Power System Protection
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Lecture 50
Fault Location Using Travelling Wave

Welcome to the NPTEL course on Power System Protection. We are continuing with Traveling Wave-based Protection Schemes. In this lecture, we will discuss on fault location using traveling wave.

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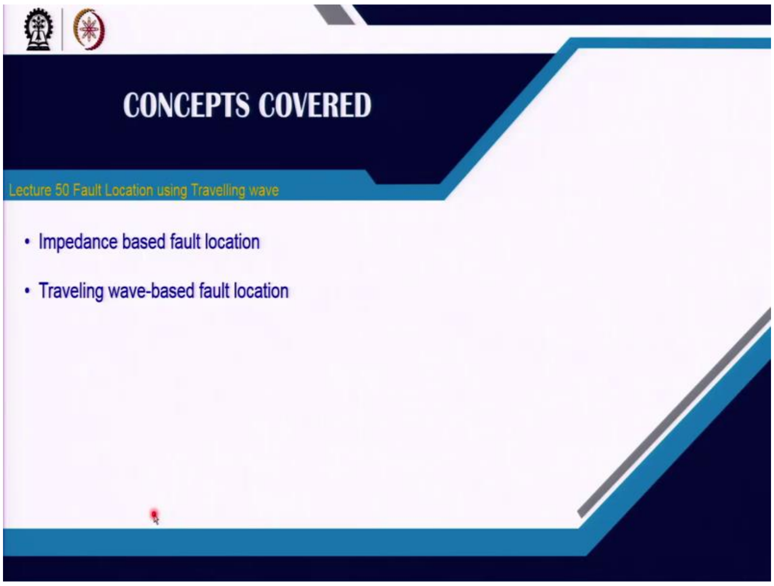

CONCEPTS COVERED

Lecture 50 Fault Location using Travelling wave

- Impedance based fault location
- Traveling wave-based fault location

How traveling wave can be used for locating faults for maintenance purpose. This is an offline task and on this perspective, we will see the traditional impedance-based approach using phasor concepts and then the traveling wave based fault location schemes.

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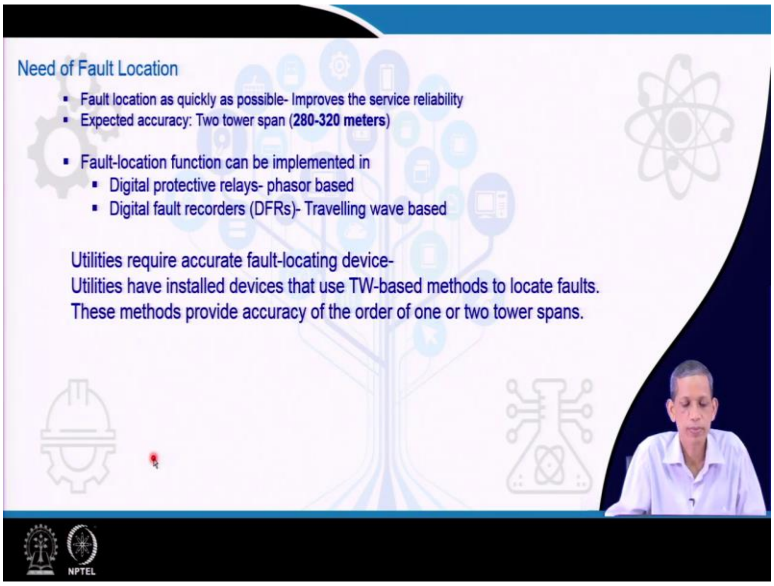

Need of Fault Location

- Fault location as quickly as possible- Improves the service reliability
- Expected accuracy: Two tower span (**280-320 meters**)
- Fault-location function can be implemented in
  - Digital protective relays- phasor based
  - Digital fault recorders (DFRs)- Travelling wave based

Utilities require accurate fault-locating device-
Utilities have installed devices that use TW-based methods to locate faults.
These methods provide accuracy of the order of one or two tower spans.

Utilities required quick assessment on the fault position of a transmission line, it has reliability issue, the sooner the line is restored, better we can manage the system. A line may be dealing with thousands of MW, so deficiency in one area may create problem. It has associated revenue loss and also service to the loads and customers.

Many relays at high voltage level do possess such functions for locating fault, which is very useful to the utilities. The expected accuracy today is on 2 tower span, typically around 300 meters or so to make a quick identification of the faulted point. And thereby, the maintenance can be done as early as possible. As per available fault location function, it is available with digital numerical phasor based relays, also, there are digital fault recorders dedicated for recording the events known as event recorder. Today they have the capability of traveling wave based approach. Many utilities have already installed traveling wave based methods for accurate fault location. This traveling based approach devices provide accuracy of the order of 2 tower spans that is the significant advantage in this approach.

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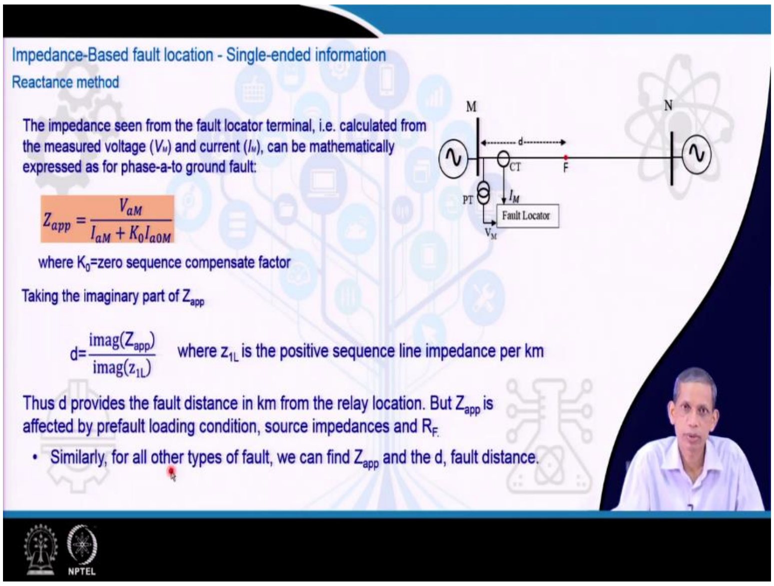

Impedance-Based fault location - Single-ended information

Reactance method

The impedance seen from the fault locator terminal, i.e. calculated from the measured voltage (V_M) and current (I_M), can be mathematically expressed as for phase-a-to ground fault:

$$Z_{app} = \frac{V_{aM}}{I_{aM} + K_0 I_{a0M}}$$

where K_0=zero sequence compensate factor

Taking the imaginary part of Z_{app}

$$d = \frac{\text{imag}(Z_{app})}{\text{imag}(z_{1L})}$$ where z_{1L} is the positive sequence line impedance per km

Thus d provides the fault distance in km from the relay location. But Z_{app} is affected by prefault loading condition, source impedances and R_F.

- Similarly, for all other types of fault, we can find Z_{app} and the d, fault distance.

Now, let us come to the methods, which are pretty old and available to this impedance based approach, which uses the phasors as the conventional relay uses the concept like distance relay. Some of the methods available are being used in the distance relay and so.

