Power System Protection
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Lecture 48
Traveling Waves Basics

Welcome to the Power System Protection course. We will continue with a new module on Traveling Wave Based Protection.

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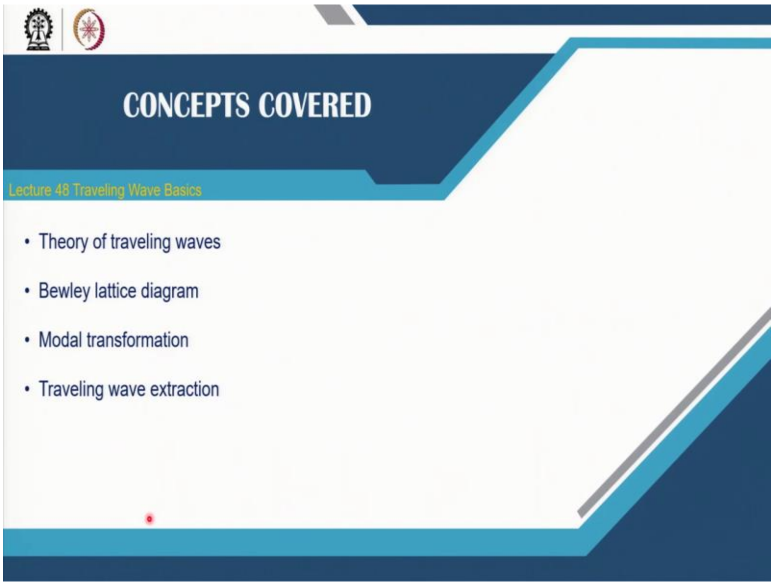

In this lecture, we will discuss on basics on the traveling wave, where we will address on Theory of Traveling Waves, Bewley's Lattice Diagram, how Modal Transformation is being carried out for this purpose and then how the traveling waving extracted and some of the features which we think will be resourceful in protection perspective.

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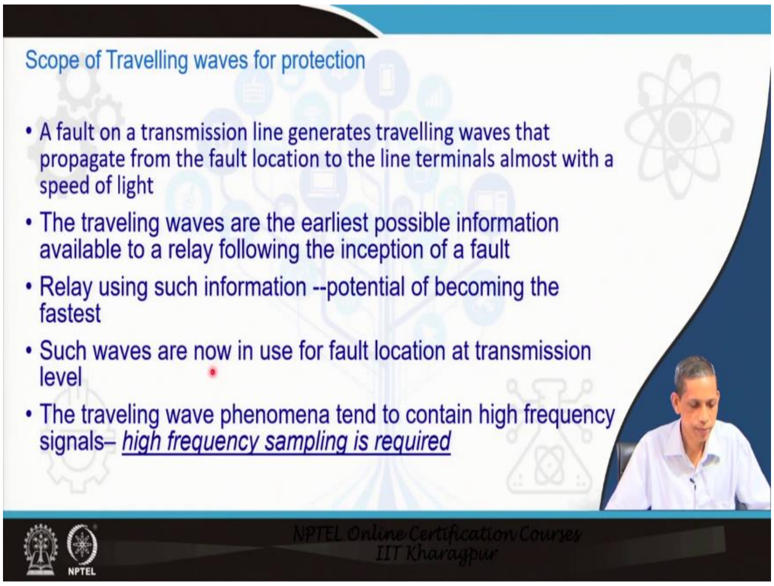

Now, we have seen so many principles in earlier presentations, lectures based on fundamental component, phasor value allied things on sequence components. So, we have mentioned that most of the available relays are based on sequence components that is fundamental component or the phasor concepts. That is 50 or 60 Hz component. Now, however, the voltage and current signals available in power system, they contain many more other frequency components, which may be informative.

So, this is what the other aspects, the traveling wave phenomena and the allied thing in the system during the disturbances, fault and from there you can say that how the corresponding traveling wave concept can be applied to protection, this is for this chapter. This is not new, this is, last so many decades the concept has emerged. But with the newer technology, both on computer perspective and on the communication perspective, such a technology is on highlight today.

Whenever a fault happens to be there, the traveling wave that propagates from the fault point to the line terminals and this happens almost at the speed of light. The traveling waves are way faster and that is the reason they are the earliest possible information that on the fault that reaches to the relay location. Therefore, using such information can have the high-speed performance, fastest fault detection can be achieved in using such information.

