Power System Protection
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Lecture No. 19
Fault Classification

Welcome to NPTEL Power System Protection course. In this lecture on module 5, Distance Relaying, we will discuss on fault classification.

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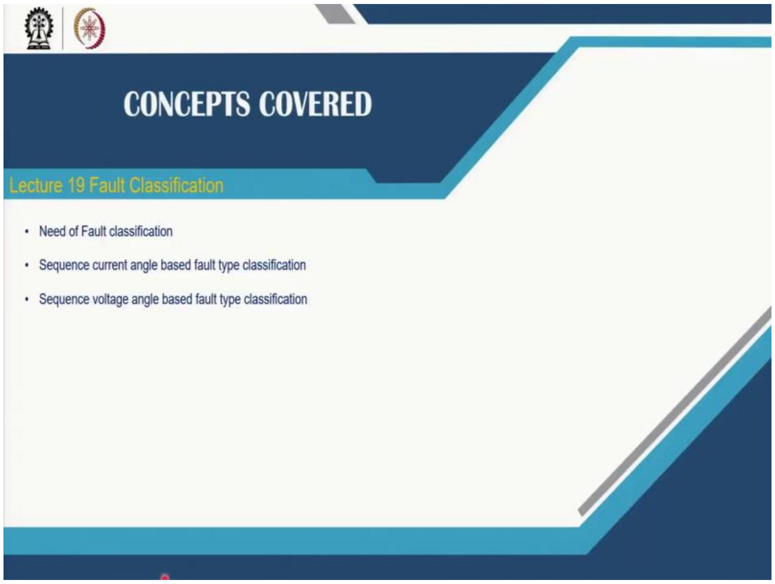

CONCEPTS COVERED

Lecture 19 Fault Classification

- Need of Fault classification
- Sequence current angle based fault type classification
- Sequence voltage angle based fault type classification

The need of fault classification, how we can achieve the fault classification using current-based approach. And at the end, we will see how we can extend the fault classification method to the voltage-based approach also.

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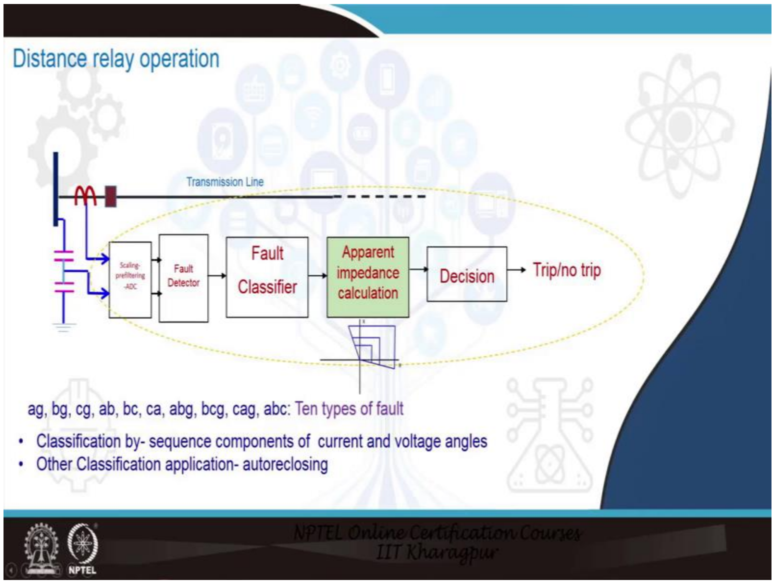

Distance relay operation

ag, bg, cg, ab, bc, ca, abg, bcg, cag, abc: Ten types of fault

- Classification by- sequence components of current and voltage angles
- Other Classification application- autoreclosing

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So, continuing with that we have already discussed on the distance relaying, how it can be applied for transmission system. From that basic idea, we can see this diagram. So, this is a transmission line, a bus here. So, we can, from the voltage transformer we can get the voltage information for the relay, and then from the current transformer, we can get the corresponding set of current formation, phase a, phase, b, phase c for the relay. So, this circuit breaker is to be controlled by the distance relay.

So, these are the different perspective which an algorithm in a distance relay has to accomplish. So, we have a fault detector, fault classifier, the apparent impedance calculation, and then decision. So, fault detector detects the fault, finds the change or so. This we have already addressed in the initial classes. We can consider a current change like sample-to-sample comparison or cycle comparison basis, or you can use any DFT based approach for a phasor-based approach also for setting a threshold and greater than threshold you can declare that a fault has occurred in the system.

Then, the distance relay requires a fault classifier, based on the fault classification, and then it computes the Z apparent or Z seen. In the last lecture, we have seen that the different characteristics in the distance relay can be used effectively for different zones, and based on the step-distance relay concept we can achieve better protection philosophy for transmission line. So, a characteristic is being used on the RX complex plan. The apparent impedance computed by the relay using the voltage and current information will be inside the characteristics in case of a fault in that line, and then a decision has been taken.

This fault classifier is useful for providing the correct voltage and current information to compute the corresponding apparent impedance. What you mean by the fault classifier is that there are 10 types of faults, which we have already addressed in earlier classes, like phase a to ground, phase b to ground, phase c to ground, phase-to-phase fault of ab, bc, or ca type and double phase to ground faults of abg, bcg, cag type or the 10 one this 3-phase balance fault abc type.

So, the corresponding 10 types of fault, anyone may occur in the transmission system. So, this first fault classifier has to identify that which type right now at this fault situation the transmission line is encountering. Accordingly, a set of voltage and current information is being used for the apparent impedance calculation which then is useful for the decision on trip or no trip.

So, this classification is generally achieved in available numerical relays using sequence components of current and also can be using the voltage information. The sequence of components of currents and voltage and their angles are useful for the classification. Fault classifier is also useful for auto-reclosing options in the relay. Such functions are also embedded in case of line-to-ground fault, you can have a single-pole or auto-reclosing phenomena, or you can go for a 3-phase auto reclosing also.

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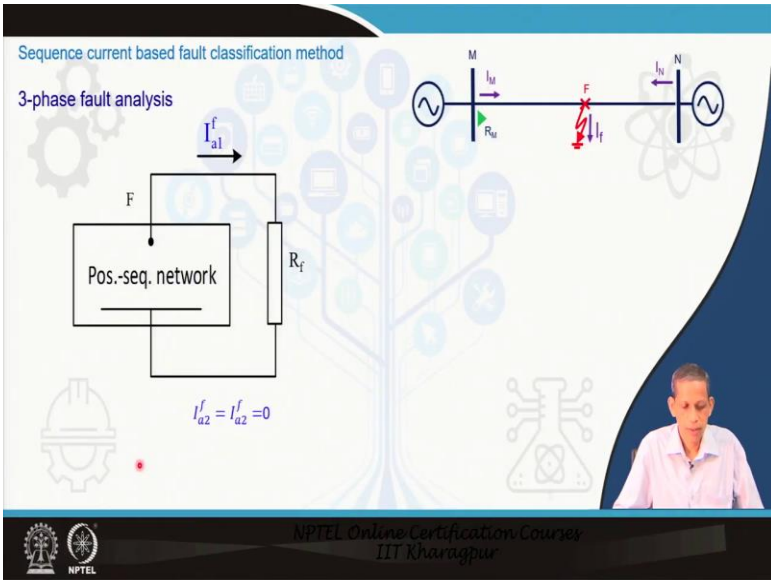

Sequence current based fault classification method

3-phase fault analysis

$I^f_{a2} = I^f_{a2} = 0$

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Now, let us go to the method perspective for fault classification. So, we will start from the basics. 3-phase fault, so this we are discussing on current based fault classifier, 3-phase fault. This is the system, the relay at bus M R_M, corresponding current I_M; fault happens to be in this line, and through the fault, a current I_f passes and then there is a contribution of this current from left source and the right source I_M and I_N.

For 3-phase fault, we have only positive sequence network as we have learned, and at that moment, only positive sequence current flows, there will be no negative sequence and 0 sequence current, so this is a balanced situation.

