Power System Protection
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Lecture No. 25
Protection of series compensated lines - Part - II

Welcome to NPTEL course on power system protection. This lecture related to distance relaying. We will have protection of series compensated lines part 2.

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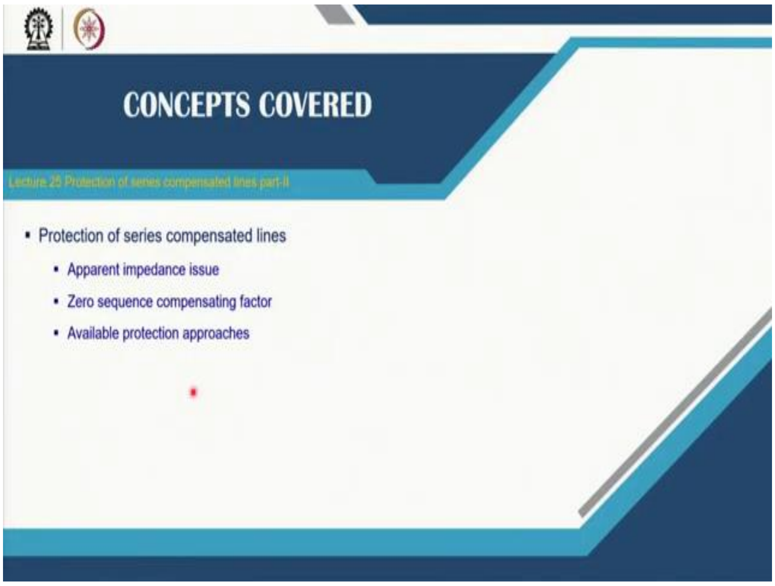

CONCEPTS COVERED

Lecture 25 Protection of series compensated lines part-II

- Protection of series compensated lines
  - Apparent impedance issue
  - Zero sequence compensating factor
  - Available protection approaches

The coverage will be on apparent impedance issues, zero sequence compensating factor and available protection approach. Two approaches, we will discuss on it.

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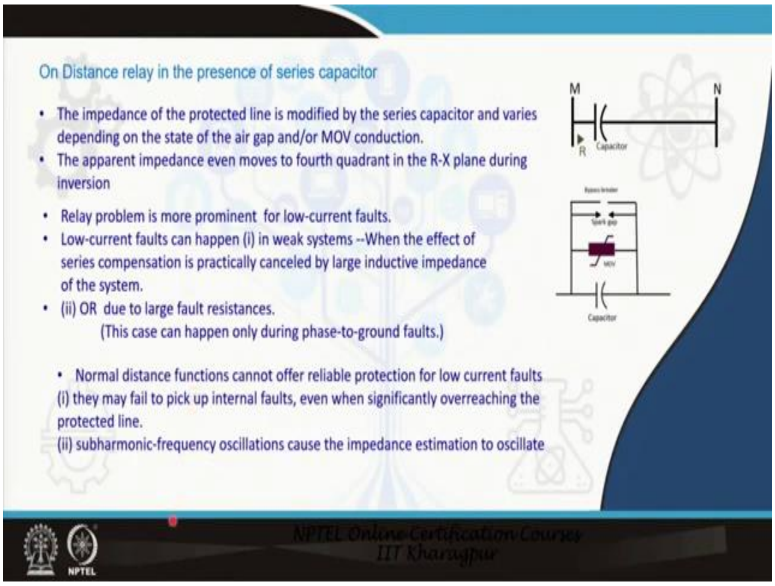

On Distance relay in the presence of series capacitor

- The impedance of the protected line is modified by the series capacitor and varies depending on the state of the air gap and/or MOV conduction.
- The apparent impedance even moves to fourth quadrant in the R-X plane during inversion
- Relay problem is more prominent for low-current faults.
- Low-current faults can happen (i) in weak systems --When the effect of series compensation is practically canceled by large inductive impedance of the system.
- (ii) OR due to large fault resistances.
  (This case can happen only during phase-to-ground faults.)
- Normal distance functions cannot offer reliable protection for low current faults
  (i) they may fail to pick up internal faults, even when significantly overreaching the protected line.
  (ii) subharmonic-frequency oscillations cause the impedance estimation to oscillate

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The last lecture on series compensation in part 1, we discussed on the operation of protection of the capacitor, the corresponding MOV operation, air gap flashing and the breaker operation. Then we discussed on the directional relaying issues, current inversion, voltage inversion and how the solutions to directional relaying can be achieved. In this lecture we will focus on the distance relay issues and the solutions. Come to a system, simple system as we have discussed earlier also, MN is transmission line section and we have a capacitor at M end and we have a relay at R a distance relay, which takes the corresponding voltage and current at bus for the line MN.

Now, we know as we have discussed earlier also there the capacitor has its own protection, metal oxide varistor. So, whenever the current becomes more through the capacitor, voltage across the capacitor goes high, capacitor has a specific rating of voltage which goes beyond that, it is dangerous, may damage the capacitor so MOV operates and then the functioning of spark gap and the bypass breaker that we have discussed in the last lecture.

Now, when it comes to the situations as observed by the distance relay here, then what are the associated issues. Whenever a fault happens to be there in the line, fault current flows through the capacitor through the relay also they are in series. Now, that whenever the capacitor happens to be there, so, in the fault loop capacitor may be there or capacitor may be bypassed by the MOV and this spark gap arrangement.

So, when capacitor is there in the for loop, 1 reactance, 1 impedance seen by the relay, when the capacitor is not there in the fault loop due to the bypassed due to the bypassing provisioned by the MOV and the air gap, then in that case, the fault loop does not have the capacitor and it will behave just like the normal transmission line. So, with that situations how the corresponding relay sees, we will have some discussion and then we will go to the further details.

The impedance of the protected line is modified by the series capacitor true, varies depending on the state of the air gap and MOV operation. Note, the corresponding state of the series capacitor in the fault loop depends upon the MOV and the spark gap arrangement. The upper impedance even moves to fourth quadrant in the RX plane, we have observed in the current and voltage inversions. So, that leads to such a situation. Relay problem is more prominent for low fault currents.

So, what we see that when the fault current is low, because of the fault may be very far away or in case of the source impedance is very large or the corresponding fault resistance is very large, then in case of that the fault current becomes low and in that case the corresponding voltage across the capacitor will not be higher than its rating and MOV operation and spark gap operation will not be there. It means in the fault loop the capacitor will be there. So, that you can say that is a critical issue you can say that.

And furthermore, sometimes that the corresponding MOV may be operating for a longer period of time before this spark gap bypasses and so. In that situations that the low current situations, you can say that we have the apparent impedance is seen by the relay, will be a more problematic case. Normal distance relay functions cannot offer reliable protections for the low current faults. They may fail to pick up internal faults even when significant overreaching is provided.