Such waves are now already in use in industry, power industry for a long transmission line for fault location perspective mainly. However, the traveling wave phenomena is a high frequency signal and that is why the associated sampling is much higher than what we discuss in case of phasor-based techniques and that is the major difference between conventional relay and relay or fault locators, which we will talk about, using traveling wave approach.

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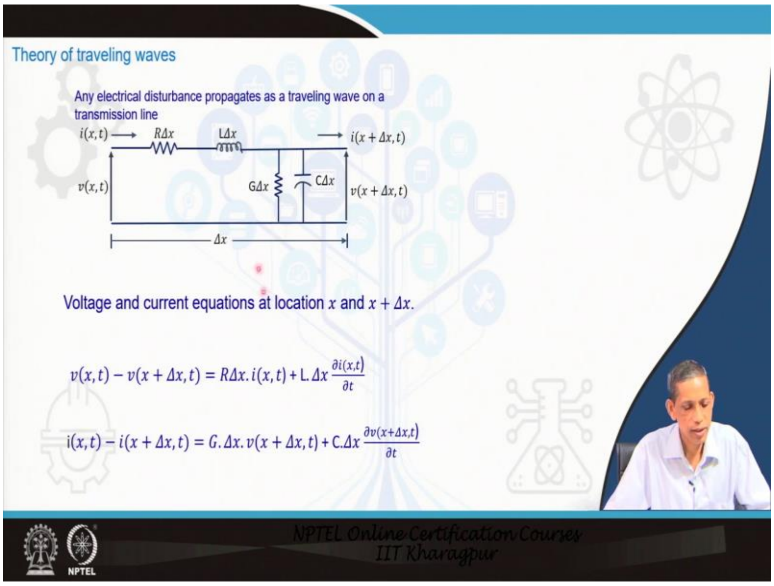

Let us go to the, what is that traveling wave, which is associated during fault. So, any electrical disruptions like lightning, load change or switching or including fault, there originates a traveling wave because of the sudden change in voltage and associated current. So, this step change kind of thing current and the related voltage leads to waves generated from there and which propagates both the waves in the system.

Now, let us consider a distributed model of the transmission system, where we have a small elementary length Δx. This is a distributed model of the transmission system, which we know in the transmission paper. Now this, if Δ x has certain value of resistance and then certain inductance and also the capacitance and conductance and then you can say that we have this corresponding i(x,t) at location x at a time t and at the same instance of time, we have $i(x+\Delta x, t)$ and so also the associated voltage $v(x+\Delta x, t)$.

Therefore, for this elementary small small portion of the network, we can write for the voltage and currents as

$$v(x,t) - v(x + \Delta x, t) = R\Delta x.\, i(x,t) + \mathrm{L}.\,\Delta x\, \frac{\partial i(x,t)}{\partial t}$$

$$\mathrm{i}(x,t) - i(x + \Delta x, t) = G.\,\Delta x.\, v(x + \Delta x, t) + \mathrm{C}.\Delta x\, \frac{\partial v(x+\Delta x,t)}{\partial t}$$

. So, this are the basic equations first, this network voltage and current relations.

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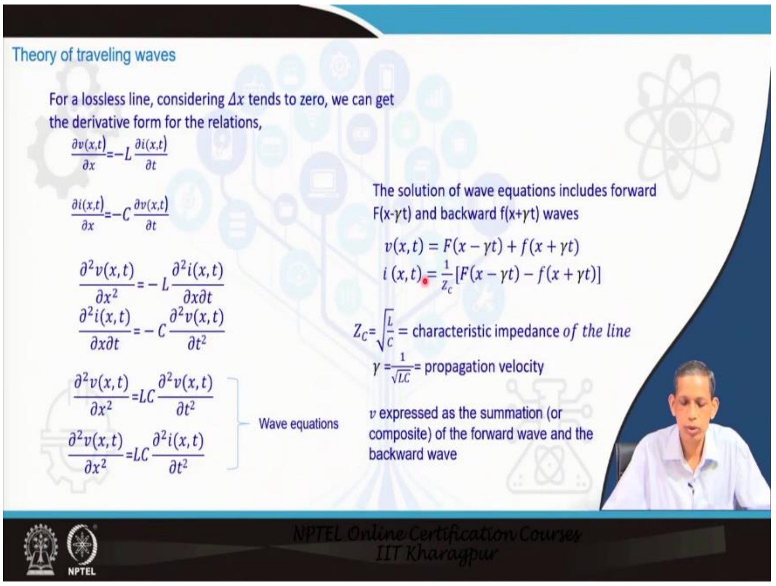

