Power System Protection
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Lecture 42
Line Differential – Part 1

Welcome to NPTEL course on Power System Protection. We are continuing with next module on Differential Protection of Transmission Line and Busbars.

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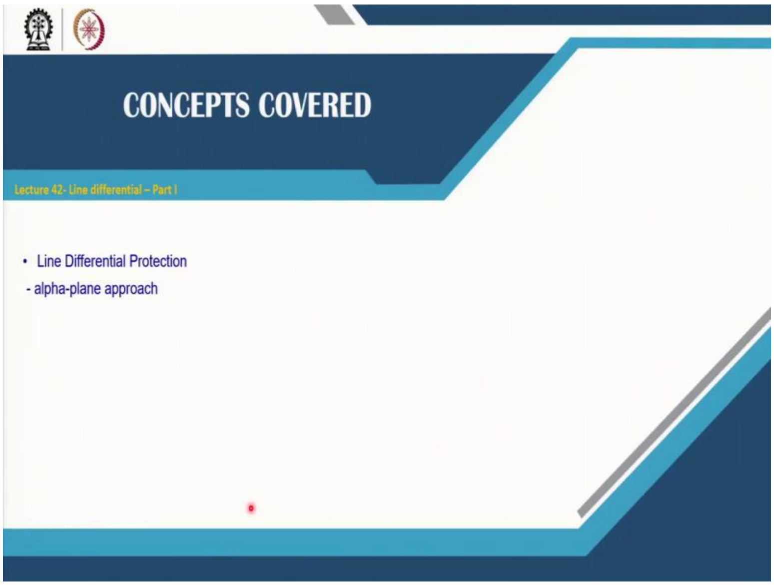

In part 1 of the line differential protection, our emphasis will be on the normal percentage bias differential relay. And there from, we will go to the α-plane Approach, a superior approach using the current differential principle. Note here, it is a differential protection of lines, cables and so. So, we need communication system, and that makes the big difference as compared to the differential protection of transformers, which we have already addressed in earlier modules.

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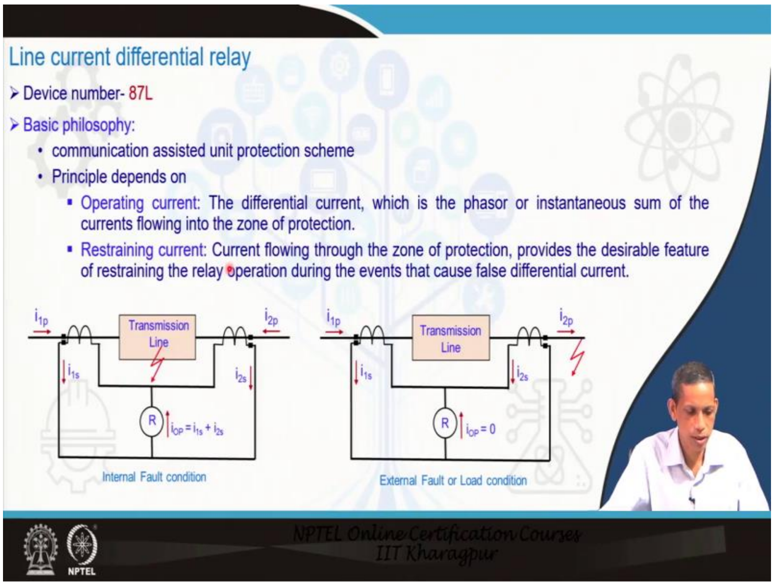

Let us see, how this line differential functions. Device number 87L for line. So, this is unit protection, but it needs communication. As usual the differential protection has 2 components of currents, operating current and the restraining current derived from the currents from the 2 ends of the line here. So, we are, let us say, considering a generic transmission line here, so this is a transmission line.

And as we discussed for the transformer, similar to that the corresponding CTs are connected here. The corresponding operating current becomes equal to the secondary current of the CT i_{1s} incoming here. So, this is internal fault. So, from the side also incoming current. So, that makes the current directions in the CTs to be like this, and then becomes, the operating current becomes i_{1s}+i_{2s}, primary side s. So, call 1 side and the 2 side.

Now, note that this a transmission line. Unlike transformer, here the voltage level is same. So, the corresponding expected CTs are of same ratio, same make or at times if the, that CT may be replaced by another make also. And with time, the partners of the CT may vary even though they may be having same ratio or so. For external fault, the current direction in the line becomes like this, unidirectional. So, therefore, you see here the current, this side becomes same as compared to the earlier case of internal fault, but this side the current direction becomes changed.

And the operating current becomes, i operating becomes equals to i_{1s} - i_{2s}, and that results the operating current to be 0 in general. So, for external fault, the operating current will be 0 and for internal fault the operating current will be higher. But the restraining current, the current flowing through the zone of protections provides the desired feature for restraining the relay, and this is similar to what we have discussed for the transformer protection. We will have more details in subsequent slides.

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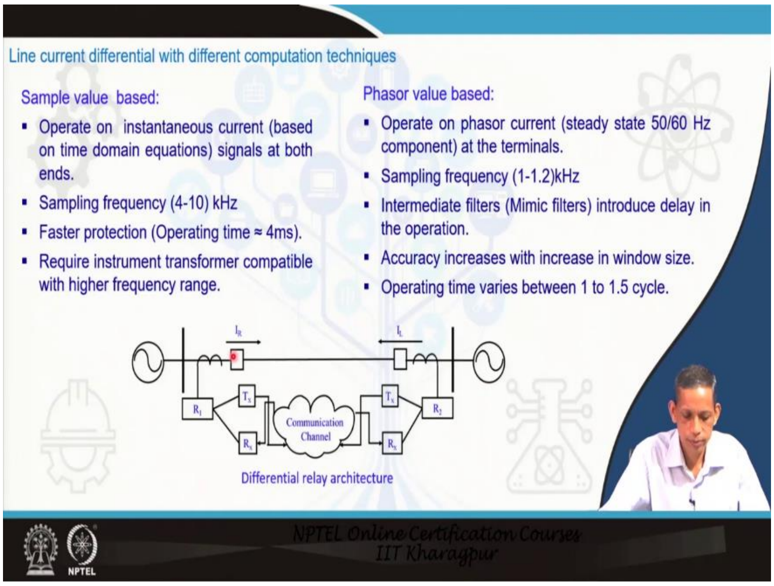

Two approaches, like in transformer also, we discuss, one is Sample Value Based Approach for Differential, Line Differential and the other is Phasor Based Approach. They have their own advantages and disadvantages. Sample value-based approach uses the sample value, the instantaneous current samples. Typically, the range is 4 to 10 kHz in available relays. Very fast protection, operating time around 4 millisecond and so.

And the high sampling rate and so, the corresponding instrument transformer should be compatible to that. Phasor value-based approach, it can be lower sampling rate also and then we have many filters, phasor estimation and all these things. So, therefore, the corresponding protection decision typically ranges from 1 cycle to 1.5 cycle for a reliable decision. But accuracy will be better as compared to the sample-based approach.

So in generic, we say if this is a transmission line having few kilometers, then essentially we require relay at this end, receiving end and, the relay at R end and relay at L end. So, the corresponding Relay R_1 and Relay R_2, one will be transmitting and the other will be receiving the corresponding sample value or the phasor values through the communication channel, and the corresponding relay will be deciding locally to trip the corresponding circuit breaker.