Furthermore, we have already discussed in the earlier lecture that because of this LC in series, sub harmonic frequency component is there in the signals and that you can say that leads to oscillations and therefore the phasor estimation accuracy and that leads to the corresponding effect that affect is also observed in the apparent impedance and which may lead to reach issue, reach setting perspective. So, we will see more details on these issues which we have addressed here in the perspective of distance delay in the presence of series capacitor.

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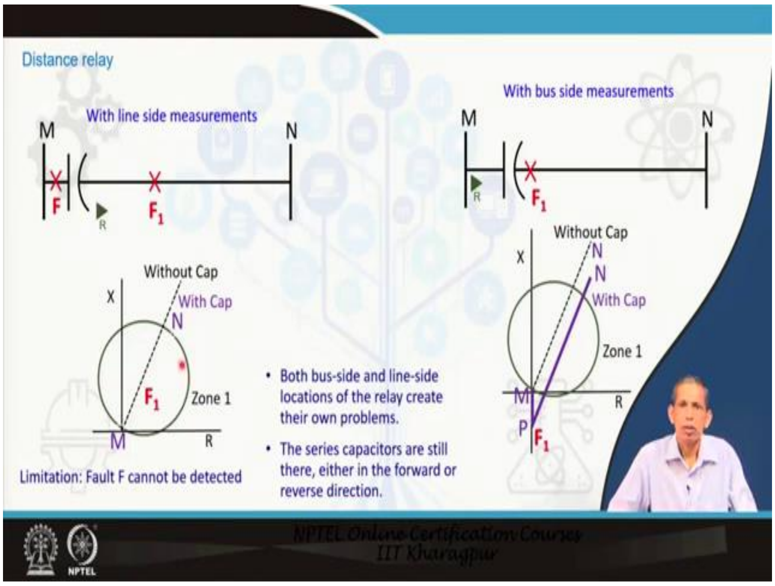

Distance relay

- Both bus-side and line-side locations of the relay create their own problems.
- The series capacitors are still there, either in the forward or reverse direction.

Limitation: Fault F cannot be detected

Now, let us have these simple issues and then we will go to the more details one. Now, we know that series capacitor, presence of series capacitor in the fault loop changes the capacitance, changes the equivalent reactance, the impedance as seen by the relay, because of this capacitive reactance, which is having -jXc as compared to jX_l of the line. Now, one perspective is that a straightforward solution comes to our mind, if you measure the corresponding current voltage in series, your current will be same here or here, we measure the voltage in the line side, you understand here line side means position at here not at here.

So, if we measure the corresponding measurements by the relay, the voltage measurements become to the line side beyond the capacitor and the corresponding relay sees this as the forward zone. Then this path does not encounter the capacitor from this to this. So, no voltage inversion, no current inversion will be observed by the relay for the forward fault that means, that the corresponding for the system the corresponding current inversion, etc. may be there but at this point the corresponding current or voltage inversion will not be observed and that solves the purpose.

But note that, if you have these corresponding relay at this one, faults for this side or fault within the line also at F, will not be seen by the relay if you consider this as a forward thing. If we accommodate this corresponding F in the quadrilateral or more relay setting by offset arrangement and so, then we will see the issue of current inversion, voltage inversion in the system, this will be a reverse direction fault, that has to be accommodated in the characteristics (())(8:08) which not that easy also.

So, this is about line side measurements, in the line side measurements as we have discussed, this is the M point, M point here and then this is a normal line we are observing without capacitor. Now, we can say that with capacitor what happens, if you consider at the line side, the relay still see the same line impedance from this to this. So, absolutely without capacitor, with capacitor the impedance seen by the relay in the forward direction will be same, so absolutely the problem is solved for this part, but for the reverse part, there is a problem.

Now, if you go to the bus side measurements, which we usually do which we have discussed till now, in general. So, the relay will be positioned at here and the corresponding measurements are the voltage measurements at the bus voltage and the corresponding current to the line. In that case what do we see that in the forward direction of the relay, the corresponding capacitor comes into picture. So, in the fault loop the corresponding capacitance will be there and then if the capacitor in the fault loop the equivalent impedance or the reactance becomes less, -jXc and if in the fault loop the capacitor is bypassed, then there is no capacitance, it means that it is a normal line impedance up to the fault point.

So, if we have this is the the dotted line is for without the capacitor with the presence of capacitor in the fault loop the corresponding at this point the capacitor at the relay location sending end side from the M bus so the corresponding depending on the capacitance compensation -jXc, this dip will be there in the R-X plane and then you can say that it will be again increasing for this line section this to this with the corresponding R & X value of the line in parallel with this.

So therefore, what we say that this dip, this two will be same in zone 1 settings of the arrangement or in the other settings. So this is for the zone 1 setting we have shown. So, what we see here that, the fault at F_1 just after the capacitor will be this point, and then the end you can say that will be this point and accordingly you can see that we have zone 1 setting for this you can say that without the capacitor becomes like this, that we have shown.

So, if we consider the line side measurements at this point, if we consider the bus side measurements at this point, then in the bus side measurements, the capacitive be effective is coming into picture in the apparent impedance, but here in the line side measurement the capacitive effective is not coming into picture, but this has associated issue that it is not able to take care of this portion between the bus and the corresponding capacitor connection and so.

And if we see the reverse side, then the corresponding capacitor is being encountered. If we see here in the forward side capacitor is there and in the reverse side no capacitor is there. So, in conclusion if we say that both options of line side or bus side have certain advantages and certain issues or problem associated. The series capacitors are still there either in the forward or in the reverse direction, whatever options we select.

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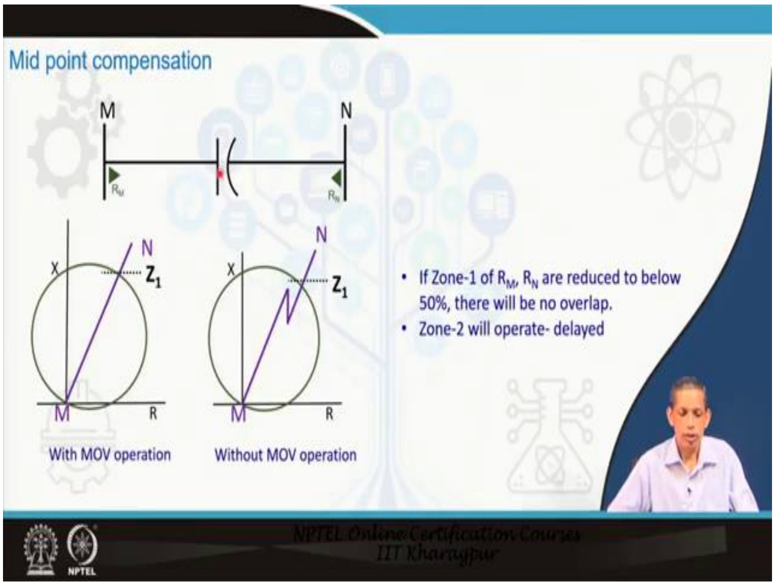

Mid point compensation

With MOV operation

Without MOV operation

- If Zone-1 of R_M, R_N are reduced to below 50%, there will be no overlap.
- Zone-2 will operate- delayed

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Now, suppose the capacitor is at the midpoint, then we have considered bus M and bus N and then we have relays at both the end interconnected system distance relay, we are considering R_M let us first and similarly, we can see also from this R_N because of the symmetry. Now, with MOV operation large fault current suppose a fault happens to be here, large fault current happens to be there, MOV operates and the corresponding capacitor is bypassed. So simple, this line so this is zone 1 setting so this is MOV relay characteristic. Now with without MOV operation, MOV does not operate then capacitor will be there in the fault loop.