Now, using that relation and considering a lossless line for simplification and when Δx tends to 0, we can get the derivative form these two relations for voltage and current as

$$\frac{\partial v(x,t)}{\partial x} = -L\frac{\partial i(x,t)}{\partial t}$$

$$\frac{\partial i(x,t)}{\partial x} = -C\frac{\partial v(x,t)}{\partial t}$$

Double derivative of that, these two equations leads to

$$\frac{\partial^2 v(x,t)}{\partial x^2} = -L\frac{\partial^2 i(x,t)}{\partial x \partial t}$$

$$\frac{\partial^2 i(x,t)}{\partial x \partial t} = -C\frac{\partial^2 v(x,t)}{\partial t2}$$

So, from this, we can write down these two are relation between the voltage and current

$$\frac{\partial^2 v(x,t)}{\partial x^2} = LC\frac{\partial^2 v(x,t)}{\partial t2}$$

$$\frac{\partial^2 v(x,t)}{\partial x^2} = LC\frac{\partial^2 i(x,t)}{\partial t2}$$

Here, if we see, both are voltage relation. One is derivative with respect to x, the other is with time. This voltage and current relations we can write down and that is known as wave equations, very common equation, wave equation, traveling wave equation.

The solution of the wave equations include both, can be there, well known, forward voltage and backward voltage, voltage waves and the associated current waves. This forward wave F(x-γt) and the backward wave f(x+γt). So, v (x, t) and i(x, t) are being expressed in terms of this forward wave and the backward wave as

$$v(x,t) = F(x - \gamma t) + f(x + \gamma t)$$

$$i\,(x,t) = \frac{1}{ZC}[F(x - \gamma t) - f(x + \gamma t)]$$

So, voltage and currents are related in that sense and with the Z_c, where Z_c is called the characteristic impedance of the line given by Z_C=$\sqrt{\frac{L}{C}}$ and γ is the propagation constant written as γ =$\frac{1}{\sqrt{LC}}$. We can that express as the summation or composite of the forward wave and backward wave and so also the current, summation of both forward wave and backward wave.

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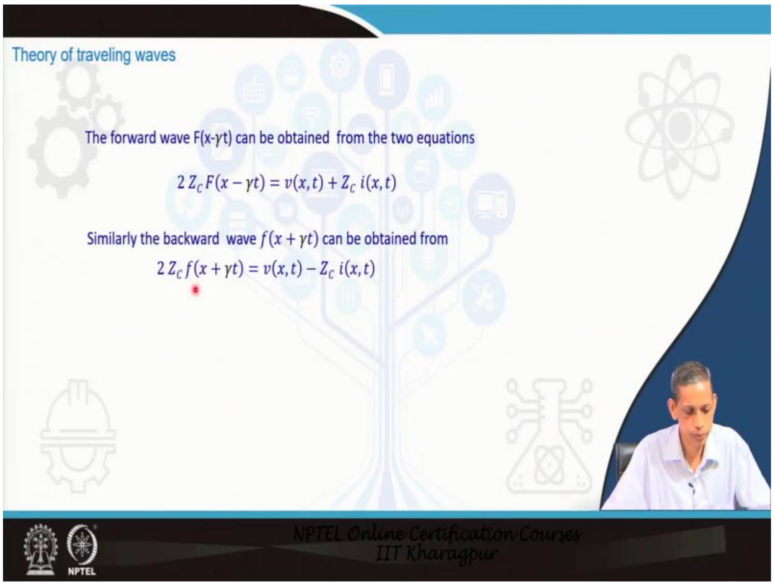

The forward wave be obtained from the given equation.

$$2\;ZC\;F(x - \gamma t) = v(x,t) + ZC\;\;i(x,t)$$

Similarly, the backward wave can be obtained from

$$2\;ZC\;f(x + \gamma t) = v(x,t) - ZC\;\;i(x,t)$$

So, what we like to say here, at a given location we have v (x, t) and i (x, t) if we have we that measurements of voltage and currents we can find the forward wave and also we can find the backward wave. So, these are available and if Z_C characteristic impedance of the line is known then you can obtain the corresponding forward wave and backward wave, which can be used for different purposes also.