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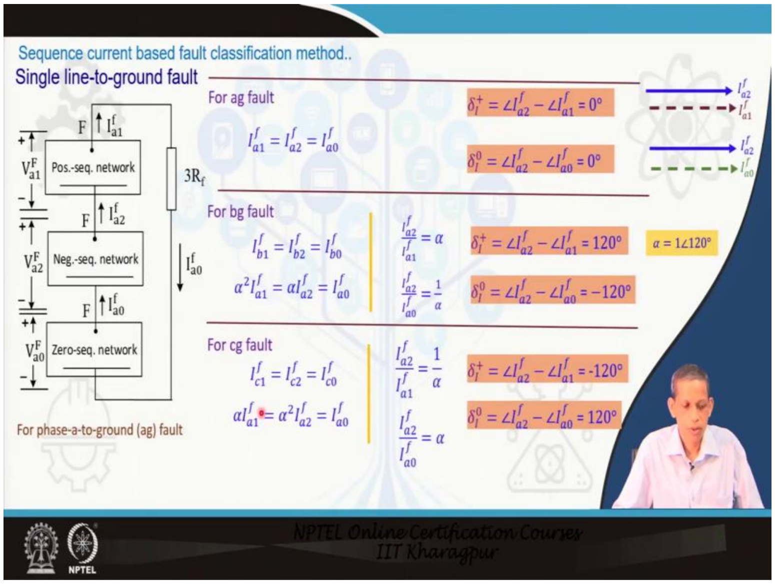

Sequence current based fault classification method..

Single line-to-ground fault

For phase-a-to-ground (ag) fault

For ag fault

$I_{a1}^f = I_{a2}^f = I_{a0}^f$

$\delta_I^+ = \angle I_{a2}^f - \angle I_{a1}^f = 0°$

$\delta_I^0 = \angle I_{a2}^f - \angle I_{a0}^f = 0°$

For bg fault

$I_{b1}^f = I_{b2}^f = I_{b0}^f$

$\alpha^2 I_{a1}^f = \alpha I_{a2}^f = I_{a0}^f$

$\frac{I_{a2}^f}{I_{a1}^f} = \alpha$

$\frac{I_{a2}^f}{I_{a0}^f} = \frac{1}{\alpha}$

$\delta_I^+ = \angle I_{a2}^f - \angle I_{a1}^f = 120°$

$\delta_I^0 = \angle I_{a2}^f - \angle I_{a0}^f = -120°$

$\alpha = 1\angle 120°$

For cg fault

$I_{c1}^f = I_{c2}^f = I_{c0}^f$

$\alpha I_{a1}^f = \alpha^2 I_{a2}^f = I_{a0}^f$

$\frac{I_{a2}^f}{I_{a1}^f} = \frac{1}{\alpha}$

$\frac{I_{a2}^f}{I_{a0}^f} = \alpha$

$\delta_I^+ = \angle I_{a2}^f - \angle I_{a1}^f = -120°$

$\delta_I^0 = \angle I_{a2}^f - \angle I_{a0}^f = 120°$

Now, we will go to a more common fault, single line-to-ground fault. Let us say a phase a to ground fault. So, we have positive sequence network, negative sequence network, 0 sequence network; they are connected in series with 3 R_f. So for such a network, we know, for line-to-ground fault we know $I_{a1}^f = I_{a0}^f = I_{a2}^f$, the negative sequence current through the fault path.

So, for line-to-ground fault of ag type, we have $I_{a1} = I_{a2} = I_{a0}$ in the faulted path. The f tends for here the fault path current. Now if this is valid, so that means that these 3 phasors are same. Means that the angle between these 3 phasors are 0 and their magnitude is also same. Here in this classifier, we will concern about only the angles part. So this, if you define an angle, δ_I^+, I for the only current part, δ for the angle corresponds to these with a positive sequence current at the reference.

So δ_I^+ positive of what, the negative sequence current with respect to the positive sequence current. So, we have I_{a1}, I_{a1} to the fault path current as reference, with respect to that the I_{a2}^f take the same position. So $\delta_I^+ = \angle I_{a2}^f - \angle I_{a1}^f = 0°$ and that is what we got from these relations which is valid for this sequence diagram.

Now we will go to other line-to-ground fault, phase b to g. For this case, we know $I_{b1}^f = I_{b0}^f = I_{b2}^f$, but I_{b1}, I_{b2}, and I_{b0} can be expressed in terms of I_{a1}, I_{a2}, and I_{a0} respectively. So, we know these relations. $I_{b1}^f = \alpha^2 . I_{a1}^f$ where $\alpha = 1\angle 120^0$ complex number. So this $I_{b2}^f = \alpha . I_{a2}^f$ and $I_{b0}^f = I_{a0}^f$. So this means that $I_{a2}/I_{a1} = \alpha$ the ratio between I_{a2} and I_{a1} in the faulted path current equals to alpha and

$I_{a2}/I_{a0} = 1/\alpha$ from this relation. So, type of fault is bg fault, relations we are obtaining in terms of this I_{a1}, I_{a2}, and I_{a0}.

So this we see that this equals to α and the $I_{a2}/I_{a0} = 1/\alpha$. So now, similar to the earlier one, if we define the δ_I^+ means with respect to positive sequence a-phase current, the corresponding negative sequence a-phase current, the angles will be $\angle I_{a2}^f - \angle I_{a1}^f = \alpha$, $\alpha = 1\angle 120^0$, so δ_I^+ becomes now 120 degree.

In a similar way, δ_I^0 with respect to 0 sequence current, the negative sequence current, so $\angle I_{a2}^f - \angle I_{a0}^f = 1/\alpha$, $\alpha = 1\angle 120^0$, so $\angle 1/\alpha = -120^0$. In a similar way, we will go to the third category of the line-to-ground fault that is cg type. So for this case, $I_{c1}^f = I_{c2}^f = I_{c0}^f$. We will express this c phase currents in terms of a phase current. So, $I_{c1}^f = \alpha . I_{a1}^f = \alpha^2 . I_{a2}^f$ and $I_{c0}^f = I_{a0}^f$.

So from this relation, we can relate $I_{a2}/I_{a1} = 1/\alpha$ and $I_{a2}/I_{a0} = \alpha$. Then from this, similar to the earlier for phase b and phase a for phase c to ground fault, we can say $\delta_I^+ = \angle I_{a2}^f - \angle I_{a1}^f$ from this one. This will be -120^0 because this is $1/\alpha$. Now, this ratio is α, so $\delta_I^0 = \angle I_{a2}^f - \angle I_{a0}^f = 120$.

So, what we see here that these relations of δ_I^+ and δ_I^0 is having 0 degree here, 120^0, -120^0, -120^0, and 120^0; so they have different angles with respect to positive sequence current or negative sequence currents.

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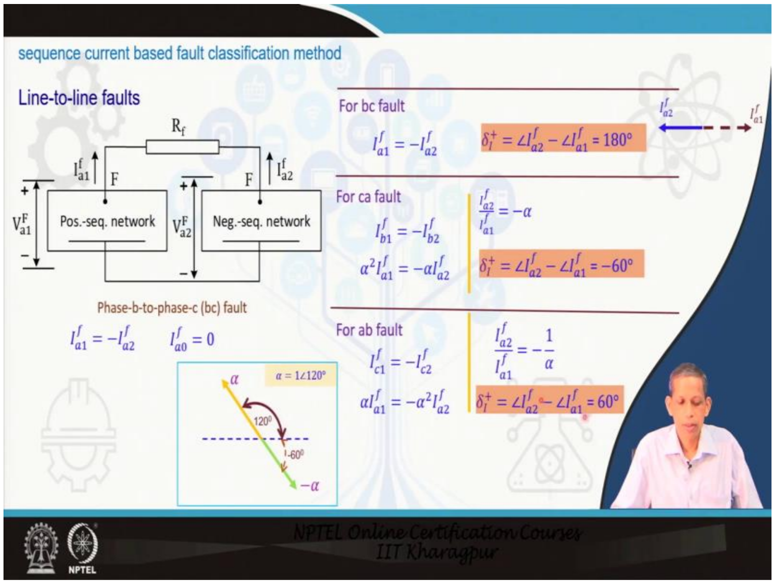
sequence current based fault classification method

Line-to-line faults

Phase-b-to-phase-c (bc) fault

$I^f_{a1} = -I^f_{a2}$ $I^f_{a0} = 0$

For bc fault

$I^f_{a1} = -I^f_{a2}$ $\delta^+_I = \angle I^f_{a2} - \angle I^f_{a1} = 180°$

For ca fault

$I^f_{b1} = -I^f_{b2}$

$\alpha^2 I^f_{a1} = -\alpha I^f_{a2}$

$\frac{I^f_{a2}}{I^f_{a1}} = -\alpha$

$\delta^+_I = \angle I^f_{a2} - \angle I^f_{a1} = -60°$

For ab fault

$I^f_{c1} = -I^f_{c2}$

$\alpha I^f_{a1} = -\alpha^2 I^f_{a2}$

$\frac{I^f_{a2}}{I^f_{a1}} = -\frac{1}{\alpha}$

$\delta^+_I = \angle I^f_{a2} - \angle I^f_{a1} = 60°$

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Now, we will extend this to the other types of fault, line-to-line faults. So, let us first discuss with phase b to phase c fault, bc fault. So, we have the positive sequence network, negative sequence network for Ia. So, I_{a1} = -I_{a2} in the faulted path, in the faulted path. So, I_{a1} = -I_{a2} for bc fault and there is no 0-sequence current because the ground is not involved.