So, this is 50% then the corresponding capacitance will be the dip value and then again you consider the corresponding line section, let us say next 30% or so that that you can see that as N so this 30% becomes this. So therefore, you can say that the corresponding characteristic what we have copied from here for the zone 1 and then we can say that the corresponding happens to be this characteristics. So, what we say here that in this case there may be overreach phenomena and so with the presence of capacitor and not any capacitor.

So, in this kind of environment, we can have a reduction in the zone 1 setting that is one approach, the other approach you can say that (())(12:52) the corresponding combination becomes very large that becomes difficult. And then in case of with the capacitor reach, let us say 70%, then 50% + 70% - 30%. Again this 30% that becomes 0 kind of thing so that situations becomes pretty difficult you can say that to adjust the zone 1 setting when capacitor is in the circuit during fault.

So, the other problem we see here from this side and that side, if the zone 1 of you can say that R_M and R_N are reduced to below 50% that is what I am talking about, if the corresponding zone 1 becomes less because of this series compensation, (X_L-X_C), so that becomes much smaller, then if the zone 1 setting from this side becomes less than 50% and from this side also less than 50%, the overlapping patch in the network becomes 0, there is no overlapping that is not acceptable in the protection schemes because that person will left out from the zone 1 setting from the primary protection.

So, that will be taken care in the zone 2 because that is extended one. So, so in that case overreaching one that case the zone 2 will be operating at a later time, which is also not desirable.

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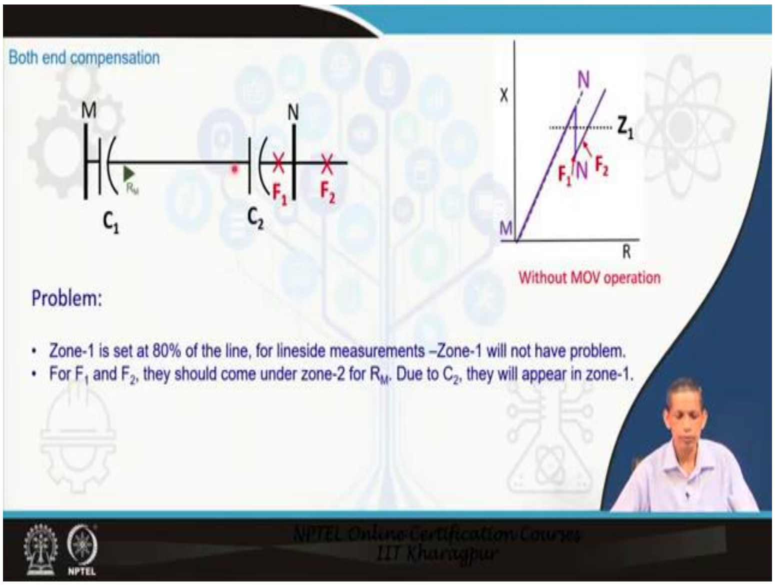

Both end compensation

Without MOV operation

Problem:

- Zone-1 is set at 80% of the line, for lineside measurements –Zone-1 will not have problem.
- For F_1 and F_2, they should come under zone-2 for R_M. Due to C_2, they will appear in zone-1.

Now, both end compensation is also an application area. So, let us say you consider this relay which is in the line side measurements because it does not encounter the first capacitor it can avoid, but see you consider it, it will see in the forward direction the second capacitor in zone 2 because this is also in line end. Now what happens that if you see the corresponding R-X plane the corresponding impedance, then what we say that at this point for this there is a dip the corresponding C_1 value then the line impedance, whole line impedance increases like this, and then again we consider a dip for the C_2 portion, and then increases for beyond N end and so.

Now what happened here? So, here you can say that if we see the corresponding point here, the zone 1 is set to be let us say 80 percent for line side measurements, zone 1 will not have any problem, but you can say that F_1 which is just after the capacitor C_2 then if we see this F_1 and F_2, then now F_1 just after the capacitor and F_2 just a few kilometres from bus N, then you can say that if we see this you can say that this becomes F_2.

So, this F_2 becomes the point, the both F_1 and F_2 will be shown in zone 1 of setting at R_M, so that becomes a problem because of this you can say that the role played by this capacitor C_2 in the fault loop. So, that however, these two you can say that fault in the zone 2 perspective and if F_2 will be seen in zone 1, then this relay may trip before the zone 1 you can say that bus N, so that is also not acceptable in protection arrangements.

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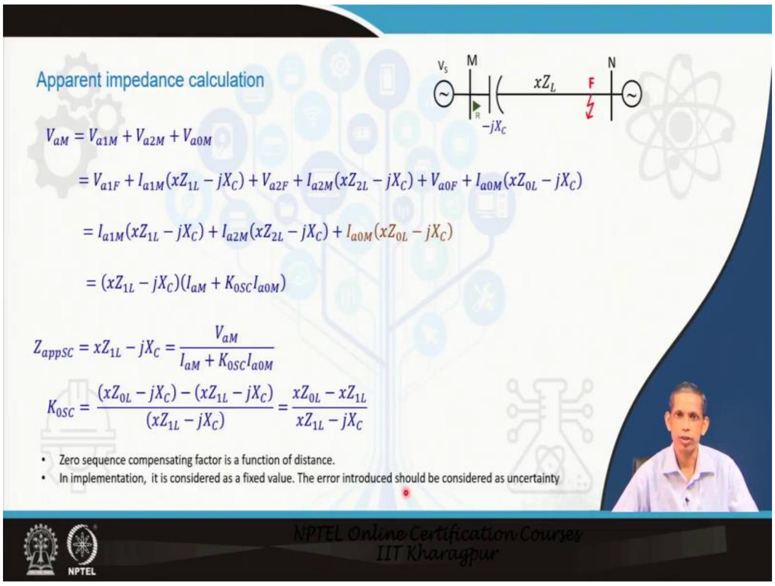