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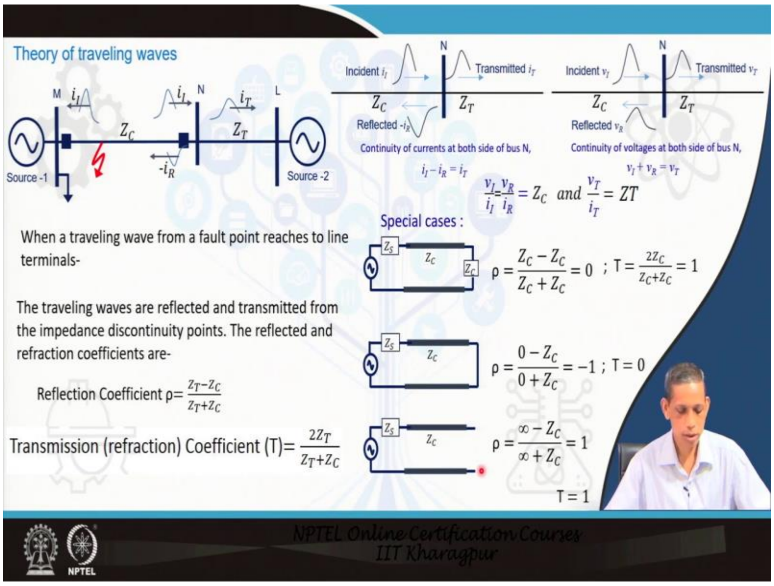

Now, let us go to the more on the theory of traveling waves. So, we see for such a system whenever a fault happens to be there, the traveling wave goes here, it goes there and now, suppose at this point, it finds a characteristic impedance of the Z_C and this side, another maybe cable, overhead line and so, Z_T and so. Therefore, when it meets, you can say such a situation, because of the associated characteristic impedance the corresponding currents and voltage get reflected and something is transmitted. That is associated at the bus, where it finds a mismatch in the characteristic impedance. So typically, we mentioned here the incident wave and the reflected wave and the transmitted wave. So, the current, as you have seen in the earlier forward or backward wave or the reverse reflected wave is having a negative sign in terms of that and relation for current as corresponding incident plus the reflected that equals to transmitted.

$$i_I - i_R = i_T$$

Similarly, for the voltage, we have the corresponding relation as

$$V_I + V_R = V_T$$

So from this relation we can conclude that the transmitted wave can be obtained from the incident and the reflected one and in all the cases,

$$\frac{v_I}{i_I} = \frac{v_R}{i_R} = Z_C \text{ and } \frac{V_T}{I_T} = Z_T$$

Z_C in the characteristic impedance and Z_T is the transmitted side impedance. So, when a traveling wave from a fault point reaches the terminals, the traveling waves are reflected and transmitted from the impedance discontinuity points that is the mismatched point. Reflection coefficient is given as

$$\rho = \frac{Z_T - Z_C}{Z_T + Z_C}$$

The transmitted coefficient becomes

$$(\mathrm{T}) = \frac{2Z_T}{Z_T + Z_C}$$

This reflection coefficient and the corresponding transmission coefficient are being used for different analysis. From a given incident wave, we can find the corresponding transmitted and reflected wave at any discontinuity or mismatch. So, there is few special cases, there are several, but here for our clarity, we will see here.

Let us say that a load impedance or a termination happens to be matching with the same as the characteristic impedance of the line. So, this load or termination is having the same L/C ratio. In that case, the ρ, the reflection coefficient, that becomes 0. It means that nothing will be reflected. Now, for the corresponding transmission system if you substitute this relation, T becomes equals to 1 and then the, in that case, the corresponding thing becomes 1. So, everything will be transmitted to this one. So this will not possess any discontinuity or mismatch at this point. Now, let us consider the short-circuit case. The corresponding ρ becomes

$$\rho = \frac{0 - Z_C}{0 + Z_C} = -1$$

And T = 0. So, this shows that the wave is totally reflected by and therefore, nothing will be transmitted to this one. So, the corresponding voltage becomes equals to this plus this becomes equals to 0 and then similarly, you can calculate for the current perspective also.