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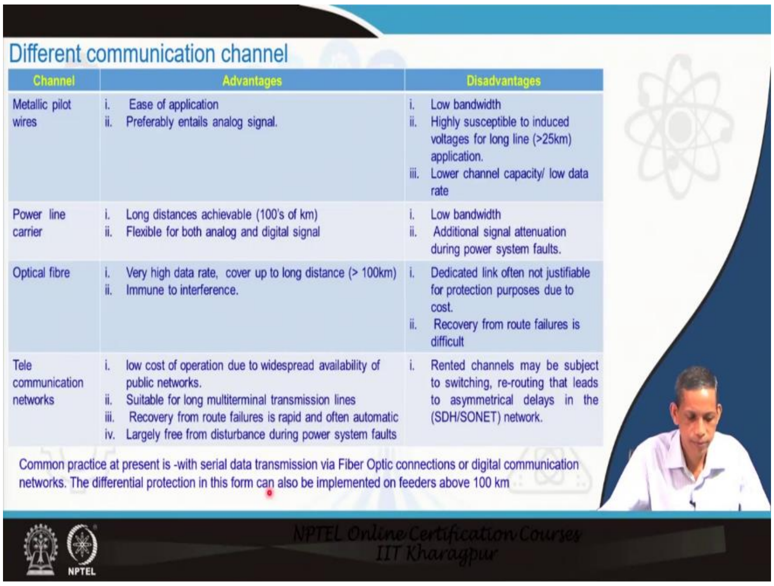

So, as mentioned, this essentially requires communication channel, which is the backbone of this operation of the differential relay principle for transmission line and so. And the varieties of approaches, we will see, speed of operation and so, solely depends on the communication channel. We can have the pilot wire; metallic pilot wire as usual; we can use the power line carrier also; the fibre optic approach, widely accepted today; other dedicated telecommunication networks.

So, they have their different advantages. For metallic pilot, it is ease of application, relatively cheaper also. So here, power line carrier, but there through the same line, so that is why it had its own applications, limitation also, advantages, you do not require any further cable or so for the communication. Fibre optic, very high rate and volume of data can pass may be, will be considered very high. It leads to advantage of larger distance of protection also. In other forms, it may be 10 kilometer, 20 kilometer limitations kind of thing, but here it can go more than 100 kilometer also. Fibre optic approach, it does not have any electromagnetic interference, that is another advantage.

Telecommunication networks, from that one, we can take a one, and then there becomes a cheaper operational cost, and investment may not be required also. These are free from disturbances from the power systems, and the recovery routes failure becomes pretty small like, because they may be maintained by others and there may be alternative routes and so.

These options have their disadvantages also like pilot wires having low bandwidth, flow channel capacity, so also, the power line carrier, interference with the, during faults the corresponding signal availability may be poor. Fibre optic cable, higher cost associated and recovery of route failures, communication link failure, recovery becomes challenging. These telecommunication channels with rented ones, they have, the demerits of because of other signals will be, they are available. So therefore, interference may be there in terms of other things.

So, in our, we can see there are different options available for communications, and accordingly the application scope remains. Today, we have fibre optic based communication to, with digital communication networks. And this leads to the scope of transmission line larger than the 100 kilometers also to be protected through such an arrangement.

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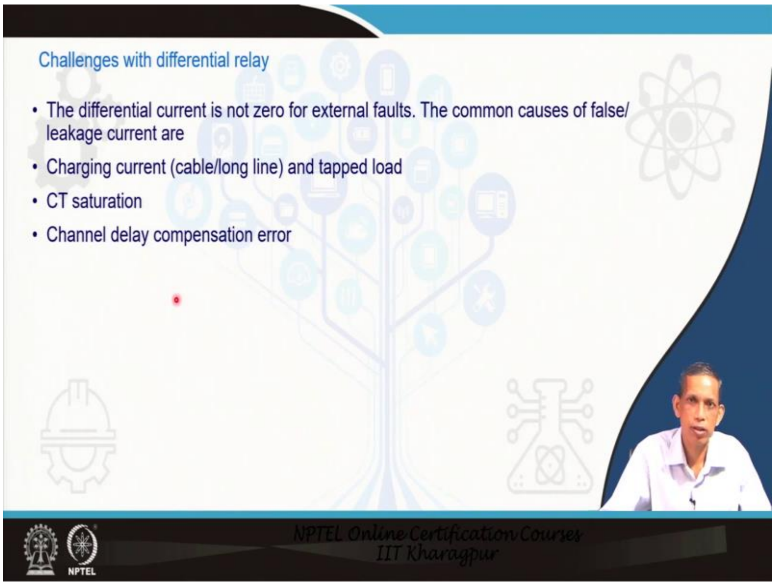

But there are generic problems with differential relay. The differential current does not become 0. For external faults, there are different regions for that. For example, high voltage system, cable or long line, charging current is pretty large sometimes. The higher the voltage and the longer the lines, the charging current becomes more. Tapped load, if there is a in between tapped load, that load has, that has to be taken care in the differential one.

CT saturation, as usual you see here. Even though the CT ratio may be same with time and so, and in case of different manufacturers, different quality of magnetization characteristics, one CT may saturate deeply and one may not saturate. That becomes a problem. Channel delay compensation error. We know, we have now communication system.

So, there will be a delay in availing the data at one end. And that leads to time difference. So, when we are talking about phasor or sample values, the comparison becomes erroneous and that leads to non-zero differential current, false current or the leakage current perspective even during external fault or so.

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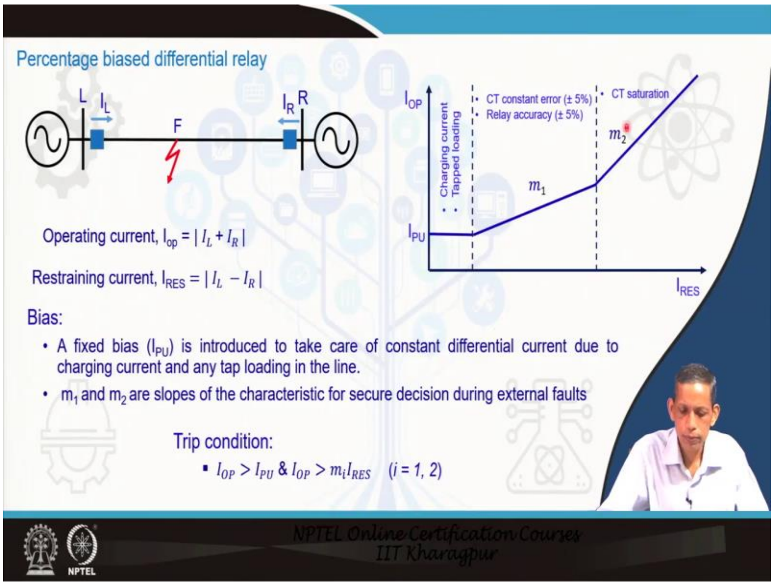

Now, let us see first the percentage biased differential relay. The way we have discussed in transformer protection also. This is the transmission line, L bus and R bus, local bus and remote bus or so. Now, the operating current, $I_{OP}=|I_L+I_R|$, this side current and the side current and the restraining current $I_{RES}=|I_L-I_R|$. So, this is the way we discuss in transformer protection also.

So, this decision of the relay will be based on the I operating current should be I_{PU}, the pickup setting, minimum current required, and must be also greater than $m_1 I_{RES}$. And we can have 2 slopes like in transformer m1 and m2. Here, we have 3 zones, we have divided the characteristics, the upper, above this line characteristics is trip and below is no trip case. The first portion is about the assign to the charging current issue. So typically, this IPU is set twice of the charging current or so.

And more than, may, then also, that also. CT constant error, there may be something like 5 percent and so. Relay accuracy, the computational perspective of the relay and associated things, error will be there, so that falls in this region. And when we have CT saturation for through fault or so, then deep saturation leads to more differential current. And that should be address here in terms of, with higher slope or so.

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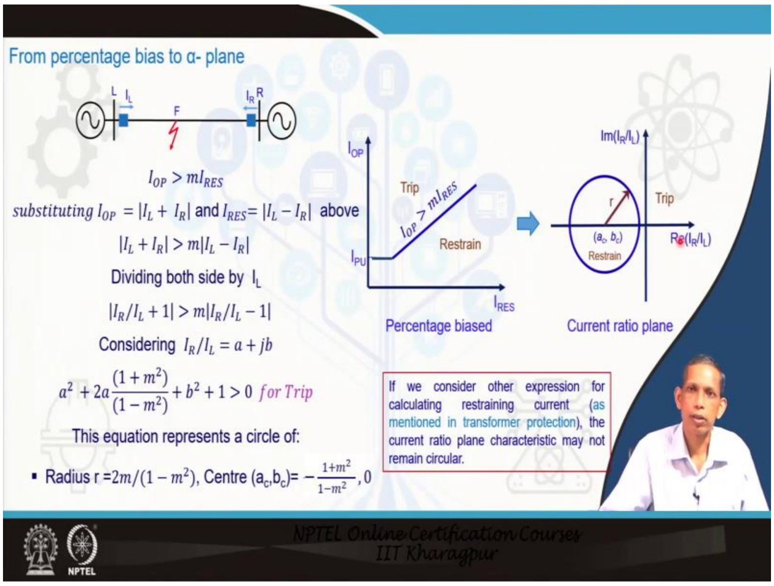

Now, we will see how we can move from percentage biased differential relay to another form of characteristics called α-plane characteristics. So we will start from the basics and then release to how that is being realised in different available percentage by, different available line differential protection schemes. So here, for this case, I operating should be greater than mI_{RES}. So, let us say, this basic equation is to be used.