Apparent impedance calculation

$$V_{aM} = V_{a1M} + V_{a2M} + V_{a0M}$$

$$= V_{a1F} + I_{a1M}(xZ_{1L} - jX_C) + V_{a2F} + I_{a2M}(xZ_{2L} - jX_C) + V_{a0F} + I_{a0M}(xZ_{0L} - jX_C)$$

$$= I_{a1M}(xZ_{1L} - jX_C) + I_{a2M}(xZ_{2L} - jX_C) + I_{a0M}(xZ_{0L} - jX_C)$$

$$= (xZ_{1L} - jX_C)(I_{aM} + K_{0SC}I_{a0M})$$

$$Z_{appSC} = xZ_{1L} - jX_C = \frac{V_{aM}}{I_{aM} + K_{0SC}I_{a0M}}$$

$$K_{0SC} = \frac{(xZ_{0L} - jX_C) - (xZ_{1L} - jX_C)}{(xZ_{1L} - jX_C)} = \frac{xZ_{0L} - xZ_{1L}}{xZ_{1L} - jX_C}$$

- Zero sequence compensating factor is a function of distance.
- In implementation, it is considered as a fixed value. The error introduced should be considered as uncertainty

Now, we will consider how the corresponding apparent impedance calculation will be in the presence of series compensated line. So, we have considered a simple series compensated line, a MN line, series capacitor reactance was at bus M side and we are looking at the relay R at bus M so it is at the bus side connection both voltage and current. Consider a fault which is having a x per-unit distance from bus M, and then we will analyze the apparent impedance, the way we analyze in all the analysis before for the distance relay perspective.

This is a line to ground fault case so let us consider here $V_{aM} = V_{a1M} + V_{a2M} + V_{a0M}$ at M bus, but then again you can say that using the fault point voltage so $V_{a1F} + V_{a2F} + V_{a0F}$ and the other you can say that portion from the sequence diagram perspective, we say for V_{a1M}, $V_{a1F} + I_{a1M}$ Z_{1L} - j Xc.Z_{1L} , - j Xc.Z_{1L} from the positive sequence diagram.

From the negative sequence diagram $V_{a2F} + I_{a2M}$. Z_{2L} - jXc .Z_{2L} - j Xc up to the fault point and then $V_{a0F} + I_{a0M}$ .Z_{0L} - j Xc. So, in all the 3 terms if I know j Xc because in all the sequence diagram, Xc component will be there in the circuit. So, when we have the algebraic manipulations, we got the V_{a1F} + V_{a2F} +V_{a0F} they become combinedly become 0 and that you know, because at fault point the V_{aF} will be phase a to ground fault case so that will be 0.

Now, you can say that similar to what we did in the phase to ground fault case. For phase a to ground fault what we did here, this is positive sequence, this is a negative sequence and then the 0 sequence, for positive sequence and negative sequence for the line they become same and then we analyze and then the 0 sequence part we have segregated, we will add and subtract the corresponding components of I_{a0M} , x of Z_{1L} - j Xc to get the corresponding combination like this.

So, x.Z_{1L} - j X_c . I_{aM}, $I_{aM} = I_{a1M} + I_{a2M} + I_{a0M}$, $I_{aM} + K_0 .I_0$ that 0 sequence compensating factor and the corresponding 0 sequence current so, that relation we are keeping here also similar to that, but keeping that we say that the Z apparent for this series compensation line in this configuration that becomes $Z_{appSC} = xZ_{1L} - jX_c = \frac{V_{aM}}{I_{aM} + K_{0SC}I_{a0M}}$. This is the current so this denominator is $I_{aM} + K_{0SC} .I_{a0M}$.

However, the K_{0SC} we can say that from this relation if we see that becomes equals to the 0 sequence impedance in the path, this part minus the positive sequence impedance in the path this path upon the positive sequence impedance in the path, so this becomes equals to jX_C, j X_C cancels out so this becomes $\frac{x.Z_{0L} - x.Z_{1L}}{x.Z_{1L} - j\ X_c}$. Now we see here in this K_0, we have earlier $\frac{Z_0 - Z_1}{Z_1}$

.

Now we have this relation, and in this lesson if you see here we have jX_C and also x. x is the location of the fault so therefore, we conclude that the 0 sequence compensating factor is a function of distance, note. That is a big challenge, because the distance really does not know the distance of the fault, it has a setting from the 0 distance to the reach, 0.8 pu or 0.9 pu depending upon the corresponding zone 1 setting so it does not know the corresponding distance.

So, this K_{0SC} for the series compensation, we will be unable to calculate and K_{0SC} is a function of this, and the jX_C part, that means that this is no more the similar case for the normal transmission line and the jX_C plays a role in this one so also the distance. So, being a distance of the functions, this cannot be exactly found out. (())(20:48) so, what is being done in many literature we will find that they take a fixed value for this K_{0SC} and using the corresponding the error part into the uncertainty in the measurement in the system and accordingly that is being adjusted in that part.

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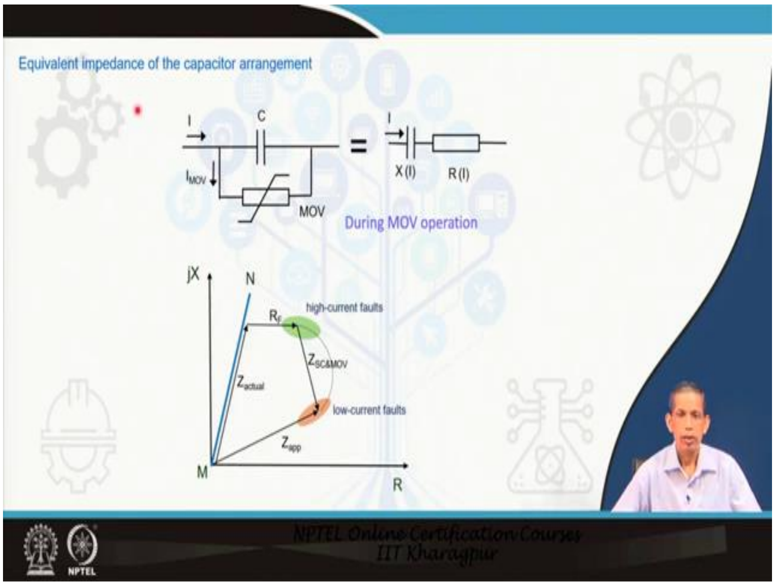

Equivalent impedance of the capacitor arrangement

During MOV operation

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Now, in detailing more on this operational perspective of the corresponding protection arrangement in the capacitor, the MOV puts a lot of challenge to the protection of the transmission system. See here, whenever the corresponding current becomes very large, the MOV being a nonlinear function it starts conducting because voltage across it becomes larger and a part of the current will be there in the MOV. Now, the corresponding the current becomes larger means the MOV shared current becomes more and more.

So, therefore, the corresponding equivalent of this part during the transient process during the fault in the system this becomes equals to this, for this the MOV offers a resistive part so this is an RC combination so therefore you can say that the corresponding equivalent impedance will be now R and X where both are a function of the corresponding current in the system.