First method, Reactance method, pretty simple. So, the relay uses the local voltage current, calculates the impedance as we learn in the distance relay. It computes the apparent impedance, let us say, for the phase *a* to ground fault, the positive sequence impedance is computed using the corresponding phase *a* voltage and the phase *a* current, zero sequence current and the zero sequence compensation factor represented by

$$Z_{app} = \frac{V_{aM}}{I_{aM} + K_0 I_{a0M}}$$

So, taking the imaginary part of this $Z_{app} = R + jX$. So, that gives us the reactance part. And then, if you divide this obtained reactance by the imaginary part of the positive impedance or the positive sequence reactance per km, the line has, then we get the distance of the fault from the relay location, from the measurement point. So

$$d = \frac{\text{imag}(Z_{app})}{\text{imag}(z_{1L})}$$

So, this d is indicative of this fault location but as you have seen that the distance relay performance is affected by pre-fault loading condition, source impedance, fault resistance, so this approach is affected in that way. However, it has certain limitation in terms of that. For other faults, like we compute the Z_{app}, Z_{app} represents for the positive sequence impedance of the fault. So, we can use this similar relation after obtaining the Z_{app}, and then we can obtain the distance of the fault.

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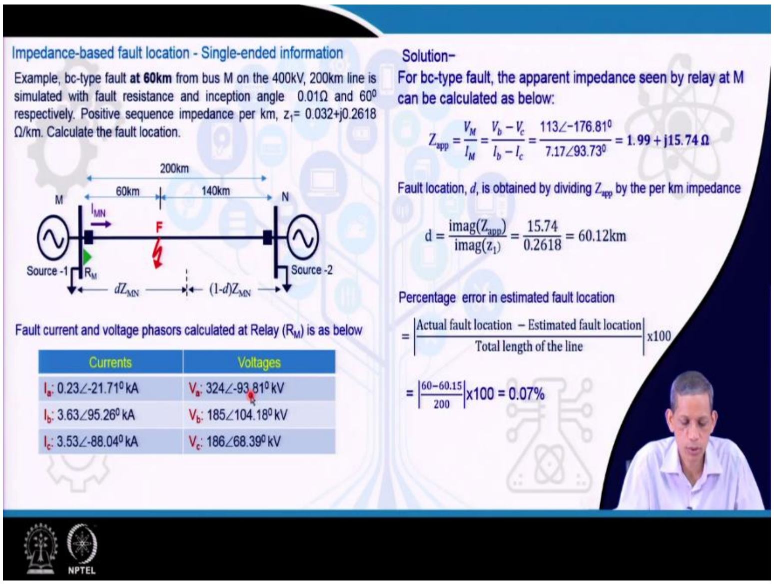

Impedance-based fault location - Single-ended information

Example, bc-type fault **at 60km** from bus M on the 400kV, 200km line is simulated with fault resistance and inception angle 0.01Ω and 60^0 respectively. Positive sequence impedance per km, z_1= 0.032+j0.2618 Ω/km. Calculate the fault location.

Fault current and voltage phasors calculated at Relay (R_M) is as below

Currents	Voltages
I_a: $0.23\angle{-21.71^0}$ kA	V_a: $324\angle{-93.81^0}$ kV
I_b: $3.63\angle{95.26^0}$ kA	V_b: $185\angle{104.18^0}$ kV
I_c: $3.53\angle{-88.04^0}$ kA	V_c: $186\angle{68.39^0}$ kV

Solution-

For bc-type fault, the apparent impedance seen by relay at M can be calculated as below:

$$Z_{app}=\frac{V_M}{I_M}=\frac{V_b-V_c}{I_b-I_c}=\frac{113\angle{-176.81^0}}{7.17\angle{93.73^0}}=1.99+j15.74\,\Omega$$

Fault location, *d*, is obtained by dividing Z_{app} by the per km impedance

$$d=\frac{\text{imag}(Z_{app})}{\text{imag}(z_1)}=\frac{15.74}{0.2618}=60.12\text{km}$$

Percentage error in estimated fault location

$$=\left|\frac{\text{Actual fault location }-\text{ Estimated fault location}}{\text{Total length of the line}}\right|\text{x}100$$

$$=\left|\frac{60-60.15}{200}\right|\text{x}100=0.07\%$$

Let us have an example, how this method can be applied in a system. So, this is a *bc*-type fault at 60 km from MN being simulated, 400 kV line 200 km length with a condition of fault resistance of 0.01 Ω and 60^0 inception point. Positive sequence impedance per km is z_1= 0.032+j0.2618 Ω/km calculate the fault location.

Solution:

For *bc*-type fault, the apparent impedance seen by relay at M can be calculated as below:

$$Z_{app}=\frac{V_M}{I_M}=\frac{V_b-V_c}{I_b-I_c}=\frac{113\angle 176.81^0}{7.17\angle 93.73^0}=1.99+j15.74\ \Omega$$

Now the fault location *d* obtained by by dividing Im(Z_{app}) by the per km impedance

$$d=\frac{\text{imag}(Z_{app})}{\text{imag}(z_1)}=\frac{15.74}{0.2618}=60.12\text{ km}$$

So, fault was created at 60 km and the d obtained from this is 60.12 km. So the percentage error in estimated fault location is

$$\left|\frac{\text{Actual fault location }-\text{Estimated fault location}}{\text{Total length of the line}}\right|\text{x}100=\left|\frac{60-60.12}{200}\right|\text{x}100=0.06\%$$

So, this shows that the accuracy of this method for this situation with an small R_F condition of this and the corresponding current and voltages, phases are available as shown.

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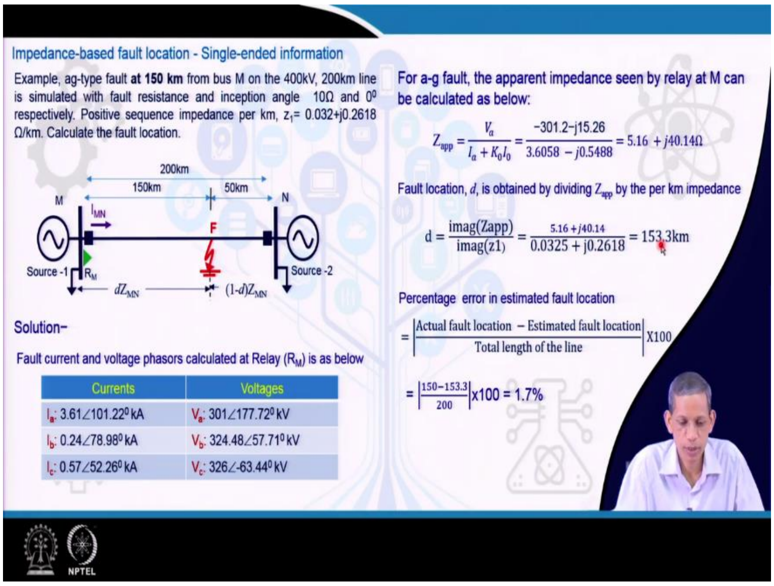

Impedance-based fault location - Single-ended information

Example, ag-type fault **at 150 km** from bus M on the 400kV, 200km line is simulated with fault resistance and inception angle 10Ω and 0^0 respectively. Positive sequence impedance per km, z_1= 0.032+j0.2618 Ω/km. Calculate the fault location.