So, if you are using only this equation, so substituting, I operating equals to IL plus IR, and I restraining equals to, sorry, $I_{op}=|I_L+I_R|$, and $I_{res}=|I_L-I_R|$. Then, we get the corresponding, from this relation, we get this relation in terms of the slope of the line. And then dividing both terms by I_L, we get $|I_R/I_L + 1| > m|I_R/I_L - 1|$.

So, these I_R and I_L are our phasors, and considering $I_R/I_L = a + jb$, complex number, so we get the corresponding inequation $a^2 + 2a\frac{(1+m^2)}{(1-m^2)} + b^2 + 1 > 0$. Note, this decision process, $I_{OP} > mI_{RES}$ is for this region, that is a trip region.

So therefore, from this what you derive, so this relation states for trip. So, this portion greater than 0 implies it for the trip decision. But this relation gives us a representation of a circle, whose radius $r = 2m/(1-m^2)$, and centre of that circle $(a_c, b_c) = -\frac{1+m^2}{1-m^2}, 0$.

So, if you we see, this mI_{RES} imply this straight line from the origin for this straight line equation only for this relation, then this can be translated into this, and this will be a circle with (a_c, b_c) at the centre, b_c being 0 in generic here for this relation. And with radius r. So, this relates to the corresponding imaginary versus the real part of the I_R/I_L. Note, I_R/I_L, it means that if we are talking about from this and local, so that remote-end current to local current.

So, this ratio, what we have found here, considering that as a plus jb, so this leads to in terms of that. Now, however we have taken a simple equation here. Now, if we consider other expressions for calculating the restraining current like I_{RES}, as K multiplied with $|I_L-I_R|$ or $\max(|I_L|,|I_R|)$, then the plane, the corresponding plane characteristics becomes different, more complex. But for simplicity, we are trying to study the translation from this percentage by differential relay to such real, imaginary plane in terms of this.

Note, one point here, a difference here that the $I_{OP}=|I_L+I_R|$, and $I_{RES}=|I_L-I_R|$ or in some case we take $I_{RES}=|I_L+I_R|/2$ or like that. So, these are on the magnitude of the phasors, but here, we see here, we are just like taking imaginary and real corresponding phasor value, both magnitude and angle part and real part and the imaginary part. Similar to that, your distance relay you consider about the impedance, the real and imaginary aspect.

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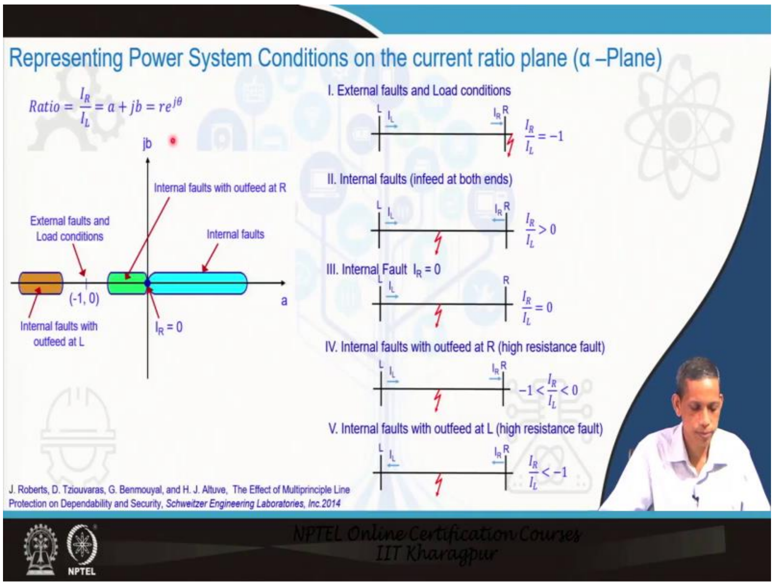

Now, coming to that, complex I_R/I_L, they are complex form. So, $\frac{I_R}{I_L} = a + jb = re^{j\theta}$. Now, let us study this nature of this equation. For external faults and, or loading condition, this is the line, there is an external fault or any loading condition, I_R/I_L, that will be equals to -1 as per the CT connection. So, that becomes equals to 1 with an angle of -180^{O} , the other way in the polar form, in this form.

So, this I_R/I_L being equal to -1, so in this complex plane, so this happens to be this point. So, this one corresponds to external fault of loading condition. Second situation, internal faults, infeed at both ends, interconnected network. So, for internal faults, current flows from this side and also from this side. So, I_R/I_L, that may be greater than 0, so this portion. I_R 0, this end 0, radial system also, then current only flows from this, so that becomes 0, so that is this point.

Internal fault with outfeed, through, high resistance fault, so even the internal fault happens to be there. And because of high resistance path, current may still perform this side to this side, it can still, load can be still to some extent be maintained. So, in that case, I_R/I_L that in the region of 1 to 0, and we are talking about that the internal faults with outfeed, so internal fault with outfeed at R. So, this green region corresponds to, for this situation.

Internal faults with outfeed at L, so now here power is flowing from this side kind of thing and the fault and then this one, so I_R/I_L, so this I_L<-1 and this falls in this region. So, what we say that these are the different condition of the system for external faults and internal faults. And that reveals that on this complex plane, there are different regions, which you can clearly state that this corresponds to internal fault and this corresponds to external fault or so. This is what, we can reveal from this relation.

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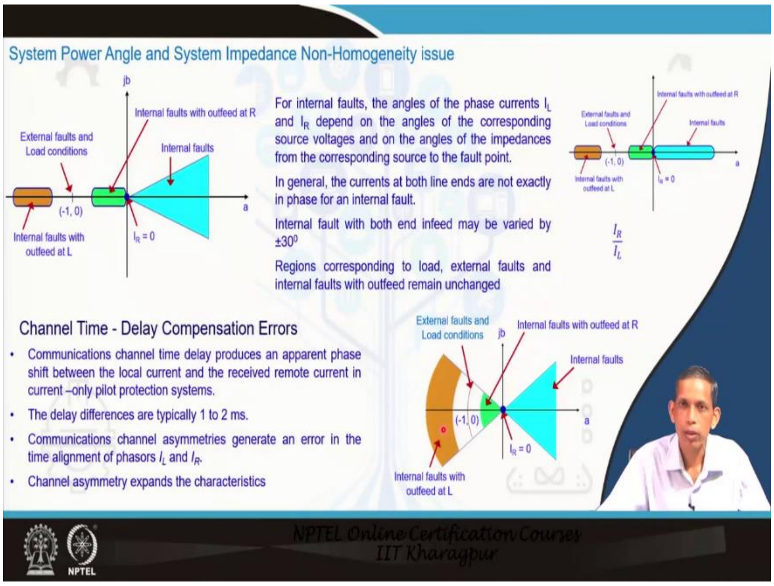

Now, in reality, this system is not ideal as expected. And like a condition, there is non-homogeneity issue, source impedance angle may not be same as the line impedance angle and it is more prominent in case of cable and so. For internal faults, the angles of the phase angle I_L and I_R depend on the angles of the corresponding source voltages and the angles of the impedances associated, that is the sources.