Note that, if the I is small, this I_0 through the MOV is 0, only the C function so there is R in that part. So, that means that the corresponding impedance offered by this arrangement when MOV is operational is something a function of current. Let us see in the RX plane that perspective MN, this portion is the impedance of the line impedance in the RX plane Now, suppose we have an impedance Z actual for the fault point somewhere in the line in this line, fault is associated with an RF so RF normal line you have an RF.

In a capacitive in the capacitive aspect the series compensation aspect, if the current is very high, it means that the capacitor is bypassed so, it behaves like normal line so the R_F will be just like we added in the normal line case almost horizontal to this R-axis. Now in case the current is low, very low, then the MOV will not operate, so in the fault path only capacitor will be there so there will be a capacitive $-jX_C$ in this so this is low current, so low current situation will be $-jX_C$ even this R_F there so R_F and this part will be there.

So, equivalently you can say that the corresponding from this actual impedance of this line up to this point where we can see that the corresponding ΔZ which has been changed is in terms of the capacitive effect up to this point. Now, currents can be intermediate between the high and the low so they can be intermediate point so therefore, the corresponding impedance seen will also be in this intermediate points between this point and this point.

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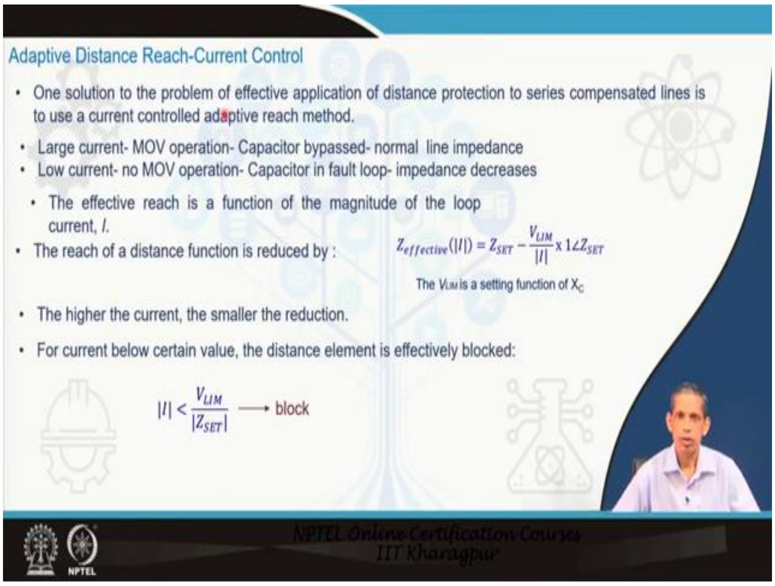

Adaptive Distance Reach-Current Control

- One solution to the problem of effective application of distance protection to series compensated lines is to use a current controlled adaptive reach method.
- Large current- MOV operation- Capacitor bypassed- normal line impedance
- Low current- no MOV operation- Capacitor in fault loop- impedance decreases
  - The effective reach is a function of the magnitude of the loop current, I.
- The reach of a distance function is reduced by :

$$Z_{effective}(|I|) = Z_{SET} - \frac{V_{LIM}}{|I|} \times 1\angle Z_{SET}$$

The V_{LIM} is a setting function of X_C

- The higher the current, the smaller the reduction.
- For current below certain value, the distance element is effectively blocked:

$$|I| < \frac{V_{LIM}}{|Z_{SET}|} \longrightarrow \text{block}$$

With that, we have solutions now for the series compensated line for the distance relay perspective, two solutions we will discuss; first one is based on a relative distance relay, distance is using the current control perspective, if current control based approach based on the current of the fault current as seen by the relay and there is another approach based on the voltage ratio perspective. So, in the first solution what is being done that in the earlier slide we noticed that the impedance as seen by the relay is a function of fault current therefore because we know large current means capacitor is bypassed, small current means that the capacitor is in the circuit and intermediate means there will be MOV and capacitor combination.

So, what we see that large current MOV operation capacitor is bypassed normal line impedance , the relay we will see. So at that time, the settings will be just like normal lines, for low current no MOV operation, capacitor in the fault loop, impedance decreases substantially considering the -jX_C. But intermediate the effective reach is a function of the magnitude of the loop current, i.e. the fault current and the reach of the distance from the reduced by the $Z_{effective}$ becomes equals to what we like to set, is Z set. With that our setting will be now different and is a function of current I now. $Z_{effective}(|I|) = Z_{SET} - \frac{V_{LIM}}{|I|} \times 1\angle Z_{SET}$

V_{LIM} is a function of X_C so that depends on the system perspective and also the particular X_C, the higher the current the smaller the reduction, if the current becomes higher these reduction part is smaller. And as you say you can say that if the corresponding current is too large, then the Z effective is Z set, no presence of capacitor. However, if the current is smaller this part becomes dominant. For current below certain value the distance element is effectively blocked why, because the corresponding $Z_{SET} - \frac{V_{LIM}}{|I|} \times 1\angle Z_{SET}$ becomes becomes too large and at times the corresponding $Z_{effective}$ vanishes.

So therefore, beyond a certain limit if $|I| < \frac{V_{LIM}}{|Z_{SET}|}$ then the relay is to be blocked, you cannot allow operation in the zone 1.

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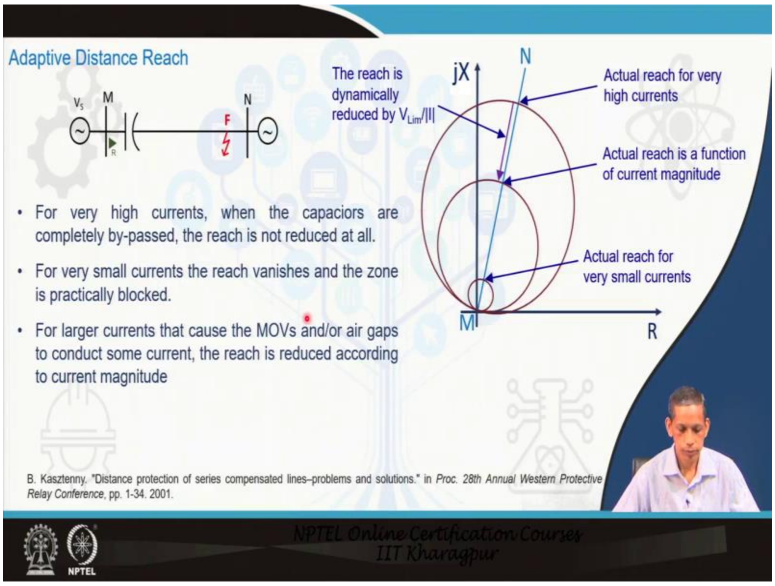

Adaptive Distance Reach

The reach is dynamically reduced by $V_{Lim}/|I|$

Actual reach for very high currents

Actual reach is a function of current magnitude

Actual reach for very small currents

- For very high currents, when the capaciors are completely by-passed, the reach is not reduced at all.
- For very small currents the reach vanishes and the zone is practically blocked.
- For larger currents that cause the MOVs and/or air gaps to conduct some current, the reach is reduced according to current magnitude

B. Kasztenny. "Distance protection of series compensated lines–problems and solutions." in *Proc. 28th Annual Western Protective Relay Conference*, pp. 1-34. 2001.

