay R_2 also I_2 and V_2. Now ϕ_2 equals to angle of I_2 minus angle of minus V_2. We see from this two angles ϕ_2 equals to -52.15^0; negative angle forward fault correct. This was incorrectly identified by the positive sequence approach. Now it is correctly identify the negative because we mentioned that R_F does not affect the negative sequence component which is true. Looking at the R_2 the corresponding ϕ_2 is -63.98^0 so minus angle forward fault. So this also correctly identified the fault so this two relays see the fault in forward even thought the R_F is 120 Ω. So this forward fault by both the relays is correct if we compare the relay performance negative sequence relay performance as compared to positive sequence one. Negative sequence gets advantage over positive sequence in terms of high value of R_F.

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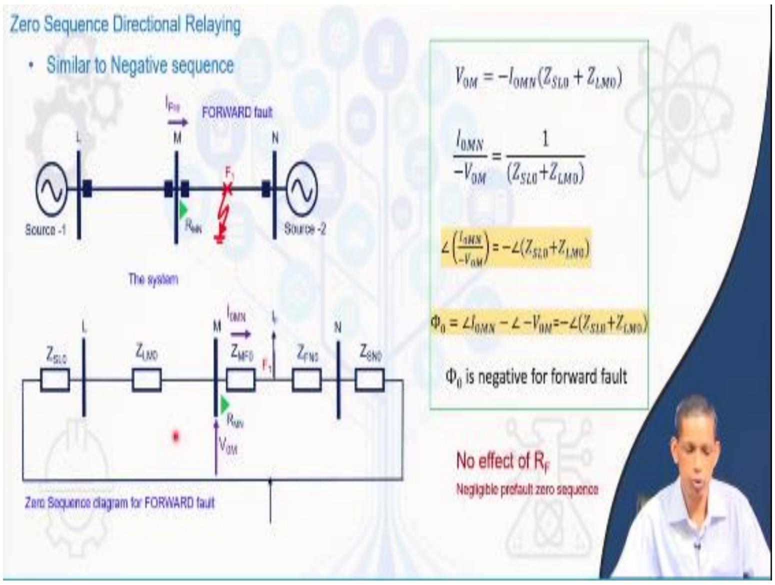

Now we will go to the zero sequence direction relaying. This is similar to a negative sequence we know the corresponding zero sequence network for these system forward fault similar to negative sequence what we discuss only replace the corresponding impedance as in terms of zero sequence component. So this I_{0F} passing through this and then if we write the corresponding equation from this side same we can say that I_{0MN} is flowing from this side.

So therefore two impedances are there behind this relay that is what you can write the expressions for the zero sequence voltage at this relay bus is

$$V_{OM} = -I_{0MN}(Z_{SL0} + Z_{LM0})$$

With similar approach followed for negative sequence here the above mentioned relation can be rewritten as

$$\phi_0 = \angle I_{0MN} - \angle -V_{0MN} = -\angle(Z_{SL0} + Z_{LM0})$$

So $\angle(Z_{SL0} + Z_{LM0})$ being positive so the negative signs implies negative angle so ϕ_0 becomes negative in case of forward fault. Same conclusion similar what we got for the negative sequence component current only we are replacing the corresponding current with the zero sequence component, computed from I_a, I_b, I_c I_a as

$$I_0 = \frac{1}{3}(I_a + I_b + I_c)$$

and the corresponding voltage

$$V_0 = \frac{1}{3}(V_a + V_b + V_c)$$

So then we found that the ϕ_0 is negative for forward fault and in case of the reverse fault current will be reversed. So we will conclude that for that case the corresponding ϕ_0 will be positive. So, here also we see that from the diagram independent of R_F no affect of R_F and in most of the transmission system also we see during normal operations the I_0 component is negligible. So this is also we say that prefault current has no affect on the zero sequence approach also.