Solution–

Fault current and voltage phasors calculated at Relay (R_M) is as below

Currents	Voltages
I_a: $3.61\angle101.22^0$ kA	V_a: $301\angle177.72^0$ kV
I_b: $0.24\angle78.98^0$ kA	V_b: $324.48\angle57.71^0$ kV
I_c: $0.57\angle52.26^0$ kA	V_c: $326\angle-63.44^0$ kV

For a-g fault, the apparent impedance seen by relay at M can be calculated as below:

$$Z_{app} = \frac{V_a}{I_a + K_0 I_0} = \frac{-301.2-j15.26}{3.6058 - j0.5488} = 5.16 + j40.14\Omega$$

Fault location, d, is obtained by dividing Z_{app} by the per km impedance

$$d = \frac{\text{imag(Zapp)}}{\text{imag(z1)}} = \frac{5.16 + j40.14}{0.0325 + j0.2618} = 153.3\text{km}$$

Percentage error in estimated fault location

$$= \left|\frac{\text{Actual fault location} - \text{Estimated fault location}}{\text{Total length of the line}}\right| \text{X100}$$

$$= \left|\frac{150-153.3}{200}\right| \text{x100} = 1.7\%$$

Another example on this for the phase-*a* to ground fault at 150 km away from bus M, the phasor data for current and voltage are provided here. Now, for *a*-g fault, the apparent impedance seen by relay at M can be calculated as below

$$Z_{\text{app}} = \frac{V_a}{I_a + K_0 I_0} = \frac{\text{-301.2-j15.26}}{3.6058 - j0.5488} = 5.16 + j40.14\Omega$$

And the fault location, d is obtained by dividing Z_{app} by the per km impedance given as

$$\text{d} = \frac{\text{imag(Zapp)}}{\text{imag(z1)}} = \frac{40.14}{0.2618} = 153.3 \text{ km}$$

Percentage error in estimated fault location becomes

$$\left|\frac{\text{Actual fault location} - \text{Estimated fault location}}{\text{Total length of the line}}\right| \text{x100} = \left|\frac{150-153.3}{200}\right| \text{X100} = 1.7\%$$

So, instead of 150 km, where the fault is created, there is more than 3 km error. So, more than 10 towers behind actually the fault happens. So, this is the level of accuracy we are talking about.

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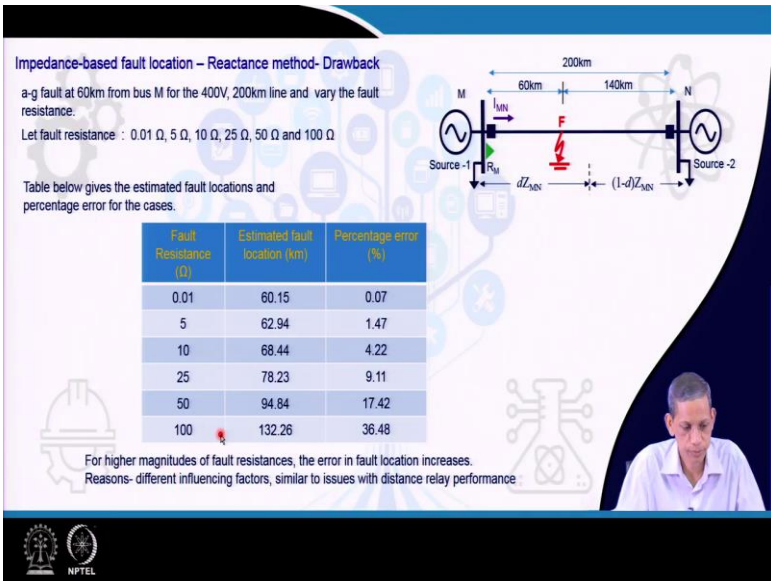

Impedance-based fault location – Reactance method- Drawback

a-g fault at 60km from bus M for the 400V, 200km line and vary the fault resistance.

Let fault resistance : 0.01 Ω, 5 Ω, 10 Ω, 25 Ω, 50 Ω and 100 Ω

Table below gives the estimated fault locations and percentage error for the cases.

Fault Resistance (Ω)	Estimated fault location (km)	Percentage error (%)
0.01	60.15	0.07
5	62.94	1.47
10	68.44	4.22
25	78.23	9.11
50	94.84	17.42
100	132.26	36.48

For higher magnitudes of fault resistances, the error in fault location increases.
Reasons- different influencing factors, similar to issues with distance relay performance

Now, the drawback of this reactance method if we, one perspective one study here. If the fault resistance varies from small value to the high value and for the phase-*a* to ground fault, then you find that the estimated fault location at one position also varies with varying fault resistance. For a fault at 60 km. with fault resistance of 100, the estimated location is 132.26 km, it is having a 36.48 % error. So, this clearly shows that the method is significantly affected by fault resistance, this is one. Also, source impedance and other factors are there, which you have already studied in distance relaying applications to transmission and protection.

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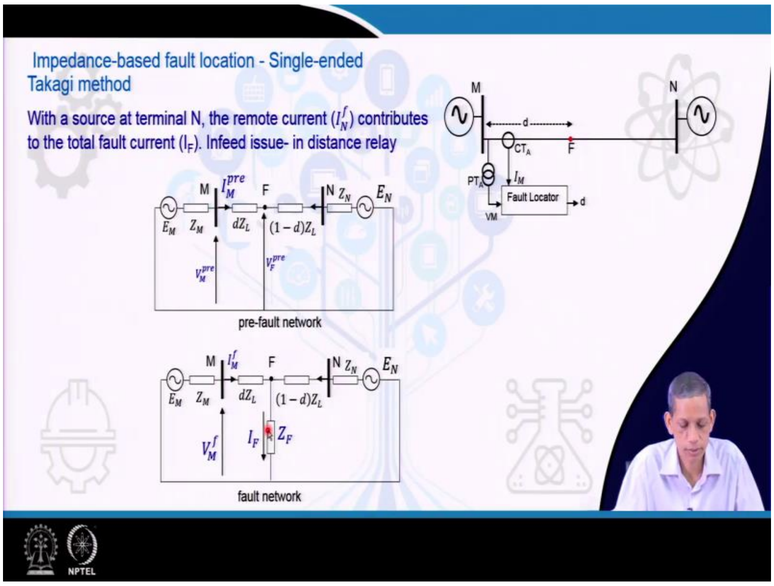

Impedance-based fault location - Single-ended Takagi method

With a source at terminal N, the remote current (I_N^f) contributes to the total fault current (I_F). Infeed issue- in distance relay

Now, the better approach in this case using the phasor concept using one end data this is Takagi method. So, this is the same N bus systems, and then we are considering as the M bus. Then the pre fault positive sequence diagram will be like this. We have learned this in case of distance relay perspective. And the fault network, when it happens to be there, we have seen that the positive sequence network and then the Z_F can be negative sequence and zero sequence combinations. So, that we have seen in the directional relaying perspective also. Equivalent diagram for this system, for any type of fault becomes this.

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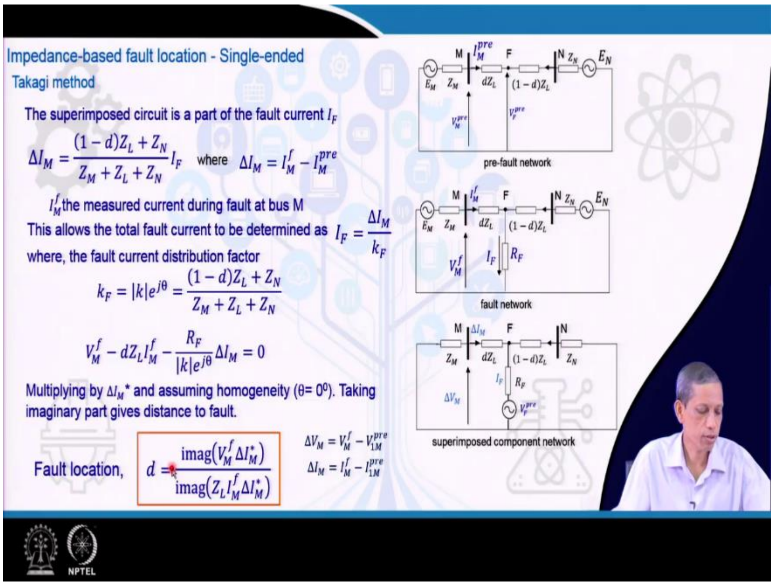