So therefore, for this transmission system, and relay at here, capacitor at here, if you see this perspective, so we have the larger one, normal one, for the M N line 80 percent let us say, normal line impedance considerations and Mho relay setting for that one. Now, with consideration of the lower current when -jX_C is there in the fault loop. And now, from this point to this point, we are changing the setting using the currents as seen by the relay for that fault. So, this is what we call adaptive, adaptive means in accordance with the system condition we will have on the concept of adaptive more elaborations in the latter part of the course.

Now, here what we say that if the fault current is larger then we have no role played by this X_C, so then you have the normal setting if the fault current is smaller than the X_C is full in the circuit fault loop, but if the fault current is in the in between the higher value and the lower value then the setting has to be adaptive in accordance with that one, the equation which is used in the earlier slide. So, that is the role played here so for very small currents the reach vanishes and zone is practically blocked that we have seen, for larger current and the cause of the MOVs and the air gap to conduct some current that is reduced according to the current magnitude.

So, the corresponding reduction path is this, the reach is being reduced this one. So, this approach is based on the magnitude of current larger current the reach is higher, smaller current the reach is lower.

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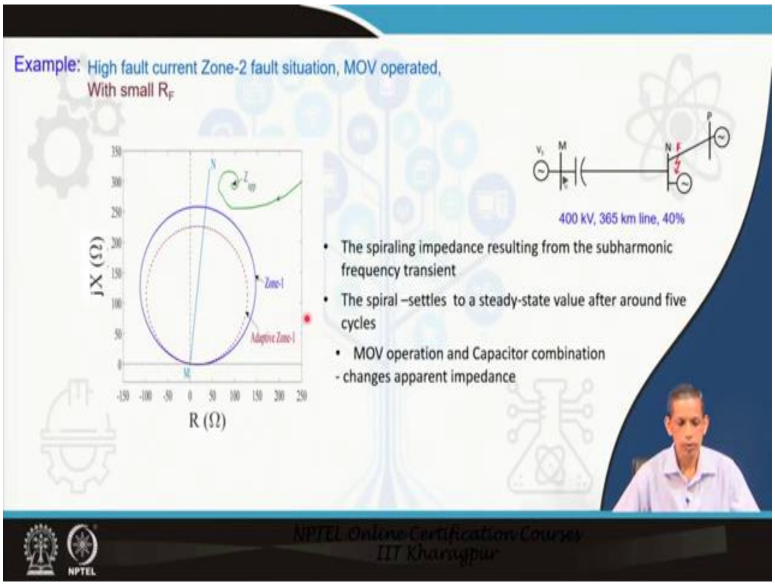

Example: High fault current Zone-2 fault situation, MOV operated, With small R_F

400 kV, 365 km line, 40%

- The spiraling impedance resulting from the subharmonic frequency transient
- The spiral –settles to a steady-state value after around five cycles
- MOV operation and Capacitor combination

- changes apparent impedance

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Now, let us see an example for a system 400 kV, 365 km system, 40% compensation at the local end of the bus M, only one series capacitor and we have created a fault of resistance R_F small value of R_F and then we see what happened to the zone apparent for the phase a to ground fault case. So, you observe that this is about zone 1 setting, normal setting for the line the blue curve, fault is created in the zone 2 next line.

So, we see here in this case with small R_F, small R_F means the corresponding fault current is significant. So, this corresponding capacitor and the corresponding MOV operation changes the apparent impedance. Now finally, what happens that the corresponding settling point that the capacitor in the MOV bypass the corresponding capacitor and the corresponding fault is beyond the zone 1, this is correct. So, what do we see that with small R_F the current becomes high, the MOV starts operation and then finally the corresponding air gap also fires and therefore the capacitor is bypassed.

But in the process because of this LC presence, there will be the corresponding sub-harmonic frequency oscillations and the oscillations will be observed for some time. Typically, these oscillations remains for around 5 cycles or so in systems and then the corresponding MOV and air-gap (())(30:39) operations happens to be there, it settles at the bypass of the capacitor it settles at a particular point.

So here, because of the large current small R_f , relay is able to adjust in terms of that, but note that in between, because of this MOV operation in the capacitors, the adaptive setting can be observed. So, accordingly the dotted line corresponds to, at one instant of time the corresponding current value, depending upon the current value the dotted line happens to be an adaptive zone 1 setting. Why we carry out this adaptive zone 1 setting here, that there is a chance that the corresponding spiralling due to the presence of this short-circuit the sub harmonic component may enter into the zone 1.

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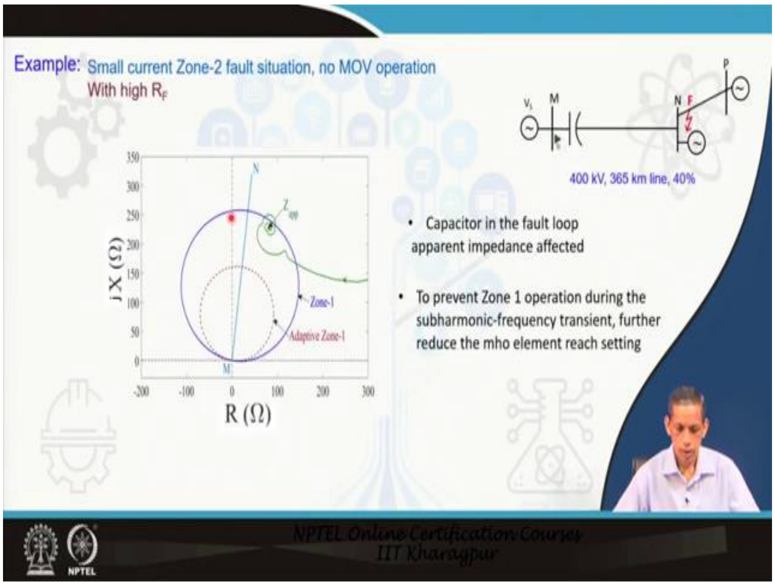

Example: Small current Zone-2 fault situation, no MOV operation
With high R_F

- Capacitor in the fault loop apparent impedance affected
- To prevent Zone 1 operation during the subharmonic-frequency transient, further reduce the mho element reach setting

See this example, it will be more clear now. With higher R_F in the same fault same arrangement, same system for 40% compensation. Now what happens we see here at the same point line-to-ground fault is being created in phase a. Now you see here, the corresponding apparent impedance settles finally after a few cycles of the oscillation, settles inside zone 1. Now the reason behind that now the corresponding capacitor is in the fault loop so therefore there will be reduced value of this. Now what we do, here the corresponding adaptive zone 1 will go for this one.