So from this relation, we say that for bc fault I_{a1} =- I_{a2}, so $\delta^+_I = \angle I^f_{a2} - \angle I^f_{a1} = 180^0$. so they are in phase opposition so that results in 180^0. So, in terms of phasors, we can show like this. For phase c to a fault, we have similar relation for b phase. I_{b1}= -I_{b2} or we can express them in terms of phase a currents. So, $\alpha^2.I_{a1}$ = -$\alpha.I_{a2}$. So therefore, I_{a2}/ I_{a1} = -α from this relation. So, that means that $\delta^+_I = \angle I^f_{a2} - \angle I^f_{a1}$, angle of these two phasors equals to -60^0.

How we obtain this? See here, if you have $\alpha=1\angle 120^0$, so then this becomes 120^0 and then if you put, you can see that -α, -α means other way 180^0 anti-clockwise, so then, therefore, $-\alpha=-60^0$ and that is how -α refers to -60^0 here the phasor domain.

For phase ab, for phase a to b fault, then we will have this relation for I_{c1} = - I_{c2} in the faulted path and therefore expressing that in currents of phase a, $\alpha.I_{a1}$ = - α^2 .I_{a2} and the (I_{a2}/ I_{a1}) =-1/α. Therefore, the $\delta^+_I = \angle I^f_{a2} - \angle I^f_{a1} = 60^0$.

So, we see that for phase-to-phase fault bc type, ca type, ab type, the corresponding the $\delta_I^+ = 180^0$,-60^0 and 60^0 . We do not have any 0 sequence current because this is not involved with ground.

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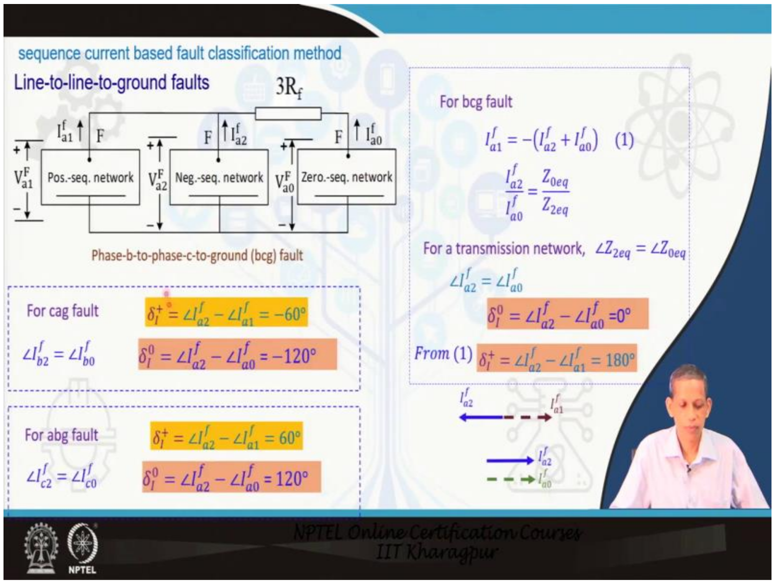

sequence current based fault classification method

Line-to-line-to-ground faults

Phase-b-to-phase-c-to-ground (bcg) fault

For cag fault

$\angle I_{b2}^f = \angle I_{b0}^f$

$\delta_I^+ = \angle I_{a2}^f - \angle I_{a1}^f = -60°$

$\delta_I^0 = \angle I_{a2}^f - \angle I_{a0}^f = -120°$

For abg fault

$\angle I_{c2}^f = \angle I_{c0}^f$

$\delta_I^+ = \angle I_{a2}^f - \angle I_{a1}^f = 60°$

$\delta_I^0 = \angle I_{a2}^f - \angle I_{a0}^f = 120°$

For bcg fault

$$I_{a1}^f = -\left(I_{a2}^f + I_{a0}^f\right) \quad (1)$$

$$\frac{I_{a2}^f}{I_{a0}^f} = \frac{Z_{0eq}}{Z_{2eq}}$$

For a transmission network, $\angle Z_{2eq} = \angle Z_{0eq}$

$\angle I_{a2}^f = \angle I_{a0}^f$

$\delta_I^0 = \angle I_{a2}^f - \angle I_{a0}^f = 0°$

From (1) $\delta_I^+ = \angle I_{a2}^f - \angle I_{a1}^f = 180°$

Now, the last category of fault phase-to-phase to ground fault or line-to-line ground faults, let us discuss one by one. So first, bcg fault. In bcg fault for phase a positive sequence network, negative sequence network, and 0 sequence network; so negative and 0, they will be in oppositions to this positive sequence current. So, we know that the corresponding relations for bcg fault is $I_{a1} = -(I_{a2} + I_{a0})$.

So now, we know that these two currents combinedly oppose this current, so, therefore, the corresponding two currents will in in terms of their sequence component impedances, because they are basic part. So, therefore, (I_{a2}/I_{a0})= (Z_{0eq}/Z_{2eq}) because they are in parallels. So, these two combinedly the oppose I_{a1}. So, from these relations for a transmission network, the $\angle Z_{2eq} = \angle Z_{0eq}$.

Note, we are not saying $Z_{2eq} = Z_{0eq}$, we are only saying $\angle Z_{2eq} = \angle Z_{0eq}$. So, with this consideration, we can say that in this case, $\angle I_{a2} = \angle I_{a0}$ in the faulted path. So, from these relations and with these considerations, we say that, in the faulted path $\angle I_{a2} = \angle I_{a0}$. So, then we got this one, so therefore, these two, you can see that components of current will be having same angle.

So, therefore, we can say that $\delta_I^0 = \angle I_{a2}^f - \angle I_{a0}^f = 0^0$ in the faulted path because of this relation. Now, if you see this equation 1 now, so $\delta_I^+ = \angle I_{a2}^f - \angle I_{a1}^f$. $\angle I_{a2}$ and $\angle I_{a0}$, same. So, therefore, we say that $\angle I_{a2}$ - $\angle I_{a0}$ =180^0. Because of the negative sign, they are in oppositions to each other. So from 1, you can conclude that $\delta_I^+ = 180^0$. So, this is for δ_I^+ and this is for the δ_I^0 for this bcg fault.

Similarly, for the cag fault, we can from the relations of I_{b2} = I_{b0} and then we can write in terms, similar way $\delta_I^+ = \angle I_{a2}^f - \angle I_{a1}^f = -60^0$. $\delta_I^0 = \angle I_{a2}^f - \angle I_{a0}^f = -120^0$. And for abg fault, $\delta_I^+ = \angle I_{a2}^f - \angle I_{a1}^f = 60^0$ and $\delta_I^0 = \angle I_{a2}^f - \angle I_{a0}^f = 120^0$. So, these are the all 10 category of faults for which we express δ_I^+ and if available δ_I^0 also. If 0 sequence is available, we express the corresponding angle δ_I^0 also.