Impedance-based fault location - Single-ended

Takagi method

The superimposed circuit is a part of the fault current I_F

$$\Delta I_M = \frac{(1-d)Z_L + Z_N}{Z_M + Z_L + Z_N} I_F \quad \text{where} \quad \Delta I_M = I_M^f - I_M^{pre}$$

I_M^f the measured current during fault at bus M

This allows the total fault current to be determined as $I_F = \frac{\Delta I_M}{k_F}$

where, the fault current distribution factor

$$k_F = |k|e^{j\theta} = \frac{(1-d)Z_L + Z_N}{Z_M + Z_L + Z_N}$$

$$V_M^f - dZ_L I_M^f - \frac{R_F}{|k|e^{j\theta}} \Delta I_M = 0$$

Multiplying by $\Delta I_M{}^*$ and assuming homogeneity ($\theta = 0^0$). Taking imaginary part gives distance to fault.

Fault location, $\boxed{d = \frac{\text{imag}(V_M^f \Delta I_M^*)}{\text{imag}(Z_L I_M^f \Delta I_M^*)}}$

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

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

Now, what we will see here that how this corresponding Takagi method is formulated. So, we have pre-fault diagram here, fault network here. And then we have the corresponding superimposed component here. So, this superimposed component as you have seen in the fault classification method, so this is about V_F^{pre} voltage at fault point before the fault. And then this drives the corresponding required current in the system. So, we can calculate the ΔV_M and the corresponding ΔI_M at the relay bus using these relations

$$\Delta V_M = V_M^f - V_M^{pre}, \Delta I_M = I_M^f - I_M^{pre}$$

So, this we have learned, how to obtain the corresponding superimposed component in distance relaying for fault classification and also in the directional relaying perspective. Now, see, how the method can be developed using the superimposed component for fault location. Now from this network ΔI_M can be represented as

$$\Delta I_M = \frac{(l-d)z_L + Z_N}{Z_M + Z_L + Z_N} I_F$$

So, what we see here that in this network, the corresponding fault path current is divided into this side and that side. So, this, the corresponding current to the impedance up to M bus divided by the total impedance. Now, this allow the total fault current I_F to be determined by

$$I_F = \frac{\Delta I_M}{k_F}$$

where k_F is given by

$$k_F = |k|e^{j\theta} = \frac{(l-d)z_L + Z_N}{Z_M + Z_L + Z_N}$$

One point here, as we have earlier also discussed, if the system is homogeneous, then $\angle Z_L \approx \angle Z_N$. And in that case, the angle of theta becomes 0. So, with that assumption, if you proceed, then you can simplify the things. Now, let the corresponding equation for this circuit becomes

$$V_M^f - dz_L I_M^f - \frac{R_F}{|k|e^{j\theta}} \Delta I_M = 0$$

Multiplying by ΔI_M* and assuming homogeneity ($\theta = 0^0$). Taking imaginary part distance to fault (d) can be represented as

$$d = \frac{\text{imag}\left(V_M^f \Delta I_M^*\right)}{\text{imag}\left(z_L I_M^f \Delta I_M^*\right)}$$

So, using this one, you can find the distance of fault in apparent or so.

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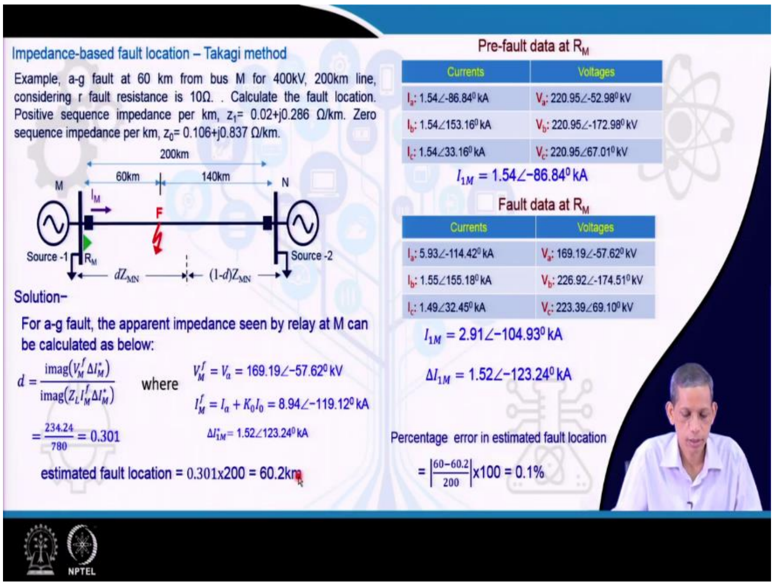

Impedance-based fault location – Takagi method

Example, a-g fault at 60 km from bus M for 400kV, 200km line, considering r fault resistance is 10Ω. . Calculate the fault location. Positive sequence impedance per km, z_1= 0.02+j0.286 Ω/km. Zero sequence impedance per km, z_0= 0.106+j0.837 Ω/km.

Solution–

For a-g fault, the apparent impedance seen by relay at M can be calculated as below:

$$d = \frac{\text{imag}(V_M^f \Delta I_M^*)}{\text{imag}(Z_L I_M^f \Delta I_M^*)} \quad \text{where} \quad V_M^f = V_a = 169.19\angle{-57.62^0}\text{ kV}$$

$$I_M^f = I_a + K_0 I_0 = 8.94\angle{-119.12^0}\text{ kA}$$

$$= \frac{234.24}{780} = 0.301 \qquad \Delta I_{1M}^* = 1.52\angle 123.24^0\text{ kA}$$

estimated fault location = 0.301x200 = 60.2km

Pre-fault data at R_M

Currents	Voltages
I_a: 1.54∠-86.84⁰ kA	V_a: 220.95∠-52.98⁰ kV
I_b: 1.54∠153.16⁰ kA	V_b: 220.95∠-172.98⁰ kV
I_c: 1.54∠33.16⁰ kA	V_c: 220.95∠67.01⁰ kV

$$I_{1M} = 1.54\angle{-86.84^0}\text{ kA}$$

Fault data at R_M

Currents	Voltages
I_a: 5.93∠-114.42⁰ kA	V_a: 169.19∠-57.62⁰ kV
I_b: 1.55∠155.18⁰ kA	V_b: 226.92∠-174.51⁰ kV
I_c: 1.49∠32.45⁰ kA	V_c: 223.39∠69.10⁰ kV

$$I_{1M} = 2.91\angle{-104.93^0}\text{ kA}$$

$$\Delta I_{1M} = 1.52\angle{-123.24^0}\text{ kA}$$

Percentage error in estimated fault location

$$= \left|\frac{60-60.2}{200}\right| \text{x}100 = 0.1\%$$

Now, let us see an example

Example, a-g fault at 60 km from bus M for 400kV, 200km line, considering r fault resistance is 10Ω. . Calculate the fault location. Positive sequence impedance per km, z_1= 0.02+j0.286 Ω/km. Zero sequence impedance per km, z_0= 0.106+j0.837 Ω/km.