Now, the corresponding fault is in zone 2, so not in zone 1, but here if we do not do the adaptive things, it enters into the zone 1 and creates a problem, even though the fault is beyond the line. So however, if we do the adaptive thing, then the corresponding advantage can be availed and this adaptive thing is then based on current control approach based on using the (())(32:37) current through the relay as we have discussed in earlier slides.

So, this is using the, the adaptive setting is based on the current through the relay and if this can be done, then you can avoid the malfunction of the relay in a better way, this is clearly observed from this example, on a zone to fault for this 400 kV system.

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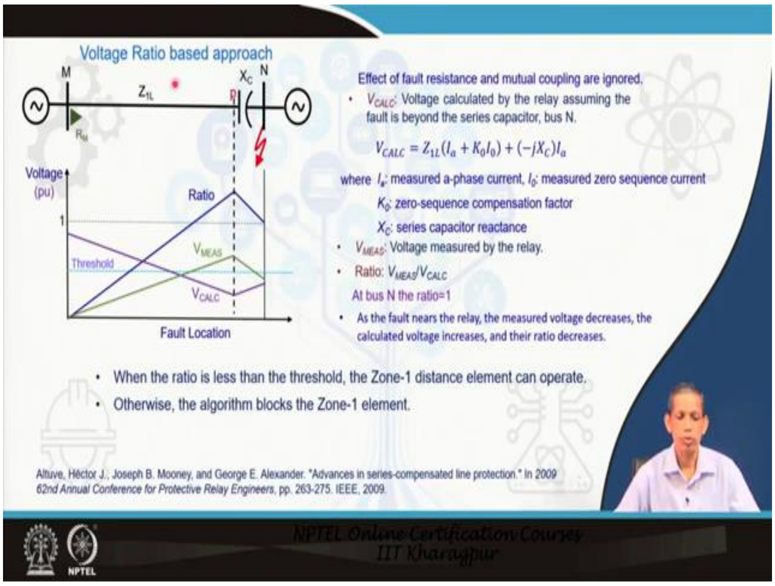

Voltage Ratio based approach

Effect of fault resistance and mutual coupling are ignored.

- V_{CALC}: Voltage calculated by the relay assuming the fault is beyond the series capacitor, bus N.

$$V_{CALC} = Z_{1L}(I_a + K_0 I_0) + (-jX_C)I_a$$

where I_a: measured a-phase current, I_0: measured zero sequence current
K_0: zero-sequence compensation factor
X_C: series capacitor reactance

- V_{MEAS}: Voltage measured by the relay.
- Ratio: V_{MEAS}/V_{CALC}
  At bus N the ratio=1
- As the fault nears the relay, the measured voltage decreases, the calculated voltage increases, and their ratio decreases.

- When the ratio is less than the threshold, the Zone-1 distance element can operate.
- Otherwise, the algorithm blocks the Zone-1 element.

Altuve, Héctor J., Joseph B. Mooney, and George E. Alexander. "Advances in series-compensated line protection." In 2009 *62nd Annual Conference for Protective Relay Engineers*, pp. 263-275. IEEE, 2009.

We have second approach also as available in the literature. So, this is called voltage ratio based approach to call for this we have 2 voltages, one is the calculated voltage and the other is the measured voltage by the relay. So, system is here like this, if you see you can say that the relay and the capacitor is at the line N, then for this section, zone 1, there is no capacitor so it does not have any problem. But if a fault happens to be in the just beyond the capacitor then if the capacitor is in the fault loop during a fault, then the relay will find (jX_l - j X_C) so it will be having an equivalent impedance much smaller and it will be having an overage phenomena.

So, fault in the zone 2 actual zone 2 will be also a fault in zone 1 and that may create problem. To have that in this approach what is being done that whether the corresponding fault is beyond the capacitor or fault is before the capacitor if we can know that then we can have solution accordingly so this approach provides that information. So, what is being done that in this case the V calculations will be done, the V calculation is calculated by assuming that the fault is beyond the capacitor, no R_F or no mutual coupling in the line is considered.

So, $V_{CALC} = Z_{1L}(I_a + K_0 I_0)$ for the phase to ground fault as usual and $V_{CALC} = Z_{1L}(I_a + K_0 I_0) - jX_c I_a$ in this case. I_a, we are not doing the zero sequence compensating because this is not-line so the 0-sequence mutual effect will not come into picture at the X_C part. So, as usual, these are all measured value of the current and the perspective and K_0 is the 0-sequence compensating factor and so. V_{MEAS} is another value that is measured by the relay as usual.

Now, we have this ratio V_{MEAS}/V_{CALC} what we have calculated here for that perspective, and along the line if you go changing the corresponding distance of the line from fault location to fault location from the bus M to the bus N, then there will be two perspective the V_{MEAS} and the corresponding V_{CALC}. So, here V_{CALC} becomes a large value from this perspective, because of -jXc and all these things, so V_{CALC} from large value to a small value it will come till the P and then it will increase at this point this is the P point, however the corresponding measured voltage from this one, if the corresponding fault happens to be here the voltage collapses so from 0 to this one 1 and after that the capacitor is again decreases.

So, at bus N the ratio becomes 1 theoretically, as the fault nears the relay, the measured voltage decreases, the calculated voltage increases and the ratio decreases. So, what we see that the ratio that is the V_{MEAS}/V_{CALC} becomes measured value 0 so that becomes increases like this and again decrease after the capacitor. This ratio is useful in determining the corresponding the position of the fault whether it is beyond the capacitor or before the capacitor.

So, when the ratio is less than the threshold, a threshold is selected suitably depending upon the reach of the line the zone 1 distance and otherwise we can say the algorithm blocks the threshold, the threshold computed by this one in the real time by the relay. If the ratio is less than the threshold, zone 1 is allowed to operate. However, if it is beyond the threshold, the zone 1 is not allowed to operate.