When it is open, so then the ρ = 1. In that perspective T = 1.

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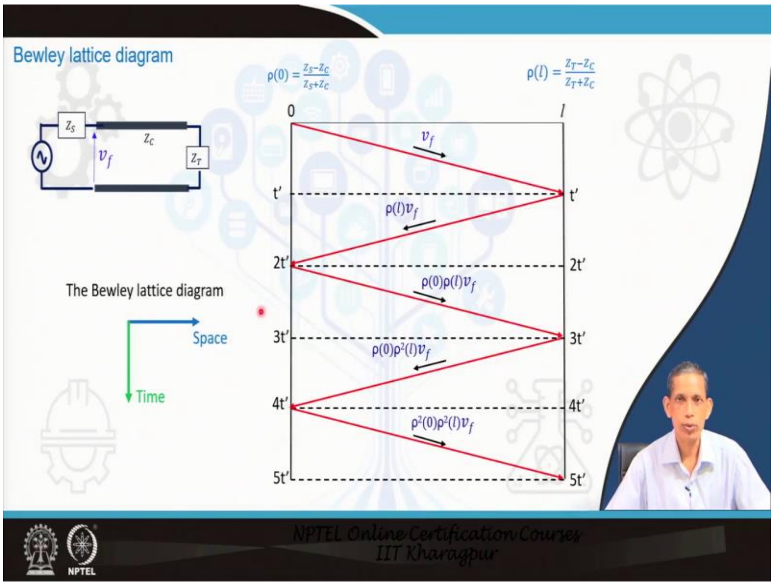

Now, let us see how this Bewley's lattice diagram happens to be there, that will clarify the reflection perspective. So, let us see a system where the source having an impedance of Z_S, and then a voltage incident is injected at this point and you have a characteristic impedance Z_C of the line and you have a terminal impedance of Z_T, the characteristic impedance of this termination. So, we have reflection coefficient that at the zero distance, where we are measuring at the observation point and for the source side that is

$$\rho(0) = \frac{Z_S - Z_C}{Z_S + Z_C}$$

And at the terminal end it would be

$$\rho(l) = \frac{Z_T - Z_C}{Z_T + Z_C}$$

Now, let us see this voltage, which is being injected at this point, either switching or whatever happens to be there for this source. So, it travels and that v_f. and then at this point, something is transmitted to the side and something is reflected. So, we are talking about the reflection. That reflected wave will be ρ(l)v_f. Which ρ? ρ at this point. So, what we are talking about, ρ(l) v_f reflected. So, this comes to here and then at this point, this again reflected back here, but the reflection coefficient at this point is ρ(0). Likewise, voltage goes here and further, with ρ(l) multiplied, it goes, comes towards this one, something transmitted, so this side, not to the Z_T side we are not saying.

So, what we see that, our observation at this point, so these are the corresponding waves arrival time and we can notice here. This will give information what is the corresponding situation there. So, point, what we say that, the travel time here becomes downward at its t' here, this one to this and then it goes midway and it goes there and reaches here and again, you can say this.

So, in a period of 2-3 t', whatever was being sent from this zero-location, I say that come backs to the same location once again. Now with a certain magnitude of this one and the magnitude depends upon the corresponding reflection coefficient of the other end.

So, this lattice diagram known as Bewley's lattice diagram. Here in this axis we talk about physical distance in terms of km or meter and then this is space and this is time, downward you go there time increases, the reflected wave comes from the other end and reaches at this point. So, this helps in different analysis of traveling phenomena, which we like to use in our subsequent applications.