Solution:

The value of $I_{1M}^{pre} = 1.54\angle 86.84^0$ kA and $I_{1M}^{f} = 2.91\angle 104.93^0$ kA. Therefore

$$\Delta I_{1M} = 1.52\angle 123.24^0\ \text{kA}$$

The fault voltage at bus M is

$$V_M^f = V_a = 169.19\angle 57.62^0\ \text{kV}$$

Simultaneously

$$I_M^f = I_a + K_0 I_0 = 8.94\angle 119.12^0\ \text{kA}$$

Therefore, for the a-g fault, the apparent impedance seen by relay at M can be calculated as below:

$$d = \frac{\text{imag}\left(V_M^f \Delta I_M^*\right)}{\text{imag}\left(z_L I_M^f \Delta I_M^*\right)} = \frac{234.24}{3.9} = 0.301 \times 200 = 60.2\ \text{km}$$

Now the percentage error in estimated fault location will be

$$\left|\frac{60-60.2}{200}\right| \text{x } 100 = 0.1\%.$$

So, see this is pretty good and promising compared to simpler reactance based method.

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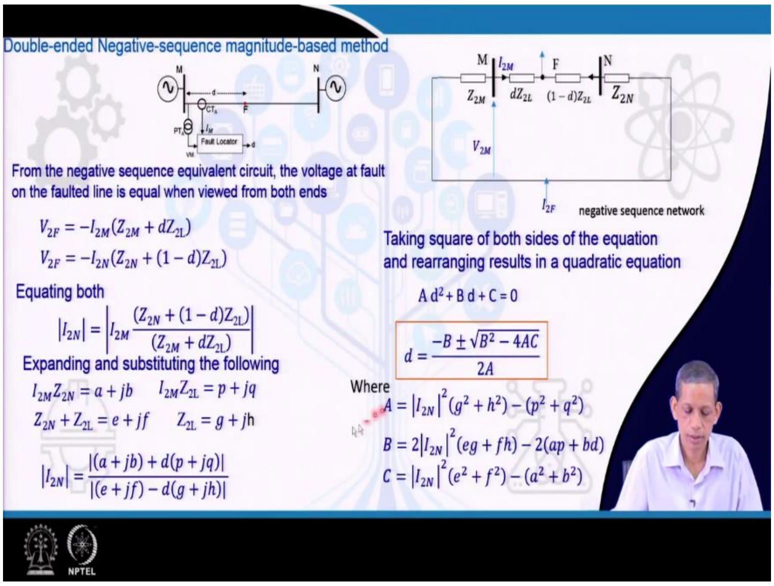

Double-ended Negative-sequence magnitude-based method

From the negative sequence equivalent circuit, the voltage at fault on the faulted line is equal when viewed from both ends

$$V_{2F} = -I_{2M}(Z_{2M} + dZ_{2L})$$

$$V_{2F} = -I_{2N}(Z_{2N} + (1-d)Z_{2L})$$

Equating both

$$|I_{2N}| = \left| I_{2M} \frac{(Z_{2N} + (1-d)Z_{2L})}{(Z_{2M} + dZ_{2L})} \right|$$

Expanding and substituting the following

$I_{2M}Z_{2N} = a + jb \quad I_{2M}Z_{2L} = p + jq$

$Z_{2N} + Z_{2L} = e + jf \quad Z_{2L} = g + jh$

$$|I_{2N}| = \frac{|(a+jb) + d(p+jq)|}{|(e+jf) - d(g+jh)|}$$

Taking square of both sides of the equation and rearranging results in a quadratic equation

$$A\,d^2 + B\,d + C = 0$$

$$\boxed{d = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A}}$$

Where

$A = |I_{2N}|^2 (g^2 + h^2) - (p^2 + q^2)$

$B = 2|I_{2N}|^2 (eg + fh) - 2(ap + bd)$

$C = |I_{2N}|^2 (e^2 + f^2) - (a^2 + b^2)$

There is another promising method, which is available in relays, but which uses both end data but not synchronized. With synchronized data, the accuracy becomes compromised with the synchronizing clock and so those are particular aspects, and we require a communication data to the other end, one end to the other end. But here, we are talking about if one end phasor data are available, then from the other end, if the magnitude of voltage currents are available, then also we can manage with. So, this is the same two bus system MN and for any unbalanced fault, when negative sequence component is there, then only this method is valid. So far we have seen very promising results with negative sequence component in directional relaying. Now, see here, how that can be also extended here also. So, this is the negative sequence diagram for this system in case of unbalanced fault. So, I_{2F} enters here leaves here and then the current division will be there from both the sides. Now, for this case, the fault point voltage viewed from bus M is

$$V_{2F} = -I_{2M}(Z2_M + dz_{2L})$$

And from N side

$$V_{2F} = -I_{2N}(Z2_N + (l-d)z_{2L})$$

Equating both equations above

$$|I_{2N}| = \left| I_{2M} \frac{(Z_{2M} + dz_{2L})}{(Z_{2N} + (l-d)z_{2L})} \right|$$

Expanding and substituting the following

$$I_{2M}Z_{2M} = a + jb$$

$$I_{2M}Z_{2L} = p + jq$$

$$Z_{2N} + Z_{2L} = e + jf$$

$$z_{2L} = g + jh$$

$$Z_{2L} = l \times z_{2L}$$

Expression of I_{2N} can be rewritten as

$$|I_{2N}| = \frac{|(a + jb) + d(p + jq)|}{|(e + jf) - d(g + jh)|}$$

Taking square at both sides of the equation and rearranging results in a quadratic equation

$$A\, d^2 + B\, d + C = 0$$

The fault location *d* can be obtained as

$$d = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A}$$

Where,

$$A = |I_{2N}|^2 (g^2 + h^2) - (p^2 + q^2)$$

$$B = 2|I_{2N}|^2 (eg + fh) - 2(ap + bd)$$

$$C = |I_{2N}|^2 (e^2 + f^2) - (a^2 + b^2)$$

Thus *d* can be obtained using the negative sequence current and line data at the local end.

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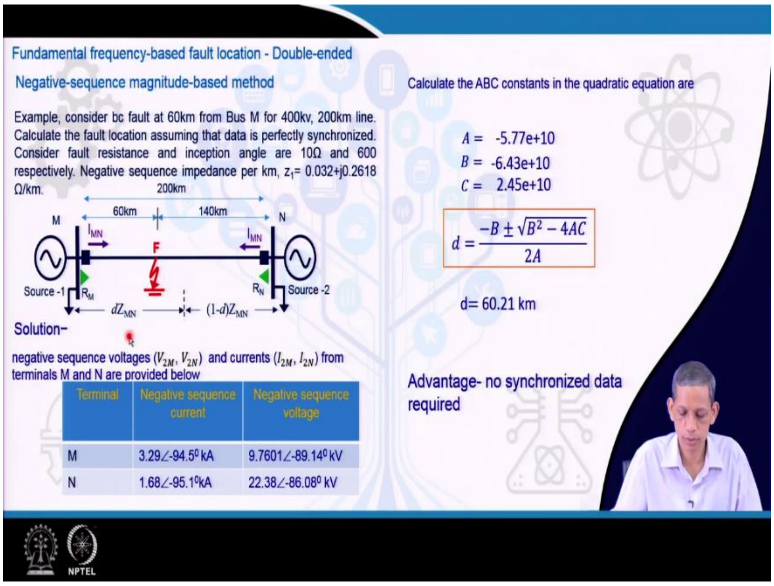

Fundamental frequency-based fault location - Double-ended

Negative-sequence magnitude-based method

Example, consider bc fault at 60km from Bus M for 400kv, 200km line. Calculate the fault location assuming that data is perfectly synchronized. Consider fault resistance and inception angle are 10Ω and 600 respectively. Negative sequence impedance per km, z_1= 0.032+j0.2618 Ω/km.