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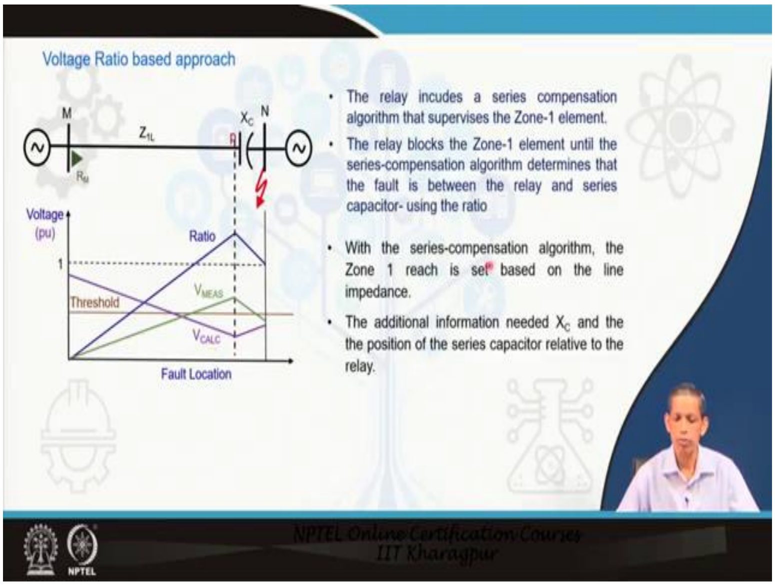

Voltage Ratio based approach

- The relay incudes a series compensation algorithm that supervises the Zone-1 element.
- The relay blocks the Zone-1 element until the series-compensation algorithm determines that the fault is between the relay and series capacitor- using the ratio
- With the series-compensation algorithm, the Zone 1 reach is set based on the line impedance.
- The additional information needed X_C and the the position of the series capacitor relative to the relay.

So, with that philosophy the series combination algorithm, the zone 1 reach is set based on the line impedance, an additional information needed on X_C that is whether the corresponding X_C is encountered in the fault loop or not, and that is by the voltage ratio and that voltage ratio decides zone 1 will be in operational or blocked.

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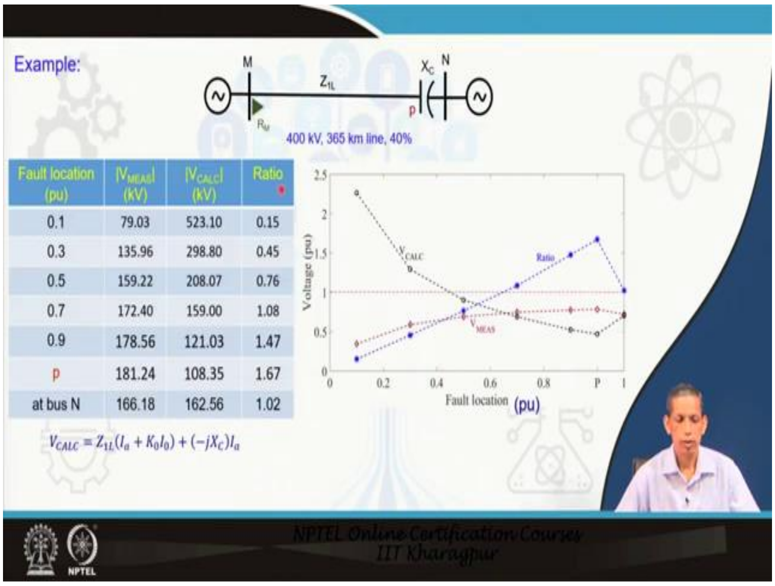

Example:

400 kV, 365 km line, 40%

Fault location (pu)	$\lvert V_{MEAS} \rvert$ (kV)	$\lvert V_{CALC} \rvert$ (kV)	Ratio
0.1	79.03	523.10	0.15
0.3	135.96	298.80	0.45
0.5	159.22	208.07	0.76
0.7	172.40	159.00	1.08
0.9	178.56	121.03	1.47
p	181.24	108.35	1.67
at bus N	166.18	162.56	1.02

$$V_{CALC} = Z_{1L}(I_a + K_0 I_0) + (-jX_C)I_a$$

Now, let us see an example, 400 kV line, 365 km as we have seen earlier 40% compensation. So, what we did here, we created fault at different points along the line 10 %, 30%, 50%, 70 %, 90% point P just before the capacitor and just after the capacitor at bus N, so we created fault and then you can see that we measured the voltages at V_M as seen by the relay through the simulations and we calculated the voltage using this relation, and then we computed the ratio for all the points. So, these ratios are plotted here along the corresponding calculated value of the voltage and also the measured value of the voltages.

So, what we find that if you put a selective threshold value then if it is less than the threshold value, then zone 1 will be allowed to operate otherwise zone 1 will not be allowed to operate. So, this is a voltage ratio driven zone 1 operation and which can be also applied for transmission and protection in this kind of scenario.

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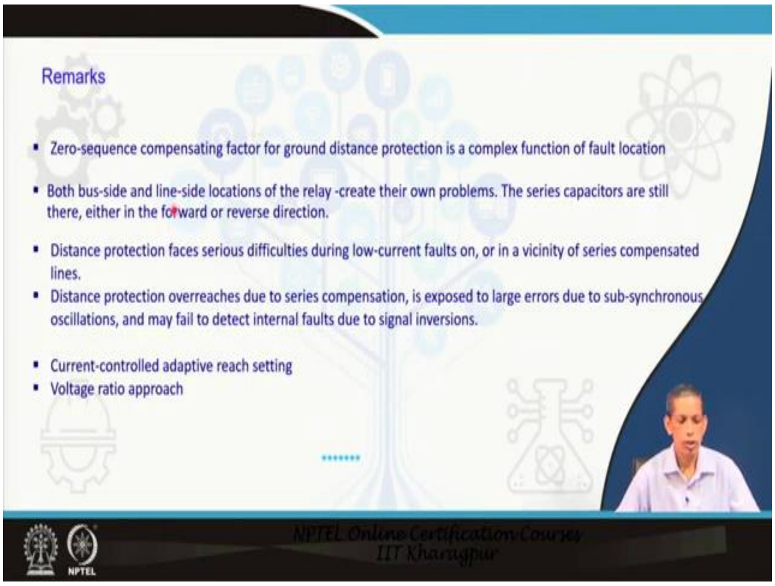

Remarks

- Zero-sequence compensating factor for ground distance protection is a complex function of fault location
- Both bus-side and line-side locations of the relay -create their own problems. The series capacitors are still there, either in the forward or reverse direction.
- Distance protection faces serious difficulties during low-current faults on, or in a vicinity of series compensated lines.
- Distance protection overreaches due to series compensation, is exposed to large errors due to sub-synchronous oscillations, and may fail to detect internal faults due to signal inversions.
- Current-controlled adaptive reach setting
- Voltage ratio approach

So, in overall we see that in the apparent impedance calculation, 0 sequence compensating factor plays a role and which is a function of x now, the fault distance difficult to calculate correctly. Both bus side and line side locations of the relay and the associated measurements have some advantage and also some demerits also. Distance protection faces serious difficulty during low current situations when the corresponding MOV may operate and may not operate that is the issue. If the fault happens to be the close to the series compensation voltage and current inversion may create problem even to the apparent impedance calculations, which will be observed in the fourth quadrant also.

Distance protection overreaches due to the series compensation that is another issue. Again sub-synchronous oscillations also during that few cycles also creates problem. We found that some solutions perspective current control adaptive reach setting and voltage ratio approach are the two methods we described in this one has its solutions to the series compensated line. So in this perspective we see that series compensation creates challenge to the distance relay operation, distance relay settings, distance relay performance. Thank you.