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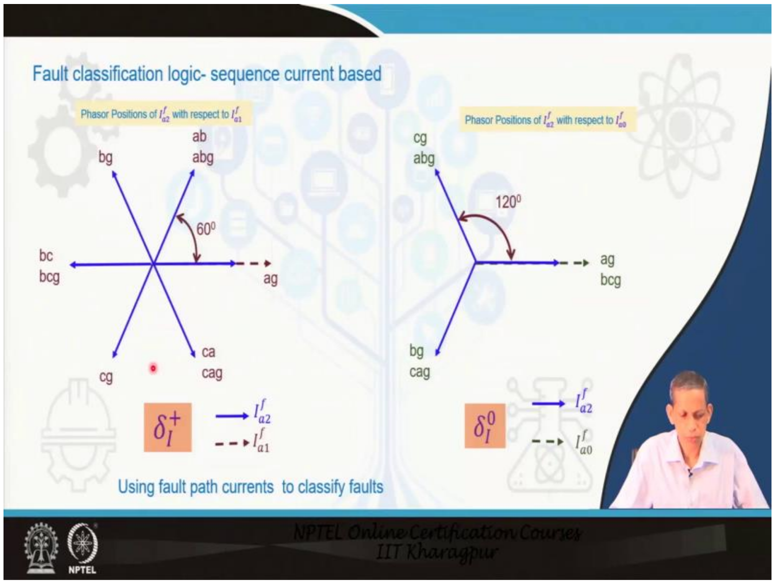

Fault classification logic- sequence current based

Using fault path currents to classify faults

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We can summarize all the 10 classes of faults into the in phasor diagram notions in terms of these corresponding δ_I^+ and δ_I^0. Now let us see first the δ_I^+. So, what we did here is that we took the reference of as I_{a1}^f, the faulted path positive sequence current in phase a for all types of fault as you have seen earlier, and then you can see that these corresponding angles are, they occupy different positions, 60^0, same angle, 180^0, 120^0, and so for the perspective.

So, we say that ab and abg here; bg here; bc bcg here; cg here; ca, cag here. So, we see that that if the corresponding cg, ag, and bg; they can be clearly classified only by using this perspective. Now, we see here that this, when the corresponding δ_I^+ takes a position of this, so ab and abg both classes fall in the same line. So, that means that we have to, we need to consider another distinctive feature. So for that, this δ_I^0 becomes useful.

So you can see that we have reference of I_{a0} and with respect to that the position of I_{a2} is being shown here. So for, you can see that different faults, you can see that the corresponding I_{a2} takes different position. Like here, ag fault, and bcg fault in this line, cg, and abg, and bg and cag. So now, using these two features, we can easily classify that which type of fault the particular situation, relay is observing. So, however, you notice here that the currents which you are using, are the faulted path currents in that situation, in that situation for the transmission line fault.

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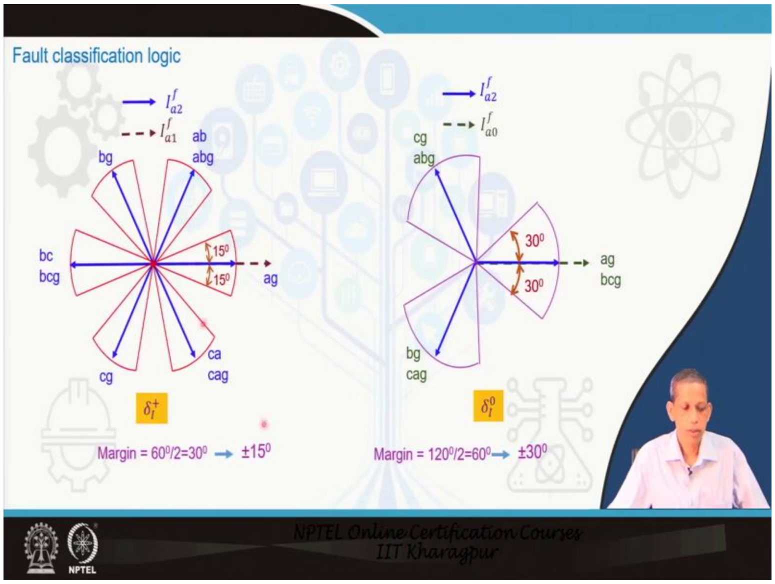

Fault classification logic

Margin = $60^0/2=30^0$ → $\pm 15^0$

Margin = $120^0/2=60^0$ → $\pm 30^0$

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Now, we observed that between these two phasors for this classification objective, we have in the δ_I^+ , 60-degree difference, 60 degrees, 60 degree each we are finding difference, so we can keep a good margin for uncertainties in the measurement process, uncertainties in our consideration of the assumption of different impedance angle and so, and also we can say that in terms of this R_f in the faulted path also so.

And then we can keep a good margin of 15^0 this side and that side. For each, you can say that reference phasor around that, or each phasor which we are plotting, the phasor we are showing in this plot. So, therefore, what is being done? With a 15^0 both the ways, we keep some margin of 30^0. Still, you can see that we have a gap of 30^0 in between. And that you can see, leaves us better options to avoid all uncertainties in the system.

However, in case of δ_I^0 , we have wanted to 120^0 separations. So we can keep, you can see there is 30^0 this side, 30^0 this side also for better judgment on fault classification.

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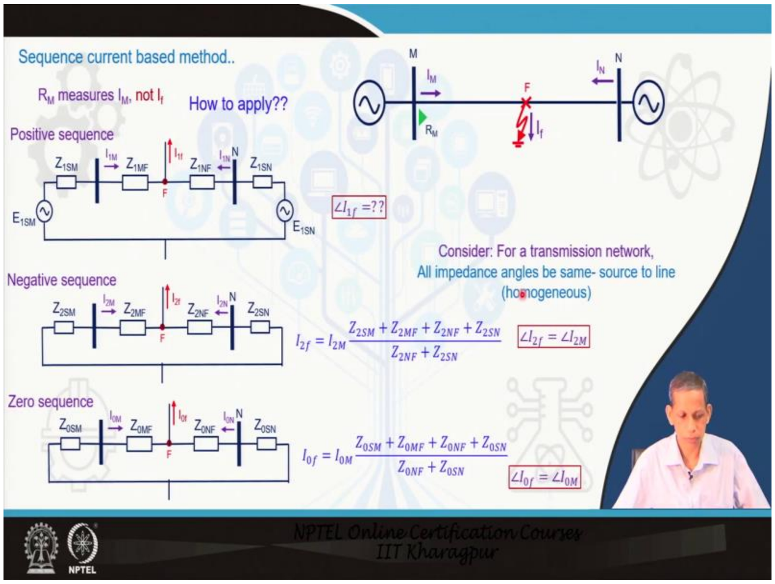

Sequence current based method..

R_M measures I_M, not I_f

How to apply??

Positive sequence

$\boxed{\angle I_{1f} = ??}$

Negative sequence

$$I_{2f} = I_{2M}\frac{Z_{2SM}+Z_{2MF}+Z_{2NF}+Z_{2SN}}{Z_{2NF}+Z_{2SN}}$$

$\boxed{\angle I_{2f} = \angle I_{2M}}$

Zero sequence

$$I_{0f} = I_{0M}\frac{Z_{0SM}+Z_{0MF}+Z_{0NF}+Z_{0SN}}{Z_{0NF}+Z_{0SN}}$$

$\boxed{\angle I_{0f} = \angle I_{0M}}$

Consider: For a transmission network,
All impedance angles be same- source to line
(homogeneous)

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Now, how this sequence current based can be applied for a fault classification aspect we will see, and then we will apply with fault data for this fault classification objective. Now, this is the system for which we are talking about the relay is here and the relay makes the use of the information available locally. So, the corresponding current contributed with this side of source is I_M for this fault I_f and this side source is I_N.

Note that in our earlier analysis, we analyzed the fault classification using the faulted path current, not the current measured by the relay. The relay does not have any options to get the corresponding I_f, so it has to use the corresponding I_M to make a conclusion on the type of fault. So, therefore, we have to relate these I_f with the I_M and how that relations are achieved we will try to figure it out. Now, before we can apply the fault classification techniques using the I_f and its associated sequence component of current.

So now, let us see, you can see that again visit the positive sequence diagram, positive sequence network of this circuit, negative sequence network, and the 0 sequence network. Now, let us come to first the negative sequence network. So, this is a passive network, no sources. So, this I_{2f} and we will like to make the relations between I_{2M}, the I_{2M} is the corresponding current seen by the relay, and I_{2f}, the faulted path current.