So, what happens, that the points and the region, which you had thought of earlier in an ideal translation in the complex plane (a, jb), now what we say, that in reality there will be some variation in there. So, in general, the currents at both ends are not exactly in phase for an internal fault. So therefore, there may be a region of like this, it might be $\pm 30^{O}$ variation, something like that. The region corresponds to load, external faults and internal faults with outfeed remain unchanged.

So, this will be unchanged, because in case of this transmission, the fault happens to be there, so fault current flows to that side, so both CTs will be observing a similar level of currents. So therefore, the ratio will be (-1, 0) for even the system may be non-homogeneous. Now next, we will go to the channel time, a channel time is delay compensation error as already mentioned, such an arrangement for a line protection or so is having communication system.

So, there is a delay associated in communication system to avail the data from the other end. So, this communication time delay leads to time corresponds to angle variation in the phasor perspective, because the discussions we are making for these characteristics is based on phasor value, not on the sample value. Typical time difference maybe 1 or 2 millisecond. So, 1 millisecond in 50 hertz system corresponds to 18^{O}, 2 millisecond corresponds to 36^{O} and so also similar things will be there for the 60 Hz system also.

The communication channel asymmetries generate an error in the time alignment phasors for IL and IR, local and remote end. So therefore, the characteristic becomes now the expanded one. So, we have discussed for this internal fault issue on the non-homogeneity. Now, on this perspective, for the different external fault region, internal fault outfeed and internal fault with outfeed at R and so, what we have discussed from this perspective.

Now, there will be some uncertainty regions, again they will be expanded because of the associated delay in the channels, that delay corresponds to angle, and therefore, we have extended the angle from this side and both these sides depending upon the delay and which end we are using. So this is from the ideal nature of this, there will be deviation in case of actual circuit realization.

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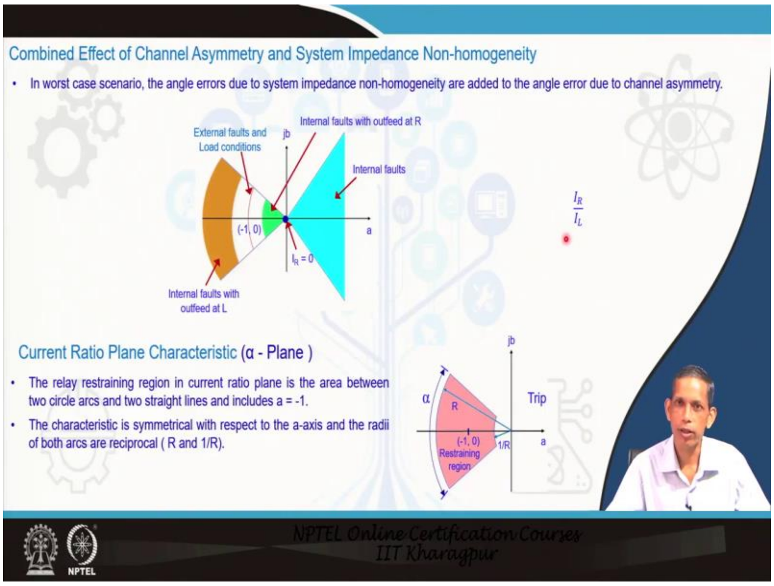

Now, combining the effects of channel asymmetry and system impedance non-homogeneity issue and all these things, so both combined and the effect may be more significant, and that leads to a characteristic like this, where this portion, you see here, these portions in -1 to 0 around, that is for the external fault or load condition, that is, it means that this is restraint region. And the other region are internal fault, this is also for internal fault, this is also for internal fault and so on so forth, this is also internal fault case.

So, this is a region of restraint region, and the other portions are, whatever has been provided with colours are being the internal fault cases for the transmission line. Now, another case situation, current ratio plane characteristics, which we talked about from this, we like to go to that α-plane, we call it α-plane.

The relay restraining region in current ratio α-plane, the area within this, so what we say here, that from this overall characteristics, some of the manufacturers provide on the complex plane to have this in terms of the characteristic is symmetry with respect to the a-axis and the radius of both arcs are reciprocal, that is, if this arc is R, this becomes 1/R.

So, that leads to situation about that this restraint region here, is being mapped like this with an angle of α, that is the name, we are talking about α-plane. And then on this complex plane, we talk about this region, a different restraint region. And rest region is called the trip region of the system. Such an approach is called α-plane. And that, we can say, ratio equals to be I_R/I_L, and we consider the ratio to be I_R/I_L, that is called the β-plane and so.

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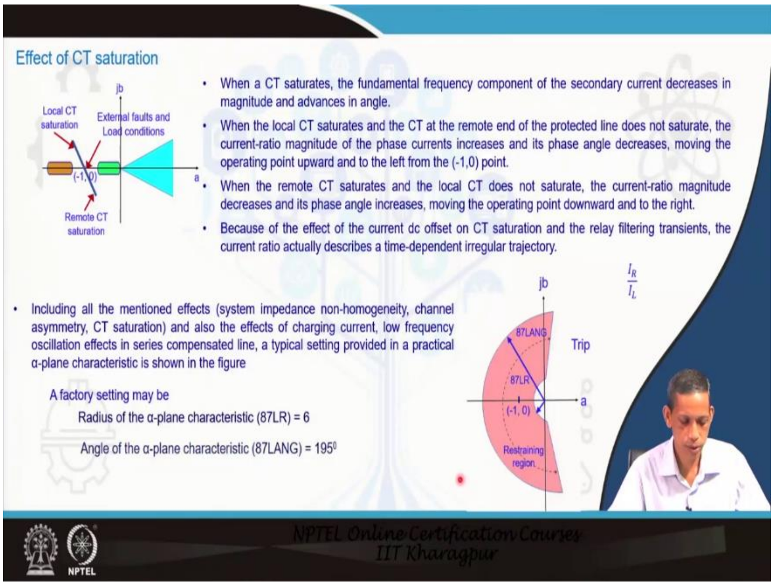

Confining only to this α-plane aspect, now let us, we led to the CT saturation perspective. In case of CT saturation, the fundamental frequency component of the secondary current decreases in one of the, let us say CT saturation in one of the CT. When the local CT saturates, and the CT at the remote end protected line may not saturate, the current-ratio magnitude of the phase current increases and its phase angle decreases, and that leads to the moving the operating point upward to the left from the -1 to 0.

So, this is what, upward, this one local CT saturation. And when the remote CT saturates, the local CT does not saturate, the current-ratio magnitude decreases, and its phase angle increases, moving the operating point towards the right. So, this, you can see this. So, this will be region, which we are talking about for CT saturation prescriptive. So, that leads to the corresponding issue with the inclusion of the CT saturation.

And because of the effect of the current dc offset on CT saturation and relay filtering transients, the current ratio actually describes a time dependent irregular trajectory, so that we will go for the turbulence kind of thing during that fault, in the initial period of fault and so.

So, including all the mentioned effects, the non-homogeneity, channel asymmetry, CT saturation and all these things, and also the effect of charging current, low frequency oscillation and all these things, so finally, manufacturers provide a region of, in the complex plane of jb versus a. The corresponding restraining region to be like this, and the rest of the region being the operating region for the systems.

And these, the larger one corresponds to the radius of the restraining region R and the smaller one is 1/R, as we have already described this. Some factory settings and all these things, which manufacturers provide, the 87LR for that radius is 6. And the corresponding angle for that may be typically 195^{O} or so, this α angle and so.