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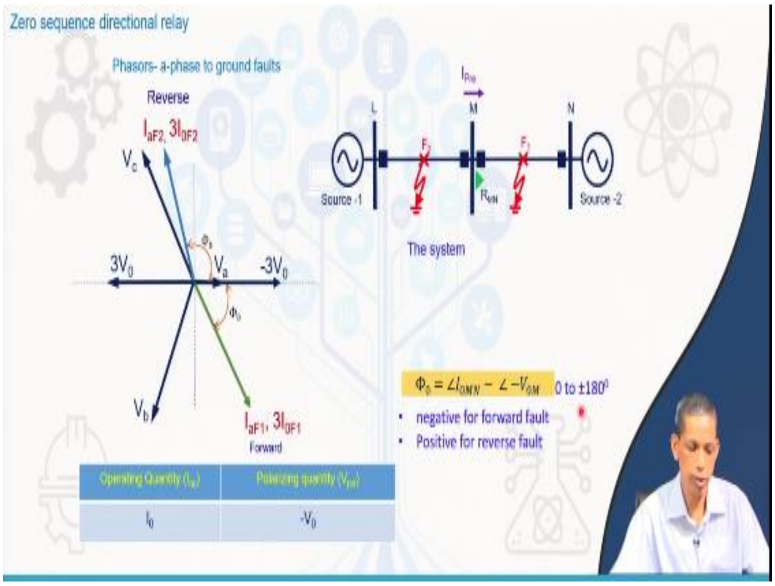

Now going to this same phasor diagram perspective similar to that one. Let us consider for the F_1 fault for the line-to-ground fault we will have this similar diagrams so V_b, V_c and this is V_a. Now we will compute the V_0, V_0 is V_a plus V_b plus V_c so we add V_b, V_c and V_a so this again comes out to be this line $3V_0$. If we like to shift it to the V_a line there are - $3V_0$ for F_1 faults I_a lags voltage substantially in terms of the impedance angle of the line and the R_F.

Now in this you can say that current is three times of the I_{0F}, $I_a = 3I_{a1} = 3I_{aF2} = 3\ I_{a0}$. So that leads to that this I_{a0} is this line and $-3V_0$ is this so $-V_0$ and I_0. So therefore if we define this as ϕ_0 as already mentioned in the earlier slide like the negative sequence component this slides. This current is lagging to this voltage reference voltage, polarizing voltage. Therefore, if ϕ_0 will be negative in terms of that and ϕ_0 negative means the corresponding fault is forward fault. Similarly for F_2 the current will be reversed and this current is also the direction of the I_0, I_0

similar to this voltage - $3V_0$ to this reference the corresponding current leads and angle of I_0 minus angle of minus V_0 that becomes positive. So ϕ_0 is positive means the fault is in the reverse direction. So that leads to situation that we can conclude using the zero sequence component defining like this angle of I_0 seen by relay minus angle of $-V_0$ seen by the relay bus then the corresponding angle if it comes out to be negative it refers to forward fault if angle comes out to be positive it says this is a reverse fault.

Therefore, the corresponding zero sequence based approach also zero sequence current seen by the relay angle of the polarizing quantity becomes minus of V_0 in this case. So that gives us you can say that the principle of zero sequence based approach of course similar to other things from the phasor we can conclude that this angle ϕ_0 is limited to $\pm 180^0$.

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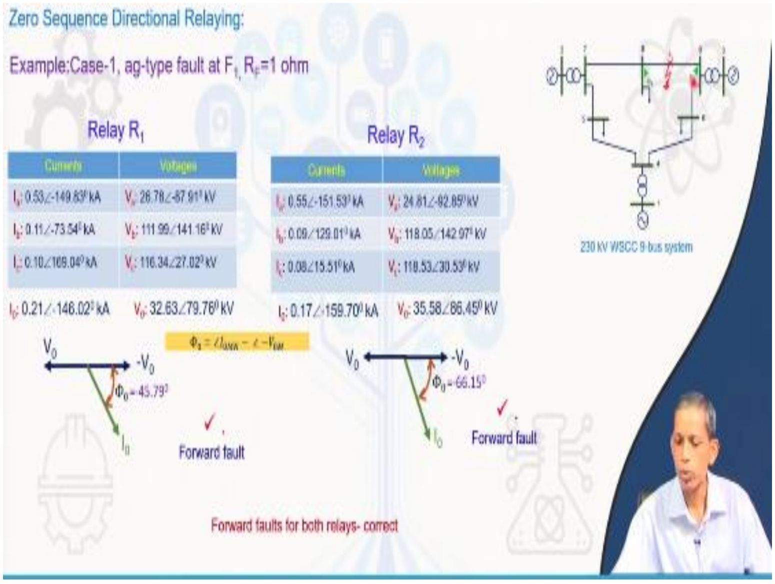