So this I_{2f}, if you see this is a combination of these side current and this side current. So, $I_{2f} = I_{2M} \frac{Z_{2sM} + Z_{2MF} + Z_{2NF} + Z_{2sN}}{Z_{2NF} + Z_{2sN}}$, in terms of I_{2M}, all the impedances in this path, summation of that divided by this impedance of the right side. We are talking about this side current, relay current I_{2M} and so, therefore, you can see that there is a parallel path. So we are talking about in terms of (Z_{2NF} + Z_{2SN}), this side summation of impedances. So, this leads to you can say that a conclusion that already we have seen in an earlier discussion, that fault classification can be achieved using the fault current angles, different sequence components' angles.

So, if you see these relations I_{2f} and I_{2M} has the relations using these sequence impedances for the negative sequence current. So, the negative sequence current has the relations in terms of this impedance. Now, if you considered all the impedances having same angle, the source impedances, and the line impedances having same angle close to each other, that is called homogeneity of the impedances, homogeneous impedances. So, from that perspective, if the all the angles of these are same angles, so the angles cancels out, so $\angle I_{2f} = \angle I_{2M}$. So, this is for the negative sequence network.

So, now we can relate the corresponding angle of this negative sequence current available to this relay with the faulted path current that is what the conclusion here, $\angle I_{2f}$, that is faulted path current, negative sequence path becomes equals to $\angle I_{2M}$, the negative sequence current as seen by the relay at that time. Now come to the 0 sequence, which is similar to this one. And therefore, the relation also becomes similar in terms of I_{0f} expressed in terms of I_{0M} and then you can see that the impedances in the parallel path.

So, if you consider again these impedances having same angle for each, then you can say that we can conclude that $\angle I_{0f} = \angle I_{0M}$, similar to the negative sequence part. So, what we will say here, that the faulted path current, 0 sequence component having an angle same as that of the angle seen by the relay at that time for the 0 sequence component. Now come to the positive sequence part. Positive sequence part we have sources at both the sides. So now, the corresponding positive sequence current seen by the relay is I_{1M} and the positive sequence current which will be flowing through this faulted path is I_{1f}.

Note that these two currents are different and this I_{1M} is also having you can say that another component of current which is flowing to this side, and that is nothing but the load component of current. So, I_{1M} at this point as seen by the relay is having two components, the fault component of currents flowing from this site and also a load component of current flowing from this side of the network to this side of the network.

So, our purpose is that to figure out you can say that the $\angle I_{1f}$ and the corresponding $\angle I_{1M}$. But we know that the corresponding pre-fault current and the fault current component of current, they are the similar things, so the corresponding angles are different. So, therefore, you can see that we need a mechanism to find out how we can find out the I_{1f} at this point.

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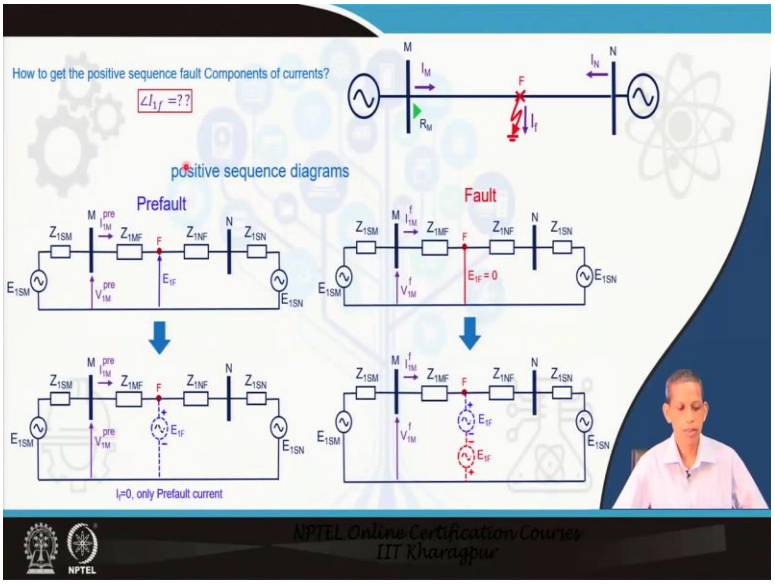

How to get the positive sequence fault Components of currents?

$\angle I_{1f} = ??$

positive sequence diagrams

Prefault

Fault

$I_f=0$, only Prefault current

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For for that, we need some analysis, let us see how can proceed. Now, this we are only using for this I_{1f}, so we are only using positive sequence networks pre-fault. So this pre-fault before the fault, we have this network, positive sequence network for this system. This is the fault point, so pre-fault voltage is E_{1F} that you can find out depending upon the pre-fault loading condition.

Now for this diagram, we can say that if you put, you can see that E_{1F} here a source then what will happen? Now, in this path even if we connect this source in this path, the current will be 0, that is if you create a fault part also with this source connecting same voltage at what we obtained here, then the fault current will 0. So then, even if it becomes say, faulted path is connected by this, the current flowing through this path will we only be this pre-fault current. So, that is what we are trying to figure out you can see that from this system network to this one.

Now come to the fault situation we have a short-circuit here, so you $E_{1F} = 0$. If I go to this diagram, if you see here, so what we have done? This E_{1F}, pre-fault voltage of this point we connect them, you can see that two same sources in anti-phase. So, this voltage and this voltage, total voltage is 0, you see this connection, as per the connection, polarity connection and because you can say that they do not contribute to the voltage, this one. So, this network is equivalent to this network, this network is equivalent to this network.

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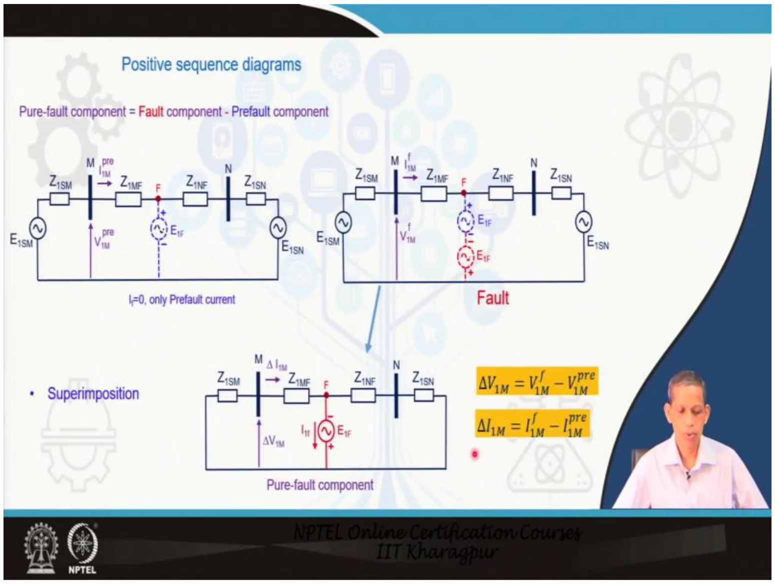

Positive sequence diagrams

Pure-fault component = Fault component - Prefault component

I_f=0, only Prefault current

Fault

- Superimposition

Pure-fault component

$$\Delta V_{1M} = V_{1M}^{f} - V_{1M}^{pre}$$

$$\Delta I_{1M} = I_{1M}^{f} - I_{1M}^{pre}$$

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Now come to next analysis. Now if you see here, in earlier case from the pre-fault network, we have this diagram. If in this diagram, we could say that $I_f = 0$, even if you connect this path current is 0, only the pre-fault current path, pre-fault current flows in the network, i.e. the load current flows. In the second diagram, we saw from the fault path equivalent diagram that if you connect, you can see that it shows two sources in anti-phase then the corresponding voltage becomes 0. So, this is the fault.

Now, we will have a third diagram. If we see here, what we did that because this part you can see that these three sources constitute gives us a faulted $I_f = 0$. So if you can see, in part 1, 2, and 3 this part; so that you can see that it gives you current to be 0, fault current. Only this part gives you the fault current which we bother about that I_f. So now here, you can see that we have this source now.