Solution–

negative sequence voltages (V_{2M}, V_{2N}) and currents (I_{2M}, I_{2N}) from terminals M and N are provided below

Terminal	Negative sequence current	Negative sequence voltage
M	$3.29\angle{-94.5^0}$ kA	$9.7601\angle{-89.14^0}$ kV
N	$1.68\angle{-95.1^0}$kA	$22.38\angle{-86.08^0}$ kV

Calculate the ABC constants in the quadratic equation are

$A =$ -5.77e+10

$B =$ -6.43e+10

$C =$ 2.45e+10

$$\boxed{d = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A}}$$

d= 60.21 km

Advantage- no synchronized data required

Example: Consider *bc* fault at 60km from Bus M for 400kv, 200km line. Calculate the fault location assuming that data is perfectly synchronized. Consider fault resistance and inception angle are 10Ω and 60^0 respectively. Negative sequence impedance per km, z_1= 0.032+j0.2618 Ω/km.

Solution:

The values of A, B, C constants obtained from the voltage and current data at both the ends are

A = -5.77e+10 , B = -6.43e+10, C = 2.45e+10

Therefore, the value of *d* calculated from expression

$$d = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} = 60.21 \text{ km}$$

So, as compared to the fault created at 60 km, the estimated value gives 60.21km which is pretty accurate. So, this, advantage of this method is accuracy based on the negative sequence component and no synchronized data required from the other end, this is an offline business. Therefore, time is not a factor like in protection schemes. So, what you do here that the, the other end information is being transferred to the other one, only the magnitude of the currents.

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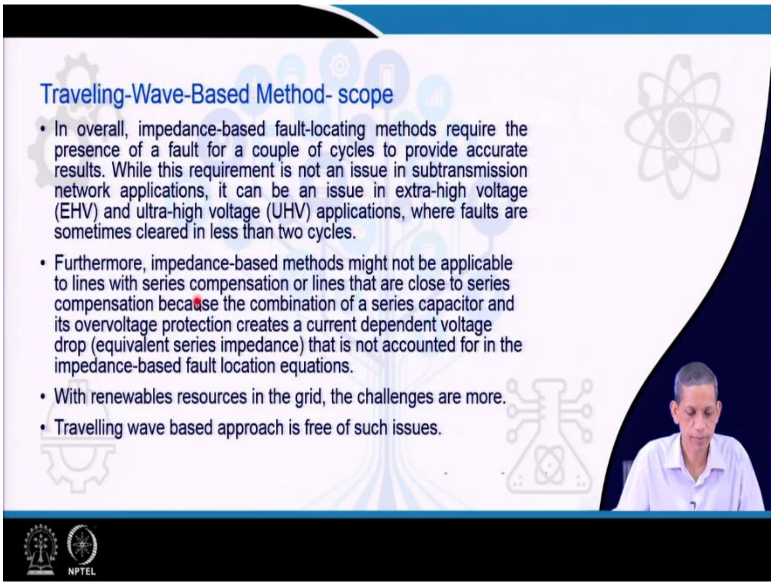

Traveling-Wave-Based Method- scope

- In overall, impedance-based fault-locating methods require the presence of a fault for a couple of cycles to provide accurate results. While this requirement is not an issue in subtransmission network applications, it can be an issue in extra-high voltage (EHV) and ultra-high voltage (UHV) applications, where faults are sometimes cleared in less than two cycles.
- Furthermore, impedance-based methods might not be applicable to lines with series compensation or lines that are close to series compensation because the combination of a series capacitor and its overvoltage protection creates a current dependent voltage drop (equivalent series impedance) that is not accounted for in the impedance-based fault location equations.
- With renewables resources in the grid, the challenges are more.
- Travelling wave based approach is free of such issues.

Now, we find that the available methods on phasor based techniques, they have their own limitations in terms of accuracy of the phasors. But most importantly, if we see, the impedance based fault locating methods require the couple of cycles to provide accurate results, because of phasor estimation, decaying DC challenges, CVT issues and so. While this recurrent is not an issue for this sub transmission level, because fault clearance may be slower, but it is an issue with extra high voltage and the ultra-high voltage system applications, where faults are being cleared sometimes less than 2 cycle also. So, you do not have sufficient data for obtaining the required accuracy for fault location. Further, the impedance based methods is not good one, from accuracy point of view for a series compensator line due to MOV operation and the associated protection scheme of the series capacitor also. So, that leads to scope of alternative ways, furthermore, today we have a lot of renewables, as already discussed in the earlier lectures. And the renewable integration puts further challenges to current and voltage patterns also. And the, those are being connected at different points also. Traveling wave based approach is free of such issues of series compensation and so, as we have already seen in the protection scheme also, because it is high frequency component, so series capacitor becomes a short-circuit only. So, that gives a scope for the traveling wave based approach for fault location.

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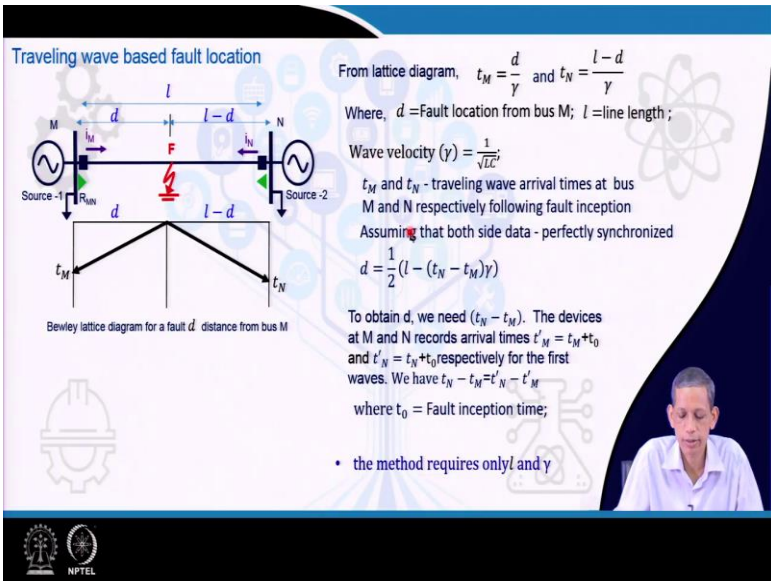

Traveling wave based fault location

Bewley lattice diagram for a fault d distance from bus M

From lattice diagram, $t_M = \frac{d}{\gamma}$ and $t_N = \frac{l-d}{\gamma}$

Where, d =Fault location from bus M; l =line length ;

Wave velocity $(\gamma) = \frac{1}{\sqrt{LC}}$;

t_M and t_N - traveling wave arrival times at bus M and N respectively following fault inception

Assuming that both side data - perfectly synchronized

$d = \frac{1}{2}(l - (t_N - t_M)\gamma)$

To obtain d, we need $(t_N - t_M)$. The devices at M and N records arrival times $t'_M = t_M + t_0$ and $t'_N = t_N + t_0$ respectively for the first waves. We have $t_N - t_M = t'_N - t'_M$

where t_0 = Fault inception time;

- the method requires only l and γ

Utilities have already used this fault locators for its accuracy advantage. So, we have already seen in the protection scheme, such a thing to our systems and fault happens to be there, so Bewley’s lattice diagram says that the fault will propagate to this side and this side. If the fault from this end is d, then from this end, then from this end is (l-d) if the length of the line is l, total length is l. So, this corresponding time recorded here at this end by this relay or the recording device a t_M and the t_N. So, from this, the traveling time t_M following the fault inception, will be

$$t_M = \frac{d}{\gamma}$$

γ is the velocity of propagation in this medium depends upon the line parameters, line constant L and C. And the t_N on this side will be

$$t_N = \frac{l-d}{\gamma}$$

So, this time t_M and t_N corresponds to the time following the fault inception. So, from this one, d as we have seen in the earlier differential protection or so, the d becomes equals to

$$d = \frac{1}{2}(l - (t_N - t_M)\gamma)$$

So, we can obtain the corresponding d. So if we have information at these two time for both the ends, and considering that they are perfectly synchronized, then the corresponding d will be very-very accurate. To obtain d, we need t_N - t_M. The device M and N records however the arrival times, and they have their own clocks. So, the corresponding inception time is not known. Let us, the inception time is t_0. So, the corresponding time which will be recorded by these devices $t'_M = t_M + t_0$ where t_M is the travel time of the fault generated surge from this to the fault point which we have described here.