Looking at this performance of zero sequence form so the first case with forward fault F_1 for R_1 and R_2 in this 9 bus system set of currents, set of voltages so I_0 computed this is the angle -146^0, V_0 this is the angle so we have to negate this V_0 so this means -180^0 to this angle and then similar to the negative sequence component what you did if you compute this ϕ_0 with angle I_0 minus angle $-V_0$. For this case if ϕ_0 happens to be -45.79^0 so this like a negative angle clearly say this is forward fault R_1 there is a forward fault so this is correct. For R_2 this is also forward fault set of measurement of currents and voltages computed this I_0 and V_0 negate the V_0 with -180^0 here for this case. Compute the angle I_0 and the angle of $-V_0$ and then the subtraction we want ϕ_0 to be -66.15^0 negative angle implies forward fault R_2 since it is forward which is correct. So both relays is the fault in the forward direction.

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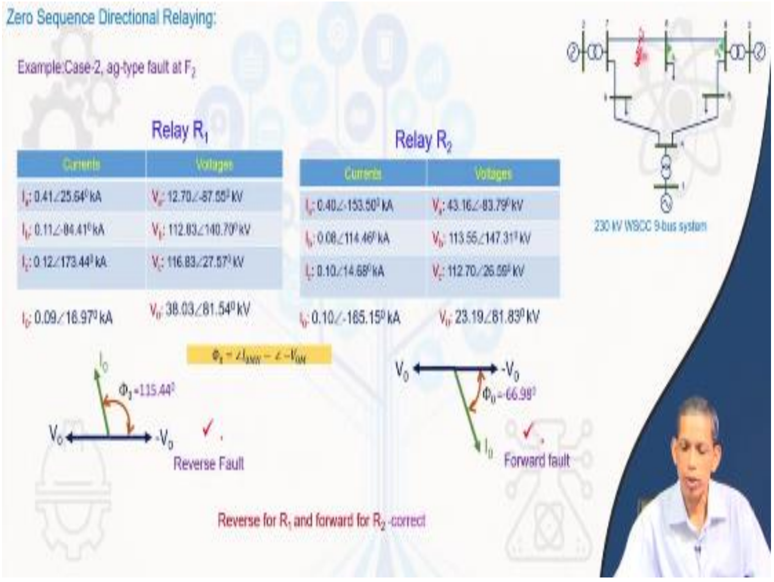

Case 2 for F_2 fault forward for R_2 and reverse for R_1 set of measurements for R_2 set of measuring ϕ_0 computation using the relation ϕ_0 for R_1 happens to be positive 150.44 less than 180^0 so this is a reverse fault clearly and for R_2 the ϕ_0 computed is -66.98^0 clearly a forward fault. So that leads to you can say that conclusion that R_1 since it is a reverse and R_2 since it is forward which is correct. So the judgment by the two relays using the zero sequence component is correct.

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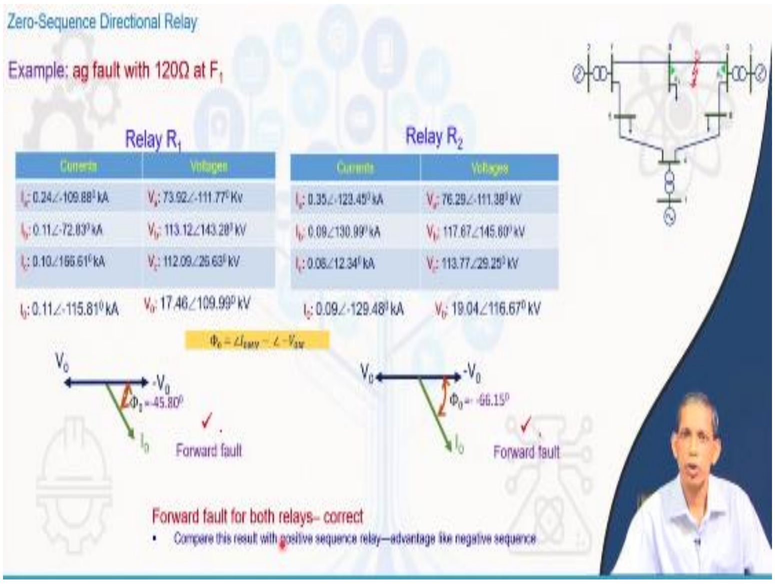

With high fault resistance already mentioned like negative sequence component this sequence component approach zero sequence component is not affected. So, we will seek and say that in this case what happens to this situation R_1 the corresponding I_0 is having an angle of -115.81^0, V_0 is having 109.99^0, ϕ_0 computed why this relations comes out to be -45.80^0. Minus angle forward fault. So for this forward fault so R_F has no affect that is true now R_2 for R_2 the corresponding ϕ_0 comes out to be -66.15^0 same we can say that so the corresponding forward fault that leads to consider forward fault case. 6So forward fault for both relays which is correct so we see that this is compared to positive sequences these are the advantage and is similar to the negative sequence perspective.