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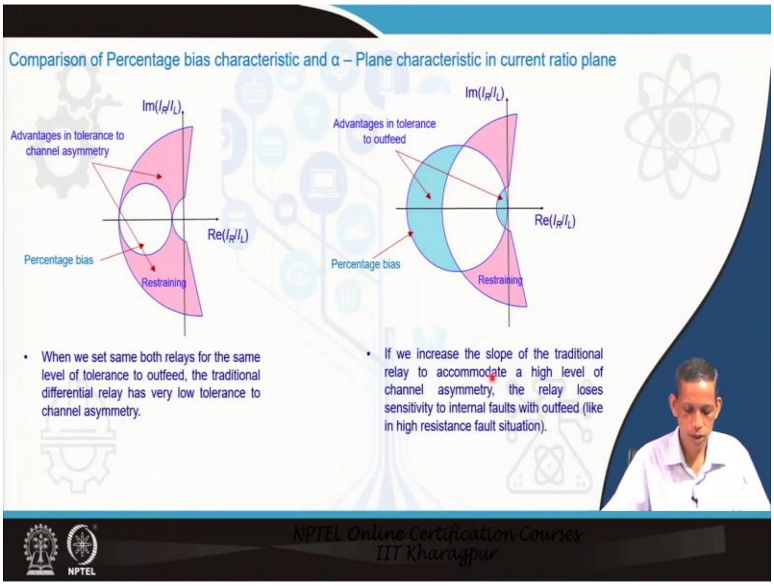

Now, when we make a comparison between the percentage biased relay and so, so in the percentage biased relay, we talk about that and making mapping of the corresponding line to be, to a circle in the complex plane. But just now, we saw that the α-plane characteristics becomes the whole region. So, the corresponding percentage biased relay, map into this complex plane in only this portion.

Now, note, this extended portion available in this α-plane, the advantages are that they have more tolerance to channel asymmetry, these regions relate to the channel asymmetry, that is the delay and so. And that is the advantage and that is what happens in a typical differential relay, line different protection and so.

Now, if we like to increase the corresponding radius of this circle by increasing the slope of the line, increasing the m in the line differential, percentage by line differential, then we can get a larger circle. R becomes more. But then what happened? On this percentage biased characteristics, mapping here in the complex plane, so, we say, this goes to this corresponding 1/R, the smaller region, which is then internal fault region that vanishes.

And therefore, that leads the sensitivity issue of the, for the particular arrangement with the percentage biased perspective. So, that is the advantage of, so the clear advantage of this α-plane characteristics over percentage biased characteristics. We make smaller, then we have disadvantages in terms of channel asymmetry, and make it larger, there is slope larger, then we have the sudden phase in terms of that on the sensitivity of the relay for internal fault case.

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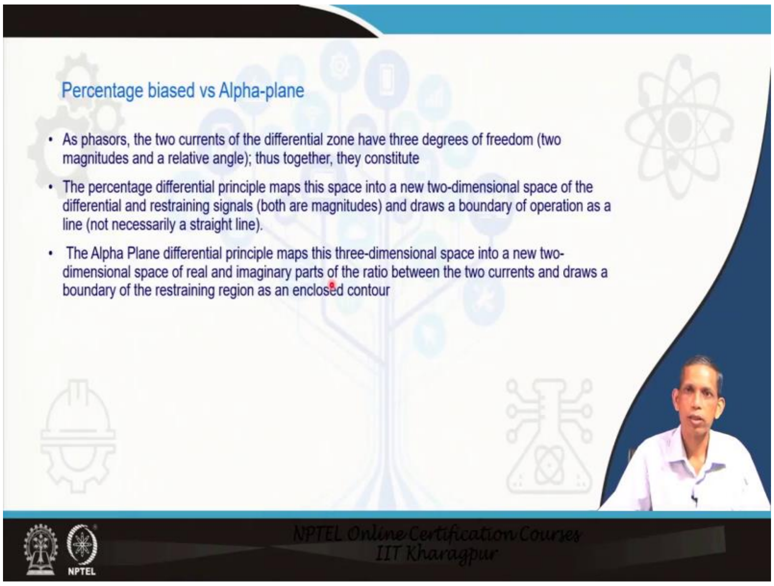

In addition, we see, what you talk about the gain or the advantages of α-plane versus the percentage biased. As already mentioned, there is a clear distinction between these 2 approaches. And why that advantages are being exploited, we can justify from, that the phasors, the 2 currents of the 2 sides of the relay, we have 3 degrees of freedom, 2 magnitudes IL and IR and the angle between them. So, these are the 3 things, 3 degrees.

The percentage differential principle maps this space into 2-dimensional space of differential and restraining signals I operating versus I restraining, but both are magnitudes, and it draw a boundary upon operation as a line, may not be straight line, may be of multiple lines and chord, or chord.

But in α-plane differential principle, we made the 3-dimensional space of IL, IR magnitude and the associated angle into a new 2-dimensional space of real, imaginary parts of the ratio between the 2 currents and they draw the boundary of the restraining region as an enclosed contour. So, here it is only related to magnitude, here we are retaining the angle also. So, that makes the difference between the 2 approaches. And therefore, we exploit more advantages in α-plane compared to percentage biased line differential protection.

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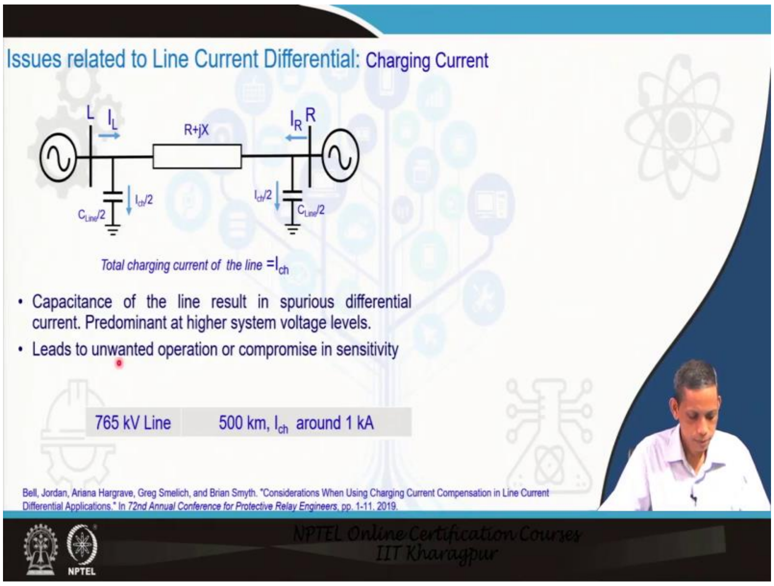

Some issues, first line current differential, related to a charging current. So, we know, over a line had associated capacitance or cable has capacitance. So, when it happens to a long line, the charging current becomes significant. For a 765 kV, 500 kilometer line length, the charging current can be as high as 1 kilo ampere, maybe sometimes more than the load current. So, so, that results in spurious differential current the unwanted differential current, and that clearly leads to a poor sensitivity of the relay unless otherwise been addressed. More voltage, more charging current; more length, more charging current.

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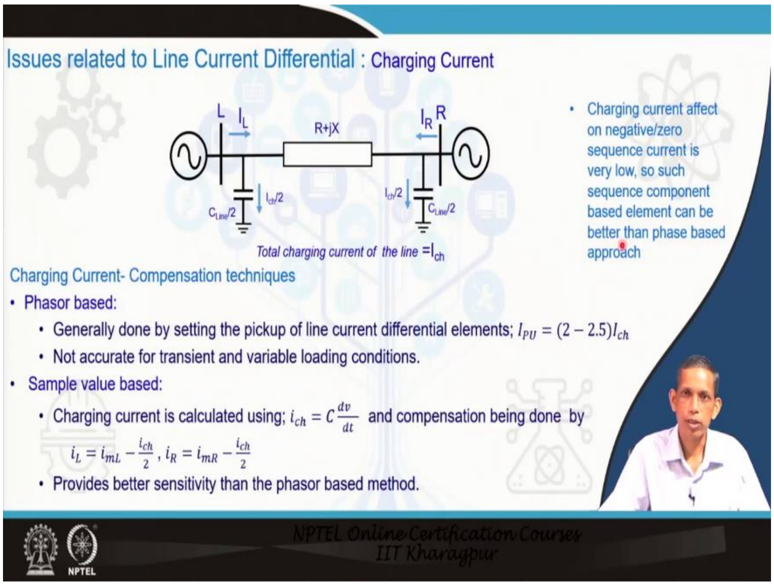

Now, how this charging current is being reflected in the protection? So, we say, the corresponding charging current if it is being, not being addressed, then the percentage biased relay, the threshold, which you talk about pickup I_V should be twice to 2.5 times of the charging current of the line. So, if the line becomes longer, charging current becomes longer. So, pickup setting becomes more and more, that means that we are compromising with the sensitivity.