So, t'_M is known to us at this device of its own clock. Similarly, from N side, the corresponding fault inceptions is t_0 and travel time t_N, so the device records at t'_N, the arrival of the first wave at the N side. Now, what we require in this relation is t_N - t_M. As, $t_N - t_M = t'_N - t'_M$. So, we do not have any problem in obtaining the corresponding $t_N - t_M$. And once we have this from this recording, then *l* is known and γ known for the system so we can find out *d*. So, from this relation, we see that the method requires only line length and velocity propagation that depends upon L and C, and that is very simple as compared to the phasor based approach or impedance based approach, which you have already seen earlier.

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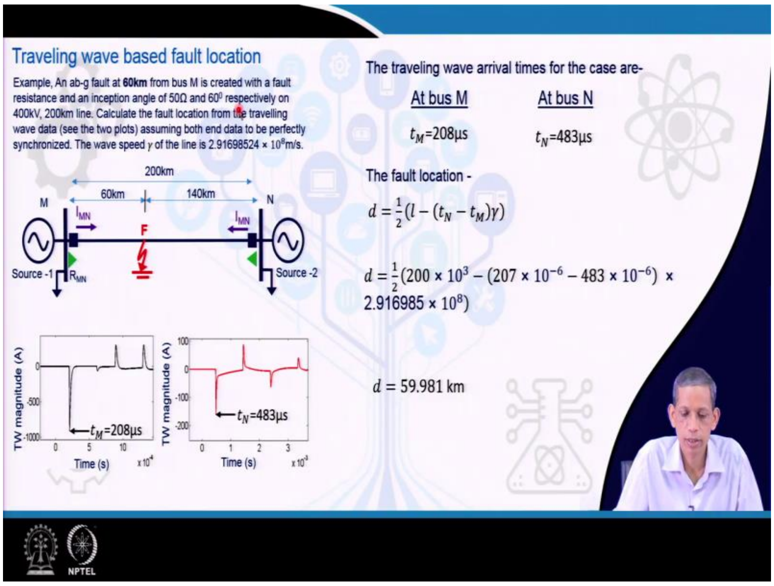

Traveling wave based fault location

Example, An ab-g fault at **60km** from bus M is created with a fault resistance and an inception angle of 50Ω and 60⁰ respectively on 400kV, 200km line. Calculate the fault location from the travelling wave data (see the two plots) assuming both end data to be perfectly synchronized. The wave speed γ of the line is 2.91698524 × 10⁸m/s.

The traveling wave arrival times for the case are-

At bus M	At bus N
t_M=208μs	t_N=483μs

The fault location -

$$d = \frac{1}{2}(l - (t_N - t_M)\gamma)$$

$$d = \frac{1}{2}(200 \times 10^3 - (207 \times 10^{-6} - 483 \times 10^{-6}) \times 2.916985 \times 10^8)$$

$$d = 59.981 \text{ km}$$

Examples, the 60 km from the bus M fault is created, and then we have the corresponding recorded waves, shown here this M end and N end. So, M the corresponding and the fault inception point is mentioned as a 0 here from the calculation in both the, both sides' clocks as recorded.

And the first wave arrive at, arrives at 208μs, and to the end side it arrives at 483 μs. So, at bus M, this corresponding t_M = 208μs, and N side, t_N = 483μs. So, if we apply the formula with available γ = 2.91698524 × 10^8m/s.

$$d = \frac{1}{2}(l - (t_N - t_M)\gamma) \ = \frac{1}{2}(200 \times 10^3 - (207 \times 10^{-6} - 483 \times 10^{-6}) \ \times 2.916985 \times 10^8)$$

$= 59.981$ km

So, as compared to the fault created at 60 km, ab-g fault created at 60 km. Note that, for any type fault, any type of fault, corresponding relation becomes same.

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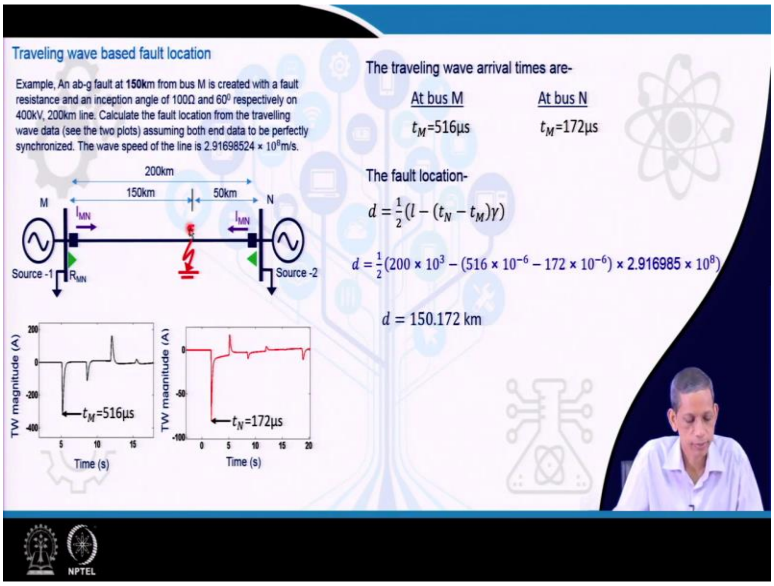

Traveling wave based fault location

Example, An ab-g fault at **150km** from bus M is created with a fault resistance and an inception angle of 100Ω and 60⁰ respectively on 400kV, 200km line. Calculate the fault location from the travelling wave data (see the two plots) assuming both end data to be perfectly synchronized. The wave speed of the line is 2.91698524×10^8m/s.

The traveling wave arrival times are-

At bus M	At bus N
t_M=516μs	t_M=172μs

The fault location-

$$d = \frac{1}{2}(l - (t_N - t_M)\gamma)$$

$$d = \frac{1}{2}(200 \times 10^3 - (516 \times 10^{-6} - 172 \times 10^{-6}) \times 2.916985 \times 10^8)$$

$$d = 150.172 \text{ km}$$

ab-g fault at 150 km, similarly these are the waves obtained at M side and N side and the corresponding arrival time 516 μs and 172 μs, note it here, apply the formula. And the d obtained is 150.172 km compared to 150 km fault created in this system. So, this shows clearly that the traveling wave approach is pretty accurate, that is independent of fault resistance. And so many factors with the impedance based approach is being affected.