So, this diagram is called the pure-fault component. This diagram refers to fault where we have pre-fault current also and also fault current. So, this is the situation which the relay will observe during the fault. So, the relay will measure I_{1M}^{f} in the positive sequence network at that time and the corresponding V_{1M}^{f}. So, this is what the relay will observe during the fault situation. But our concern is as per the fault classification requirement, we require pure-fault component only you can see that contribution of the faulted path.

So, what we see that these fault, during fault which includes both pre-fault current and fault current as observed by the relay is a superposition of the fault component and the pre-fault component and that is what we see here that the pure fault component, this one is having fault component of current from this network minus the pre-fault component, minus the pre-fault component. So, we see that this is combination of this plus this.

So from that, we say that the corresponding ΔV_{1M} for this network is nothing but ($\Delta V_{1M} = \Delta V_{1M}^{f} - \Delta V_{1M}^{pre}$) ΔV_{1M} is V_{1M}^{f} during fault minus the V_{1M}^{pre}. Similarly, current; ΔI_{1M}, current contributed by the left-hand side source which is passing through the relay during the fault I_{1f} current is nothing but I_{1M}^{f}, the fault (comp) the fault current which is measured by the relay minus the pre-fault current which is measured by the relay $\Delta I_{1M} = I_{1M}^{f} - I_{1M}^{pre}$. So, these pure-fault component gives us the I_{1f} which we are going to use for the fault classification objective.

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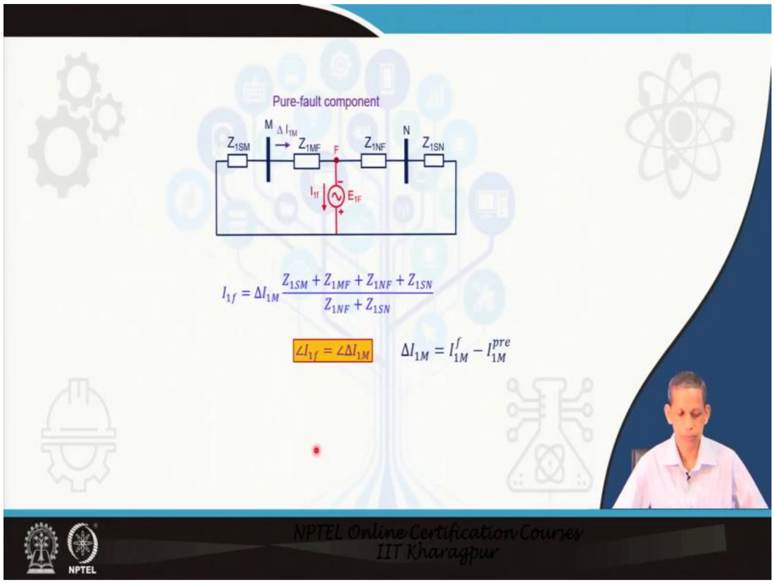

Pure-fault component

$$I_{1f} = \Delta I_{1M} \frac{Z_{1SM} + Z_{1MF} + Z_{1NF} + Z_{1SN}}{Z_{1NF} + Z_{1SN}}$$

$$\boxed{\angle I_{1f} = \angle \Delta I_{1M}} \qquad \Delta I_{1M} = I_{1M}^{f} - I_{1M}^{pre}$$

So therefore, from the above analysis, we see that we require this diagram, which is a pure-fault component and in this diagram, we have this I_{1f} and we have considered if you have this source connected in this manner and E_{1F} is the pre-fault voltage at this point. So, this corresponding I_{1f}, now if we analyze that, because we have to analyze this I_{1f} in terms of this relay current at that time, ΔI_{1M}, where $\Delta I_{1M} = I_{1M}^{f} - I_{1M}^{pre}$, ΔI_{1M} you can see that we have is computed in terms of $I_{1M}^{f} - I_{1M}^{pre}$.

Now, if you see this diagram, positive sequence diagram, the fault, pure fault component diagram, $I_{1f} = \Delta I_{1M} \dfrac{Z_{1sM} + Z_{1MF} + Z_{1NF} + Z_{1sN}}{Z_{1NF} + Z_{1sN}}$. ΔI_{1M} into the sum of these all the impedances divided by the right-hand side impedance. If you consider all the impedances having the same angle as you have already done for the negative sequence and 0 sequence, then you say that the angle of $\angle I_{1f} = \angle \Delta I_{1M}$.

Once again, ΔI_{1M} is the pure fault component of current seen by the relay and that equals to the fault component of current seen by the relay minus pre-fault current seen by the relay, $\Delta I_{1M} = I_{1M}^{f} - I_{1M}^{pre}$. So thus, we got the angle for negative sequence current through the faulted path, the angle for the 0 sequence current for the faulted path, and from this relation, we got the angle for the positive sequence current through the faulted path.

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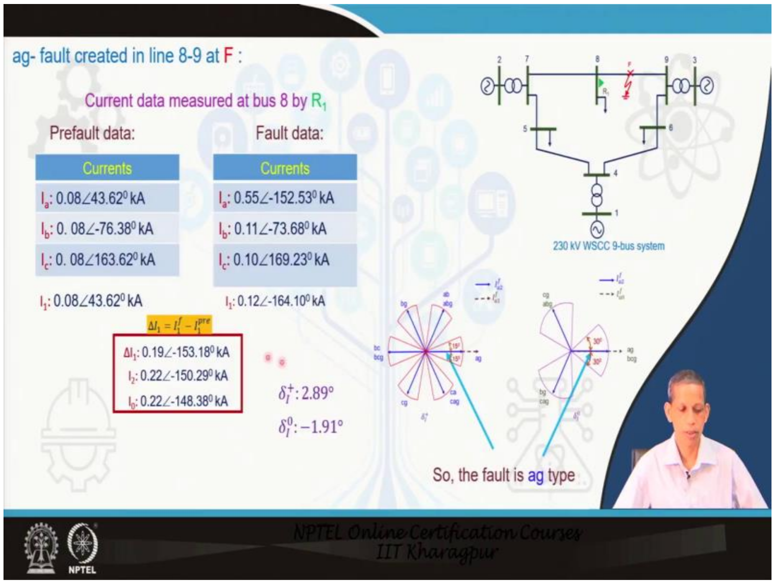

ag- fault created in line 8-9 at F :

Current data measured at bus 8 by R_1

Prefault data:

Currents
I_a: 0.08∠43.62⁰ kA
I_b: 0. 08∠-76.38⁰ kA
I_c: 0. 08∠163.62⁰ kA

I_1: 0.08∠43.62⁰ kA

Fault data:

Currents
I_a: 0.55∠-152.53⁰ kA
I_b: 0.11∠-73.68⁰ kA
I_c: 0.10∠169.23⁰ kA

I_1: 0.12∠-164.10⁰ kA

$\Delta I_1 = I_1^f - I_1^{pre}$

ΔI_1: 0.19∠-153.18⁰ kA
I_2: 0.22∠-150.29⁰ kA
I_0: 0.22∠-148.38⁰ kA

$\delta_I^{+}: 2.89°$
$\delta_I^{0}: -1.91°$

So, the fault is ag type

Now, therefore, only from the measurements of the, at the relay bus, we can conclude the fault type where the fault type is based on this kind of diagram where it uses the faulted path current. So we say now, let us, you can say that this 230 kV 9-bus system which we have already addressed in earlier lectures also. So, relay at bus 8 is our concern, so for a fault at F in this 8 and 9 connecting line different types of faults can happen.

So, for that how the relay at R_1 can compute the different phasors and from there the sequence current, and from the sequence current how can we get the corresponding type of fault we will see. So, we have current data measured at bus R_1, so the fault type simulated is phase a to ground fault. So, the relay records pre-fault data, current data, Ia, Ib, Ic, balance current kind of thing, and then the fault data for this ag fault created in this system and the simulated data. And from there the phasors are computed.

We found the corresponding positive sequence current pre-fault balance current and we found the corresponding ag fault, the corresponding positive sequence current for this case. We know that we require ΔI_1 for the positive sequence network fault component current. So, $\Delta I_1 = I_1^f - I_1^{pre}$. I_1^f is this one, fault from the fault data, I_1^{pre} is from this side, this pre-fault data. So, this minus this gives you ΔI_1. So, ΔI_1 obtained is $0.19\angle -153.18^0$ kilo ampere.