Sample based approach, the charging current can be computed CdV/dt according to the side which we are computing. And then, we can subtract the corresponding charging current using the sample value, the corresponding measured value of the line current through the CT and then subtract that this charging current upon 2. So, that gives you I_L. So, this way we can compensate the corresponding charging current and that will give you a better sensitivity of the relay, because we are already subtracting the corresponding charging current from the sample's value of current.

After getting the samples, you can compute the corresponding phasors, and this way, you can exploit that, that each corresponding charging current can be mitigated in a better way for the line protection. In addition, you know that the positive sequence, negative sequence and zero sequence, sequence-based approach. So, we have negative and zero sequence current, the corresponding charging current becomes much smaller. And therefore, if we use the sequence based approach of percentage biased element, then the negative and zero sequence approach will be a better solution for managing charging current aspect.

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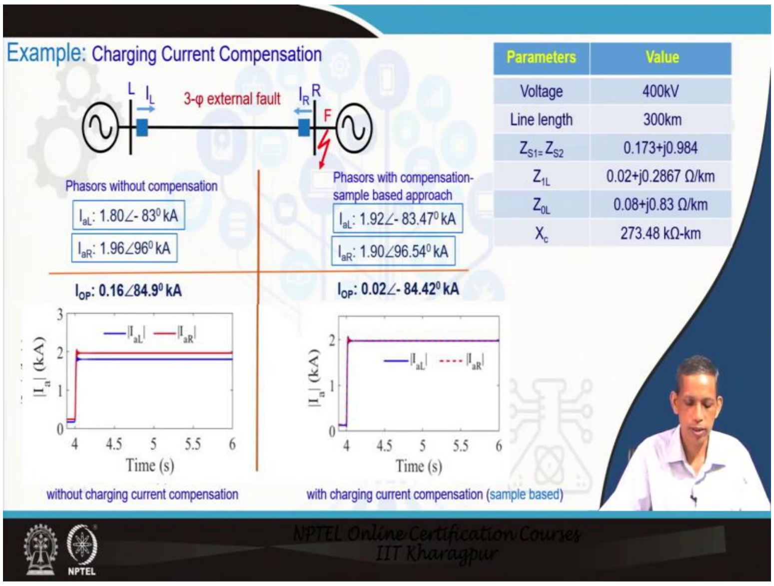

One example on how charging current affects, and then how to mitigate that. This is a 400 kV line, 300 kilometer. Line parameters are available as here in terms of kilometer basis and these source parameters also. So, at an instant, the corresponding phasor's value for this external fault, 3-phase external fault, 1.8 and 1.96 at the 2 ends with angles of -83^{O} and -96^{O}.

Now, what we say here, that the phasors, this is without any compensation, line charging compensation or so. So, then the operating current becomes summation of these two, that leads to a current of $0.16\angle 84.9^{O}$ kA. And if you use, using the phasor compensation with the sample value approach, just like the way we talk about $(I_m - I_c)/2$, so that leads to the corresponding operating current to be $0.12\angle 84.42^{O}$ kA.

So, we see, a substantial reduction in operating current, and that is, it is also evident from the 2 plots, which we see here from this, the corresponding phase A current here and for the phase A current here, in here and in the here case. Here, with charging current being compensated using the sample value approach and here there is no charging current compensation. So, that means that this spurious current will lead to less sensitive differential protection for this perspective, so that the advantage you can exploit by compensating the charging current.

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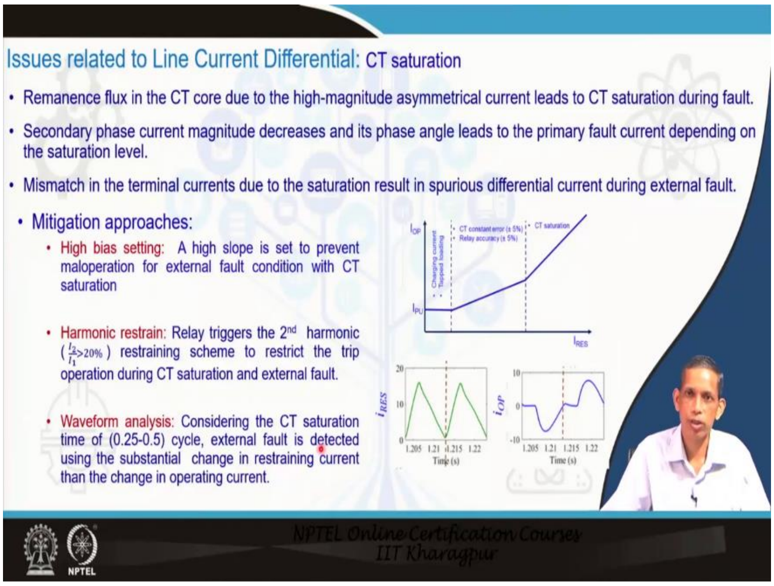

Now, issue with, second issue is the CT saturation. So, in CT saturation, percentage biased relay, what we do with that, we increase this slope and we exploit that. But we increase that slope you compromise the corresponding sensitivity, that is true, and that we have observed in the α-plane approach discussion also. Now, what are the mitigation of the line differential perspective for CT saturation issue, we go for high bias setting, the end to be 0.8 or so, something like that.

Harmonic restraints, we say, in this CT saturation, the harmonic content of the signal becomes, signal harmonic component becomes high. So, I_2/I_1, if we do, that becomes greater than 20%, we can restrain the corresponding situation, you can add the restraining feature more, you can add restrained to that one also. In the transformer protections, these things we have already observed.

We can go for the waveform analysis like I restraining initial portions becomes linear, and then the differential current becomes small and afterwards it becomes large. So, these, up to this external fault, that behavior, the corresponding waveform behavior for external fault with CT is different than, than that of internal fault situation. So, doing that way, just like the transformer, we can also distinguish CT saturation for external fault.

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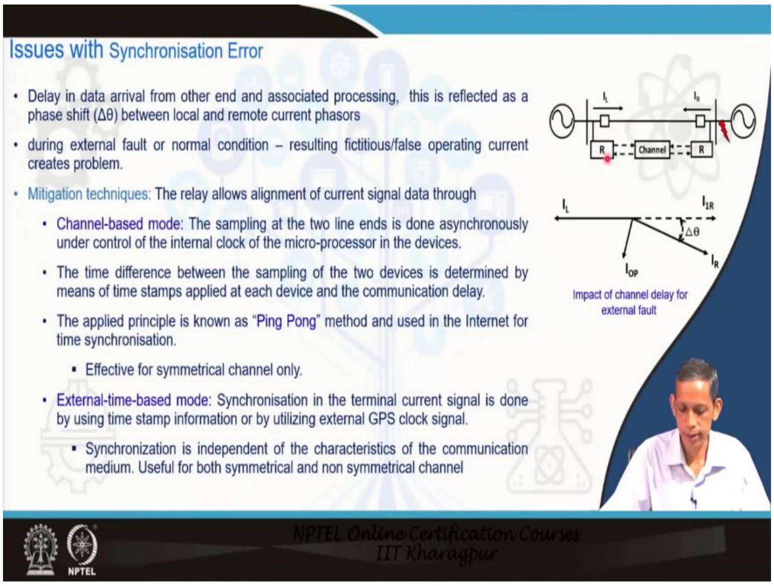

Synchronization Error, this is about the time for the communication perspective and so, and I have already mentioned, any error in time will be reflected in θ and that leads to the phasor differential computations erroneous. So, there are mitigation techniques on this, channel-based mode. We can have the 2, there are different approaches, 2 approaches we will discuss here.

One is the ping pong approach and the other one, with the inclusion of the GPS clock signal and so, which can be, read signal and the, other things there. This, GPS clock and all the details, we will discuss in wide area measurement system or the PMO technology phasor measurement in a technique in details, there also.

Now, what we see here, that the local end phasor is this at a given instant of time and the remote signals when the communication channel arrives here and then it becomes this. So, what we say, that in actuality for this external fault, the corresponding I_R should be here. And because of the channel delay, because this is all the old data, so this anti clockwise rotating phasor should take inside this position.