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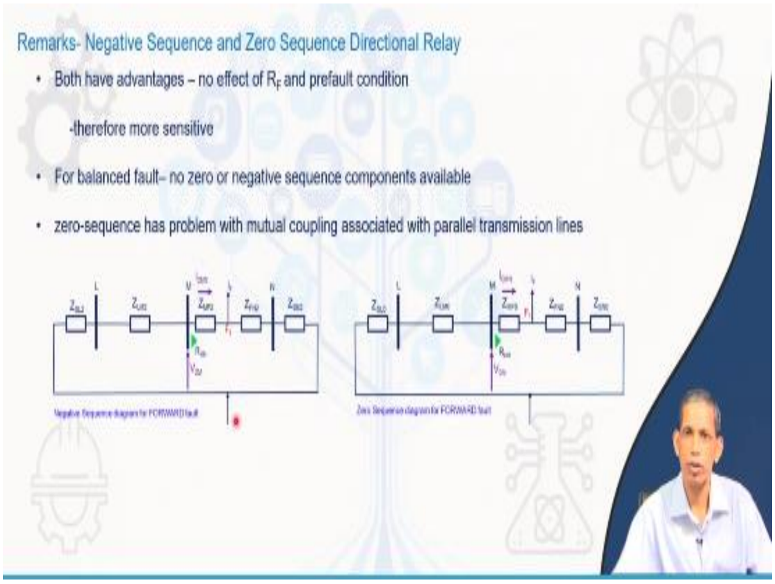

Now in general remarks the negative sequence and zero sequence directional relaying both have advantages over positive sequence because they were not affected by R_F and also not affected by the prefault conditions because system generally operate in close to balance conditions. So, no negative sequence or zero sequence component normal kind. Therefore, such an approach is also more sensitive because the effect of prefault is negligible.

For balanced fault however there is no zero sequence or negative sequence component so they do not have any answer to the direction of fault in case of three phase fault. It means such an approach cannot provide solutions for all the situations that means we have to switch over if we are using this sequence approach we have to use the positive sequence approach. That means the sequence component can complement each other. Zero sequence has problem with the mutual coupling particularly on parallel transmission system and so. We know zero sequence is a single phase perspective so therefore flux becomes additive. So it has zero sequence mutual component issue and that means that if we are going to apply for such lines then it may be disadvantageous. In that case negative sequence can have advantage. Negative sequence and positive sequence there were not affected by the mutual component perspective and so. So we say from these two diagrams that clearly sequence diagram for the positive and negative they are not affected by the R_F that is beauty of the two sequence component; zero sequence and negative sequence components.

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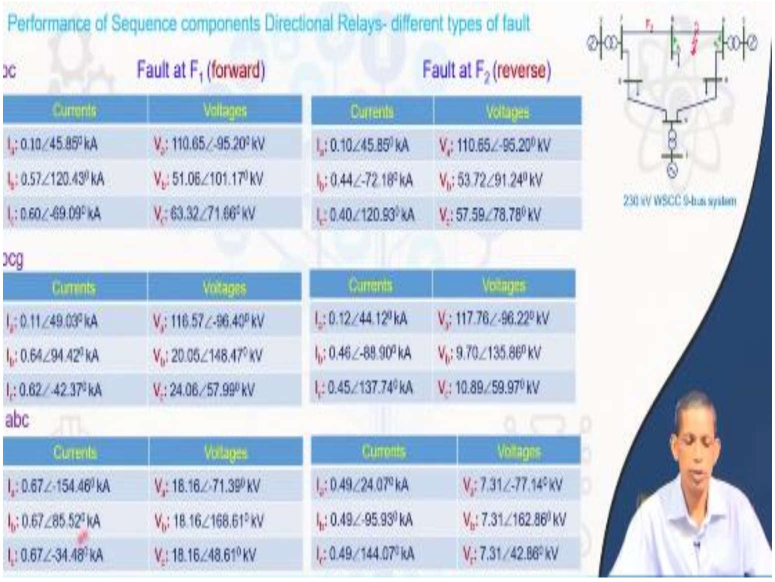

We throughout this discussions for positive and negative sequence and the zero sequence relays we discuss about only line-to-ground fault, *ag*-type fault. Now going beyond that for all other categories of fault line-to-line, double line-to-ground and three-phase fault *bc*, *bcg* and *abc* we have set our measurements for fault at F_1 and fault at F_2 reverse fault for the corresponding relay R_1. So forward fault and reverse fault case we have set our measurements for line-to-line fault, double line-to-ground fault and *abc* faults. So these are the sets of currents and voltages for this case for the both forward and reverse fault case for relay R_1.