I_2 from this data, straightforward, through fault path is $0.22 \angle -150.29^0$ kilo ampere. And I_0 from (Ia + Ib + Ic)/3 gives us $0.22\angle -148.3^0$ kilo ampere. So now, we got all the Ia, ΔI_1, I_2, and I_0. These corresponding angles of these are same for our corresponding I_{f1}, I_{f2}, and I_{f0} for the phase a component of current. So, therefore, we can compute the δ_I^+ and δ_I^0. δ_I^+, you can say that it is nothing but $\delta_I^+ = \angle I_{a2}^f - \angle I_{a1}^f$, and $\delta_I^0 = \angle I_{a2}^f - \angle I_{a0}^f$.

So after doing this, we get the corresponding angles from these 3 angles. We get the corresponding $\delta_I^+ = 2.89^0$, this angle minus this angle. So, then you can see that we get the δ_I^0 to be this angle with subtracting this this angle minus this angle, so we got to $\delta_I^0 = \angle I_{a2}^f - \angle I_{a0}^f = -1.91^0$. So, these small angles of δ_I^+ and δ_I^0, so we refer to the corresponding diagrams which I have already shown earlier.

So in this diagram, if we see 2.89^0, so 2.89^0 with respect to this reference, it is a small value. So, with respect to this so it falls in 2.89 positive side here. So in this region, it falls. So, this tells us about ag fault. δ_I^0, you can see that it is very small, -1.9^0; this also here in this you can see that diagram, phasor diagram on this point. So, that also says about ag or bcg, this side ag, this ag, so this confirms that this is ag fault.

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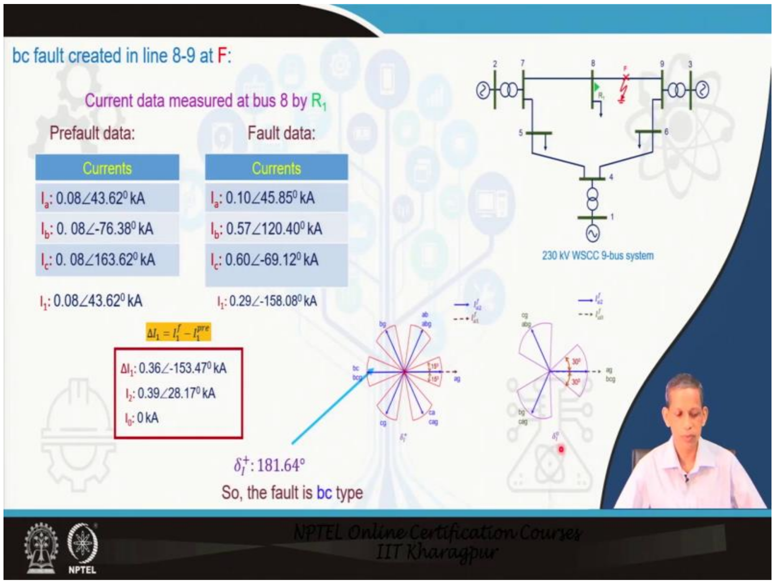

bc fault created in line 8-9 at F:

Current data measured at bus 8 by R_1

Prefault data:

Currents
I_a: 0.08∠43.62⁰ kA
I_b: 0. 08∠-76.38⁰ kA
I_c: 0. 08∠163.62⁰ kA

I_1: 0.08∠43.62⁰ kA

Fault data:

Currents
I_a: 0.10∠45.85⁰ kA
I_b: 0.57∠120.40⁰ kA
I_c: 0.60∠-69.12⁰ kA

I_1: 0.29∠-158.08⁰ kA

$\Delta I_1 = I_1^f - I_1^{pre}$

ΔI_1: 0.36∠-153.47⁰ kA
I_2: 0.39∠28.17⁰ kA
I_0: 0 kA

δ_I^+: 181.64°

So, the fault is bc type

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Now I will go to another fault created in the same point, bc fault, phase-to-phase fault. Pre-fault current measurements, fault current measurements, I_1, I_1 during fault. You see here, now bc fault so these currents are pretty high as compared to the a phase fault. $\Delta I_1 = I_1^f - I_1^{pre}$, so ΔI_1 we got. We bother only about only angle. I_2 from this side, I_2 =0.39; I_0=0; this is bc fault confirm.

Now, similarly, you can say that from these two things, this angle minus this angle gives us δ_I^+ $=181.64^0$, so this is in this range. So, this tells about bc and bcg fault, but know you can see that there is no 0 sequence current so this one is bc type. So, you cannot use this because there is no zero sequence current. So, this ensures, this is bc type fault and that is what we have simulated and that confirms that the method is able to classify the fault properly.

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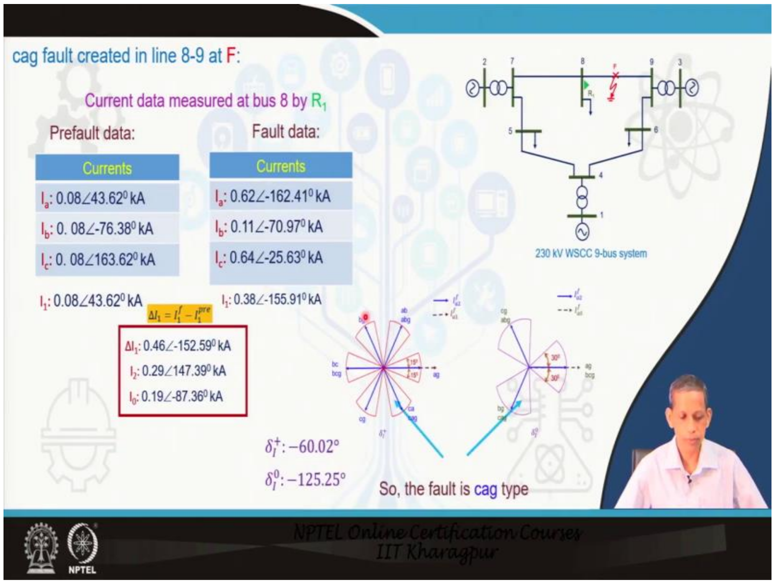

cag fault created in line 8-9 at F:

Current data measured at bus 8 by R_1

Prefault data: Currents	Fault data: Currents
I_a: 0.08∠43.62^0 kA	I_a: 0.62∠-162.41^0 kA
I_b: 0. 08∠-76.38^0 kA	I_b: 0.11∠-70.97^0 kA
I_c: 0. 08∠163.62^0 kA	I_c: 0.64∠-25.63^0 kA

I_1: 0.08∠43.62^0 kA

I_1: 0.38∠-155.91^0 kA

$\Delta I_1 = I_1^f - I_1^{pre}$

ΔI_1: 0.46∠-152.59^0 kA
I_2: 0.29∠147.39^0 kA
I_0: 0.19∠-87.36^0 kA

$\delta_I^+: -60.02°$

$\delta_I^0: -125.25°$

So, the fault is cag type

Third category of of fault is cag fault which created here and we have the datasets for that; pre-fault and the fault. So, you have computed I_1 and I_1^f and I_1^{pre}. So, I_1^f - I_1^{pre} , ΔI_1 and similarly 0 sequence and negative sequence from the side, fault component of currents and then you got these 3 angles, computed the δ_I^+ and δ_I^0 , this is cag fault so we are having some 0 sequence current so we can compute this part also.

Now, -60^0 from here -60^0 this side, so this falls on this side. So, either it can be ca or cag. And δ_I^0 , this side you can see the -125^0, so this falls on this. So, this you can see that bg or cag, but the common between these two sets you can see that it is cag. So, therefore, the fault type is cag, that is what is being confirmed.

So, we conclude that we have created cag fault and data generated fault data and pre-fault data and then identify the corresponding cag correctly. So, what we have used? We have used the corresponding measured current by the relay and based on that, we used the corresponding phasor plots and for δ_I^+ and δ_I^0 and successfully achieved the correct classification of fault type.