And because of the time delay, the associated angle Δθ, so therefore, whatever available phasors that must be in accordance with the time delay, that must be, the phasor must be advanced and then we should compare I_L/I_{1R}, then the differential current will be 0 for this external feed. Otherwise, the differential current of I operating will be of this value will be obtained if we do not go for the compensation of the time synchronization between the 2 ends due to the communication channel.

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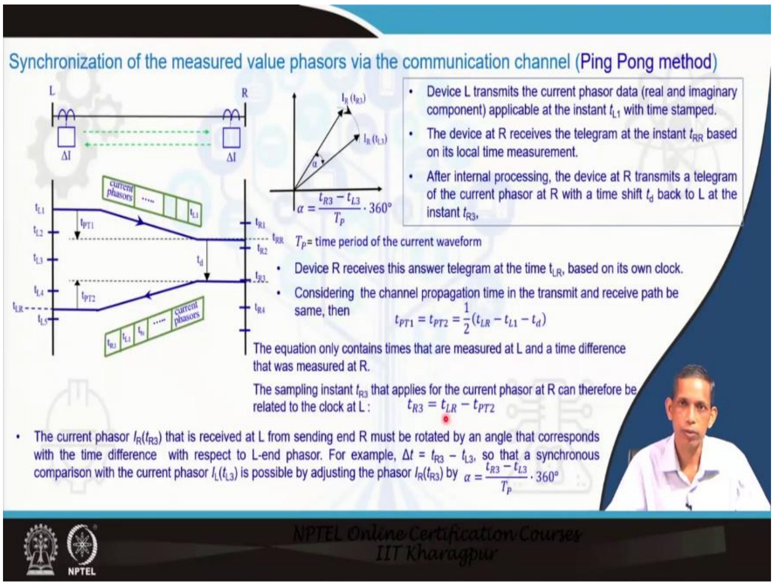

Now, let us try to understand what is ping pong method. So, these are the 2 sides. And here, communication channel available for both the sides. And the associated time diagram is shown here, we will be using this for the explanation of the method. So, device L transmits the current phasors data, device L transmits the current phasor data, real and imaginary components for the phasors, applicable at the instant t_{L1}. So, at t_{L1}, it transmits, it completes the phasors here at the local end and transmits the current phasors with time information, timestamp.

Device R receives at t_{RR} after certain time delay. So, this corresponding time delays is t_{PT1}, so this is t_{RR}. So, $t_{PT1}=t_{RR}-t_{L1}$. After internal processing at R end, R transmits a telegram to phasor of, at R with a shift of, with a time delay of t_d here at t_{R3} to the other end. So, this end, phasor available at t_{R3} is being transmitted to the other end with a delay of t_{P2}. And that is being received at the other end at t_{LR}. So, device R, device at L receives answer the corresponding telegram at t_{LR} based on its own clock.

So now, the corresponding, considering the channel propagation time in the transmission and receive path be same, that is t_{PT1} and t_{PT2} to be same delay. So, $t_{PT1} = t_{PT2} = \frac{1}{2}(t_{LR} - t_{L1} - t_d)$, the processing time at R end. So, this equation if we see here, which computes the corresponding delay time in the communication system, assuming symmetry, it contains only the corresponding measure time at L, the time difference and the corresponding associated time, td computed at the R end.

So, these are the time indices to compute the corresponding delay. So, the sampling instant t_{R3} that applies for the current phasors at R can be related to the clock at L, this end. t_{R3} equals to t_{LR} whatever we have received here, that phasors, corresponding phasor minus t_{PT2} delay in the communication system. So, if you can know the t_{PT2} and at the local end whatever time you are recording, so we can know the corresponding t_{R3} at what time it is being dispatched.

So, if we can know this t_{R3}, then corresponding angle, that t_{R3} angle can be associated with the relative phasor positions with the local phasor can be computed. For example, so if this phasor at tR3 will be compared with t_{L3} phasors at local end, then $\alpha = \frac{t_{R3}-t_{L3}}{T_P} \cdot 360°$ where t_P is the time period of the current waveform, 20 millisecond 50 Hz system, so each millisecond corresponds to 18^O. So, that factor is coming to here.

So, whatever time, we will be having corresponding associated angle. So, what is being done here, that the corresponding angle, corresponding time which you have, at which time the corresponding phasor is being dispatched from the remote end, and with which phasor we are comparing because this is a past phasor as compared to this phasor. So therefore, the remote end phasor I_R is shifted by an angle of α and computed as $\alpha = \frac{t_{R3}-t_{L3}}{T_P} \cdot 360°$.

However, if the corresponding phasors at t_{L3} will be compared with at t_{L4} the phasor is at later phase angle, then the corresponding t_{L3} should be shifted the other way. So, that leads to situation in this ping pong approach, that the corresponding angle can be computed from this time information, and, that time information relate to the channel delay time, and using that assuming the symmetry of time delay, assuming that it computes the angle and adjust the angle for the particular phasor of the other end.

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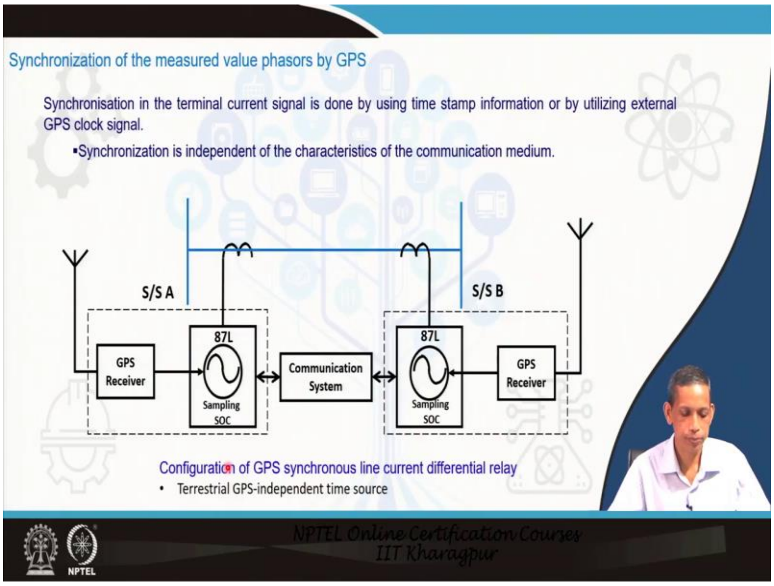

The synchronization approach, which is being widely used today in technology also, modern technology with the global positioning system, the satellite clock signals. So, we have antenna and this antenna receive the corresponding timing from some, from the satellite, both the ends. This is at remote end and this is local end.

So, through their GPS receiver, they receive the corresponding signal and therefore the corresponding time is being adjusted in terms of the corresponding satellite base time. And that gives that, the phasors are being timestamped. And therefore, at what time the corresponding phasor is being computed, that is been transmitted to the other end.

So, this phasor will be aligned in terms of this corresponding phasor value at this end, and that removes the corresponding channel delay to be significantly reduced in terms of that. So, there is a better scope today to reduce the channel delay-based error and so, and gives accuracy to be high considered for the line differential protection. Today, even more advancement is going on in terms of terrestrial GPS-independent time sources in this domain.

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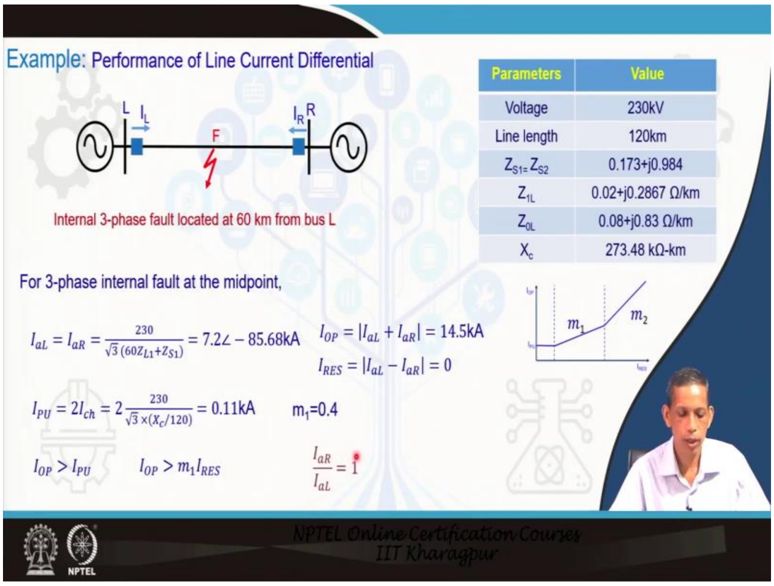

Performance of line differential through an example, we will see. So, this is a 3-phase internal fault case, 230kV 120 kilometer line and these are the line parameters with source parameter also available. So, we will talk about a percentage biased relay and then we will go to the α-plane perspective. 3-phase internal fault at the midpoint of the line, so we have the corresponding I_{aL} and I_{aR}.