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Now for forward fault F_1 first case for this relay R_1 if we see *bc*, *bcg* and this then this sequence based directional relaying positive sequence I_1 computed, V_1 computed, angle ϕ_1 is - 66.13^0 so this is identified as forward which is true. Negative sequence, zero sequence. Negative sequence component becomes I_2 and $-V_2$ and then the corresponding angle is - 52.15^0 so this is correctly obtained directional relaying. For *bc* fault there is no zero sequence they do not have any considered answer to this. So they cannot decide on this. For *bcg* fault positive and negative and zero so this set we can say things are there. So then we have this and all the three considered correctly identified because negative signs indicate forward fault. Now in case of the *abc* fault positive and negative and zero.

So, *abc* fault means only positive is available negative sequence and zero sequence they cannot respond to consider to this such a situation. So positive sequence face the angle comes out to be - 83.08^0 and this angle is because of the R_F value angle of this transmission impedance so this is forward fault. So that means that for all the other types of fault in the forward directions the corresponding relays principle perform as expected.

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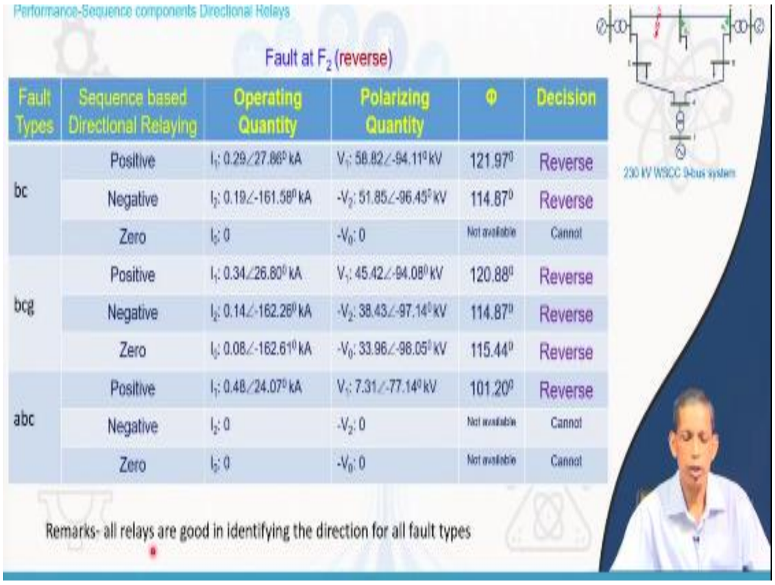

When do the reverse fault for F_2 fault for this R_1 the set of relay considered *bc* considered for all the cases the corresponding angles are positive and therefore the corresponding reverse fault will be identified properly by the different sequence component. However, as usual for the line-to-line fault and for the three-phase fault the zero sequence components is not available and the negative sequence is not available for the three-phase fault case. So, in general from the set of observations for different types of fault besides line-to-ground fault we see that they are good in identifying the find the direction of the faults.

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So, in overall we can have some remarks on the different aspects of performance in respects of the positive, negative and zero sequence relaying principles. Positive sequence is available for all faults they can conclude for all fault, but they are affected by R_F no R_F poor performance. Affect pre-fault if the prefault is dominating close to the fault component of current kind of thing values then the relay decision may be affected.

No effect on mutual coupling. Negative sequence available only for unbalance fault not affected by R_F, not affected by the prefault because prefault does not negative sequence component, no mutual affect. So this is the strength zero sequence is only available for ground faults, no affect for R_F, no affect for the prefault condition, but it is affected by the mutual coupling particularly applications to parallel transmission line or so.

So we see that there are different sequence components which can be applied for identifying the direction of fault. They are very good at and they can complement each other for a better performance relaying principle. Thank you.