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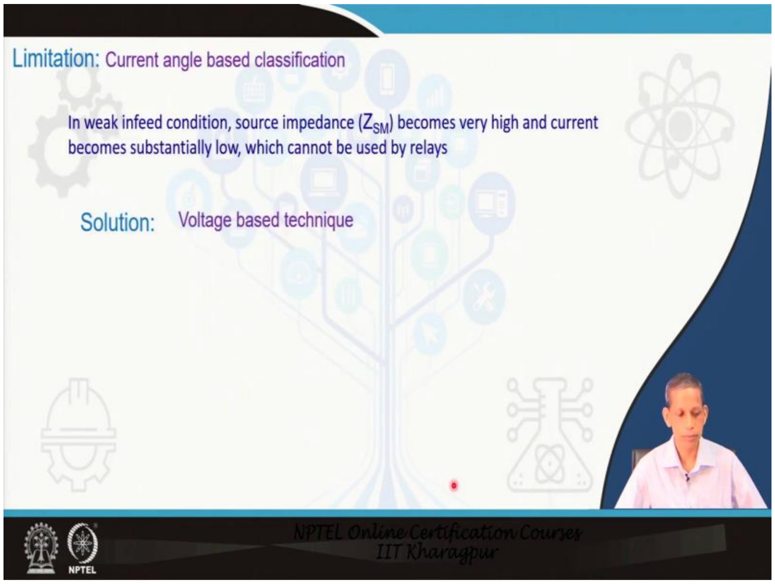

Limitation: Current angle based classification

In weak infeed condition, source impedance (Z_{SM}) becomes very high and current becomes substantially low, which cannot be used by relays

Solution: Voltage based technique

But there are limitations to this current based classifications. In case of weak infeed, when the source impedance becomes very high the current magnitude become substantially low and that leads to, the phasors computed by the relay not reliable, and therefore, we may not able to use the corresponding angle correspondingly. Then what is the solution? The solution is can we use the voltage information? Yes.

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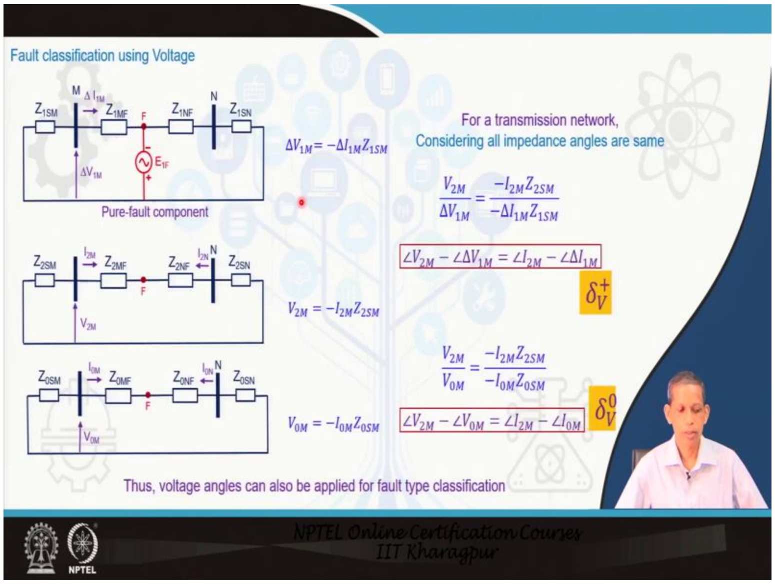

Fault classification using Voltage

Pure-fault component

$\Delta V_{1M} = -\Delta I_{1M} Z_{1SM}$

$V_{2M} = -I_{2M} Z_{2SM}$

$V_{0M} = -I_{0M} Z_{0SM}$

For a transmission network,
Considering all impedance angles are same

$$\frac{V_{2M}}{\Delta V_{1M}} = \frac{-I_{2M} Z_{2SM}}{-\Delta I_{1M} Z_{1SM}}$$

$$\boxed{\angle V_{2M} - \angle \Delta V_{1M} = \angle I_{2M} - \angle \Delta I_{1M}} \quad \delta_V^{+}$$

$$\frac{V_{2M}}{V_{0M}} = \frac{-I_{2M} Z_{2SM}}{-I_{0M} Z_{0SM}}$$

$$\boxed{\angle V_{2M} - \angle V_{0M} = \angle I_{2M} - \angle I_{0M}} \quad \delta_V^{0}$$

Thus, voltage angles can also be applied for fault type classification

Now we will see, you can see that how the voltage information becomes useful at that situation, we will see. This diagram, positive sequence diagram in the superimposition perspective we have seen. So, this is the pure fault component diagram. If you see this diagram, the ΔV_{1M} =-ΔI_{1M} .Z_{1Sm}. ΔV_{1M} =-ΔI_{1M} .Z_{1Sm}. In the negative sequence diagram, V_{2M} = - I_{2M} .Z_{2SM}, and similarly, in this 0 sequence diagram, V_{0M} = - I_{0M} .Z_{0SM}.

For a transmission network considering all impedance has angule same sources and these that we have already assumed earlier also. So from this relations, you can see there, $\frac{V_{2M}}{\Delta V_{1M}} = \frac{-I_{2M} Z_{2SM}}{-\Delta I_{1M} Z_{1SM}}$. So from this relations, these two angles are same, so, therefore, $\angle V_{2M} - \angle \Delta V_{1M} = \angle I_{2M} - \angle \Delta I_{1M}$ the way we did earlier.

So, these voltage angles at this situation relates to the $\angle I_{2M}$ - $\angle \Delta I_{1M}$. Note this is what same thing we got for this current-based approach that the corresponding angle for angle of negative sequence current with respect to the positive sequence current. So, therefore, we designate this to be a δ_v^+ similar to the current-based approach.

Similarly, V_{2M}/ V_{0M}, so this we can correlate and then we find the $\angle I_{2M}$ - $\angle I_{0M}$. In a similar way we designate this as δ_v^0. Thus, the voltage angles can also be applied for fault classifications similar to the angles, current based angles.

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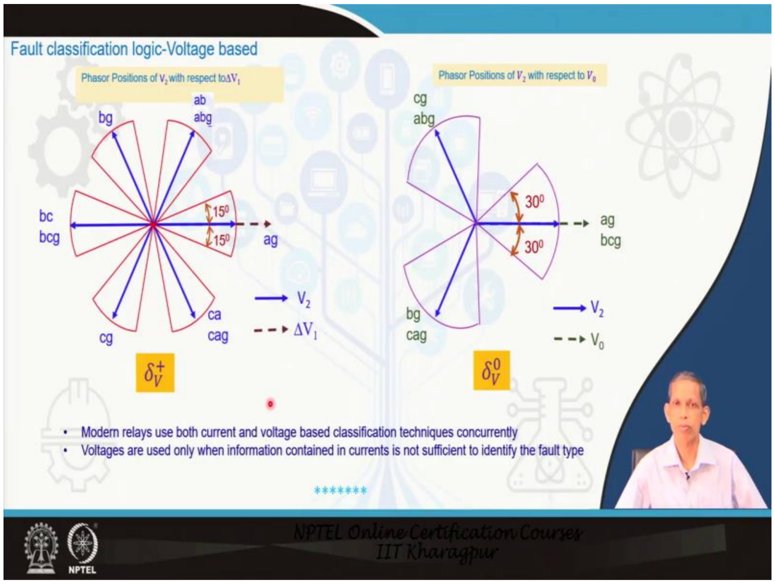

Fault classification logic-Voltage based

Phasor Positions of V_2 with respect to ΔV_1

Phasor Positions of V_2 with respect to V_0

- Modern relays use both current and voltage based classification techniques concurrently
- Voltages are used only when information contained in currents is not sufficient to identify the fault type

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So, therefore, what we see that the voltage-based angles what we have seen in the current based angle. So here, we are talking about a ΔV_1 as the reference and V_2 as the different positions it obtains. And we call different corresponding types of fault in terms of that. And then you can see that ΔV_0 also we put like this and then, you can see that similar to the current based phasors, we plotted this.

And this, if we can use in case of the infeed problem, when current becomes smaller, as seen by the relays, then we can use the voltage based approach successfully for that perspective. So, what the modern relays use, that the modern relays avail both voltage and current information and it uses the current for fault type classification. In case the current is not, strength is low, then they relay can use successfully the voltage information.

So, the fault classifications can be achieved using the sequence component of currents in case they are small values, not acceptable, then the corresponding sequence component of voltages are being used. Thank you.