So, this midpoint, if you calculate 230 kV divided by √3, and then 60 kilometer into Z_{L1} plus the Z_{S1}, that will be level of current, this level of current will flow from this and this, because of the symmetry from both sides. I_{OP} will be addition of these 2 currents. And so, that leads to in terms of this value 14.5 kilo ampere and I_{RES} becomes equals to 0 without considering any line charging or, assuming the line charging current to be compensated.

So, this leads to I_{PU} to be, let us say, assume twice of the charging current. So, these 2, twice of the charging current, charging current will be computed like this, and that becomes equals 0.11 kilo ampere. Considering m1, this first level of slope to be 0.4, we see the I_{OP} current 14.5 kilo ampere, and that is greater than I_{PU} and also greater than $m_1 I_{RES}$. And that means it would go for a trip decision. On the complex plane, we talk about I_{aR}/I_{aL}, and that becomes equals to 1, because both are same. But that this 2, a clear trip decision by the α-plane approach also.

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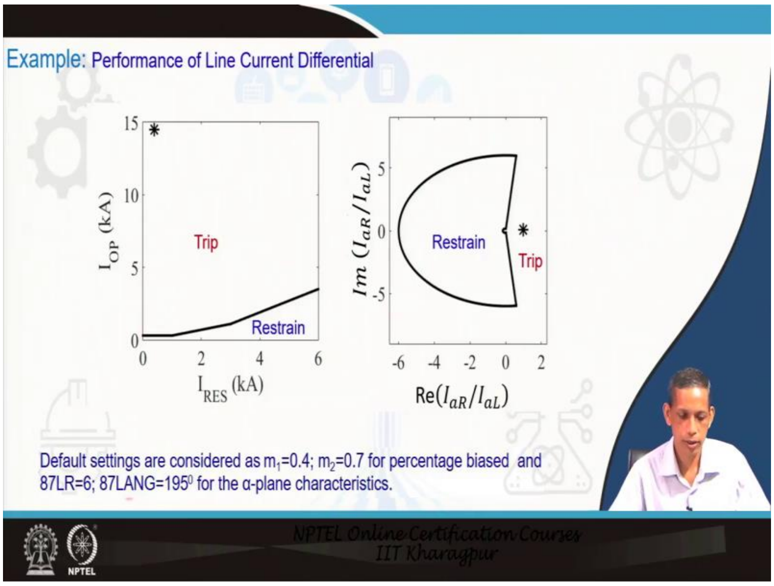

So, if we see this, the percentage biased in the α-plane, then that becomes equals to the corresponding points will come here and here. So, this is restrained region, this is a trip region, so both methods successfully identify the corresponding 3-phase internal fault, which is a severe fault in nature in terms of that. So, for this percentage biased, we have considered the first m to be equals to 0.4 and the m_2 to equals to 0.7. And then, for the α-plane, we talk about 87LR to be 6 and 87L angle to be 195^{O} for the α-plane characteristics.

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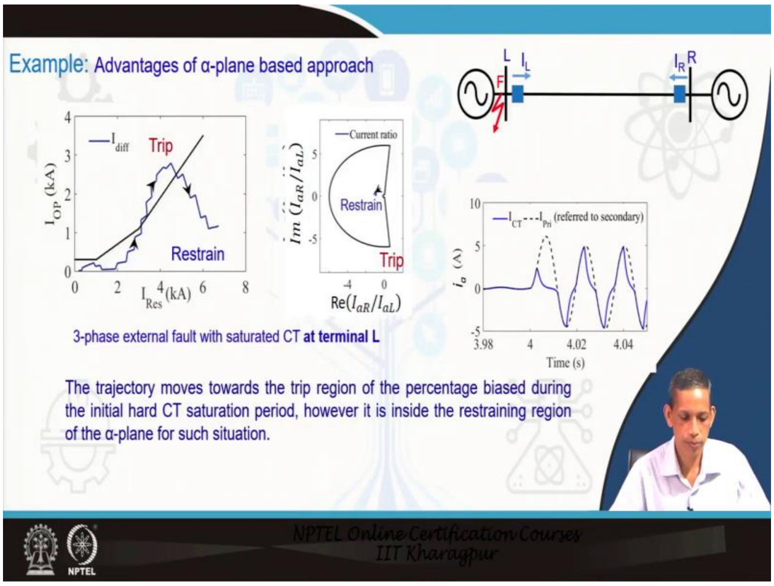

For another case, same case with 3 faults, external fault with one side CT getting saturated, L side let us say, and R side having remain intact. And the saturated CT current, blue curve shows the secondary current of the CT secondary. Then, in that case, the nature of curve, the running plot shows like this. In the I_{OP} versus I_{RES} for the percentage biased case. So, it is sometimes entering into the trip region also.

So, unless that is being blocked from the other way of identifying the CT saturation, the relay may malfunction and trip unnecessarily even though the fault is external one. Whereas, in case of α-plane, the corresponding point remains in the restrained region, and that is about the strength of this one, this external fault for that perspective. So therefore, that, the advantage of α-plane approach is clear for the CT saturation case for an external fault from this example.

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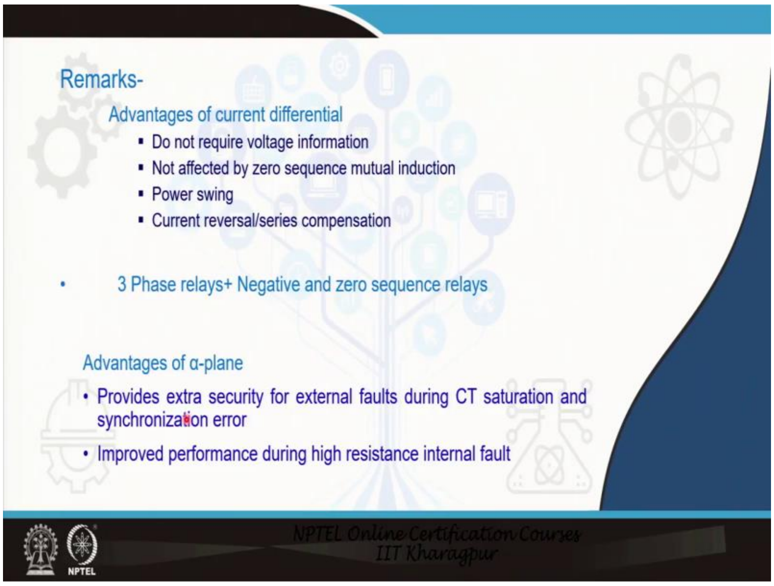

So, in overall, the current differential protection for line has advantages as compared to other forms of protection, overcurrent, distance relay and so. These does not require any voltage information. It is not affected by the zero-sequence mutual induction like the distance relay and so. No power swing issue and so. Current reversal or series compensation challenges with directional information and so, those are not the issues with such current differential principle.

A typical relay today is just also 3-phase, 3-phase differential relays, along with negative and sequence relays, total 5 relaying, relay perspective in the line differential perspective. Furthermore, we saw that α-plane approach has advantages compared to the percentage biased approach also. It provides extra security for external fault during CT saturation and synchronization error and so. Improved performance during high resistance internal fault case, even though outfeed or infeed situation happens to be there. Today, relays can also provide line charging compensation to make it more sensitive. Thank you.