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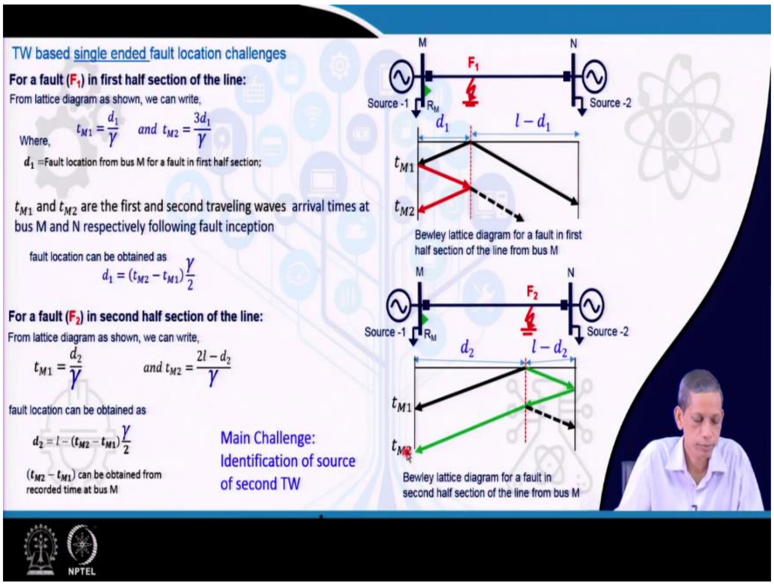

TW based single ended fault location challenges

For a fault (F_1) in first half section of the line:

From lattice diagram as shown, we can write,

$$t_{M1} = \frac{d_1}{\gamma} \quad and \quad t_{M2} = \frac{3d_1}{\gamma}$$

Where,

d_1 =Fault location from bus M for a fault in first half section;

t_{M1} and t_{M2} are the first and second traveling waves arrival times at bus M and N respectively following fault inception

fault location can be obtained as

$$d_1 = (t_{M2} - t_{M1})\frac{\gamma}{2}$$

For a fault (F_2) in second half section of the line:

From lattice diagram as shown, we can write,

$$t_{M1} = \frac{d_2}{\gamma} \qquad and \; t_{M2} = \frac{2l - d_2}{\gamma}$$

fault location can be obtained as

$$d_2 = l - (t_{M2} - t_{M1})\frac{\gamma}{2}$$

$(t_{M2} - t_{M1})$ can be obtained from recorded time at bus M

Main Challenge: Identification of source of second TW

Bewley lattice diagram for a fault in first half section of the line from bus M

Bewley lattice diagram for a fault in second half section of the line from bus M

There are other simplified waves, where the time synchronized is not required, we call traveling wave single handed approach, but it has own limitation on this perspective. Let us see, how the corresponding single handed fault location using traveling concept can be applied. two considerations, one in the, first, the fault F_1 is closer to this bus N and in between the midpoint. And the second case is, it is closer to the N side, and it is beyond the midpoint from the M bus. So, we are considering the relay to be here only, which records the data or data recorder, with these corresponding Bewley's lattice diagram for the first case, let us say, fault distance is d_1, this side becomes $(l - d_1)$. So, this d_1 position is less than 50 % from bus M. So, the wave starts following the fault inception, and reaches here at t_{M1}, and again is reflected at this point because of the load and other things, and goes towards the fault. And again, from the fault point, it is again reflected. So, the second wave is received at t_{M2}. So now, if we think about this fault F_1, that within the first half, then the $t_{M1} = d_1 / \gamma$, we already know. And t_{M2} equals to $3d_1 / \gamma$. How? This is d_1 travel, again another d_1 travel and another d_1 travel. So, this leads to, the t_{M2} equals to the total time from here to here is $3d_1 / \gamma$. Now, let us come to the second case, where the fault is beyond the 50 % from M end. So, you see here, the fault traverses these portions d_2 distance and arrives here. And again, we go to this fault point, and again we will reflect a bit. There is another one, the green one, which goes to the other end, and at this end it is reflected and traverses and some portion again transmitted to this side at the fault point. Some, which is reflected to the side, something will be transmitted to the side. The transmitted one reaches to this at t_{M2}. Note, this is the second wave, which has been received at M location for this case, first wave and the second wave. Now, note that the corresponding reflected one and again coming back here that will be the subsequent one, because the distance is more than 50 %.

So, considering these two fast waves which are arriving here, in the second case, the corresponding distance between the two cases

$$t_{M1} = \frac{d_2}{\gamma};$$

And

$$t_{M2} = \frac{2l - d2}{\gamma}$$

How? So, this distance travelled is (l -d_2) this is (l - d_2) again. So, these are the two equations, but now the question is that for a given instant, we do not know the fault is beyond 50 % or within 50 %. If we know that, then we can apply, if it is within 50 %, we can apply this relation. And it is beyond 50 %, we can apply this relation. So, that is the challenge. So, some method for that one that they, we integrate the impedance based approach to see how far is the fault, is it beyond the midpoint or within the midpoint? If there is a clear indicative of that, then the fault distance can be obtained like the earlier case if you can record the corresponding two wave's arrival times.

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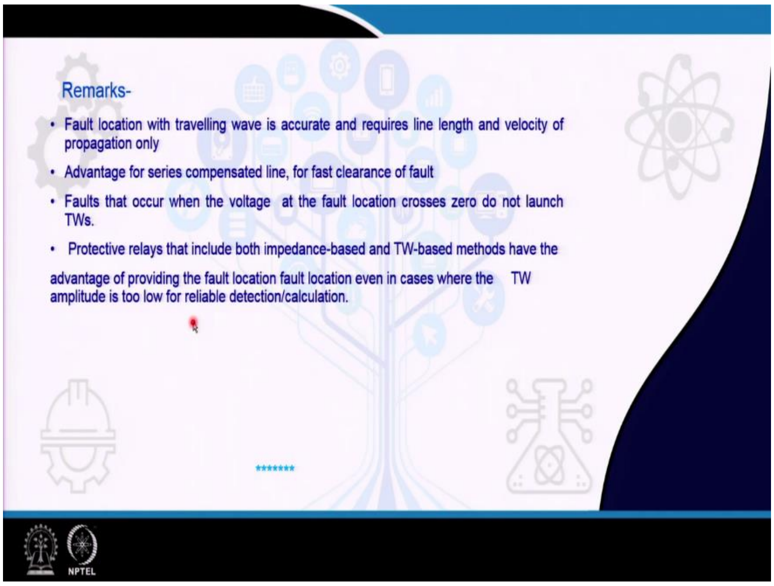

Remarks-

- Fault location with travelling wave is accurate and requires line length and velocity of propagation only
- Advantage for series compensated line, for fast clearance of fault
- Faults that occur when the voltage at the fault location crosses zero do not launch TWs.
- Protective relays that include both impedance-based and TW-based methods have the

advantage of providing the fault location fault location even in cases where the TW amplitude is too low for reliable detection/calculation.

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So, what we see, that fault location can be obtained very accurately and that is what they also using the traveling wave based approach recorders with synchronized data from both the ends from the, for the traveling waves. But traveling wave is high frequency, so it has high sampling rate as we have already seen in earlier lecture on the protection perspective. It has advantage for series compensated line because series compensator does not influence its traveling wave propagation. But there are issues, when fault occurs when the voltage at the fault location crosses 0. So at that time, the fault will not launch any traveling wave. So, we do not have any travelling wave. So in that case the method becomes ineffective. Therefore, the good solution is protective relay that include both the impedance based and traveling wave based methods have a better solution advantage in locating fault for all situations. And traveling wave will most of the time, will provide you accurate solutions, and as and when it required, it can supplement it by the impedance based approach also, an integrated approach will be a better choice. So, in overall, we see that the traveling wave is a newer concept for protection schemes. And it is advancing and wish it will provides in future excellent protection solutions. Thank you.