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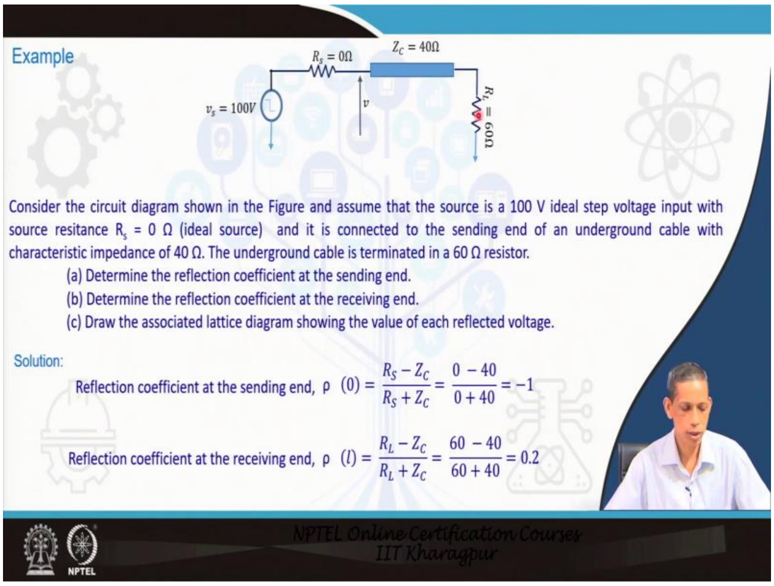

Let us see an example.

So, we have a step change in voltage of 100 V, a step change of voltage and then we have a system like this sources, some ideal source, we have considered here $R_S = 0$ and this step change voltage being injected to the system, which has a characteristic impedance of a cable. And then, we have terminations with a low resistance, $R_L = 60\ \Omega$. Now, the question here is, determine the reflection coefficient at this sending end, determine the reflection coefficient at the receiving end, and draw the associated lattice diagram showing the value of each reflected voltage.

Solution:

Reflection coefficient at the sending end,

$$\rho(0) = \frac{R_S - Z_C}{R_S + Z_C} = \frac{0 - 40}{0 + 40} = -1$$

Reflection coefficient at the receiving end,

$$\rho(l) = \frac{R_L - Z_C}{R_L + Z_C} = \frac{60 - 40}{60 + 40} = 0.2$$

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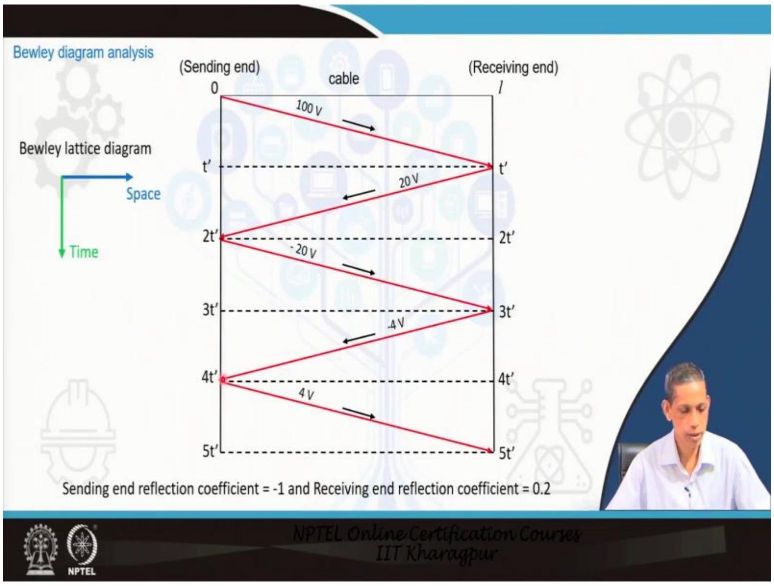

Now, let us see, what will happen to the voltage. So for 100 V step input was given. So, that will you can say that that step voltage traveling wave will be going to this and then it will be reflected with a 0.2 coefficient, that we have calculated here and then with 0.2 means, only 20V will come and here, we have a -1 coefficient, so whatever comes with phase change, it goes to these, so that will be -20 V without any magnitude change. And here is again 0.2 multiplication of that, so that gives to - 4 volt and then here, the phase change with 4 volt, and like this It continues. Now, what we notice here, if you are observing at this point, so initially 100 V and then finally - 20 V and then again for - 4 V. So, this observation will reveal that on the reflected wave and all these things from which information can be traced out at different instant of time, what is the corresponding position of that traveling wave that can be inferred from this Bewley's lattice diagram.

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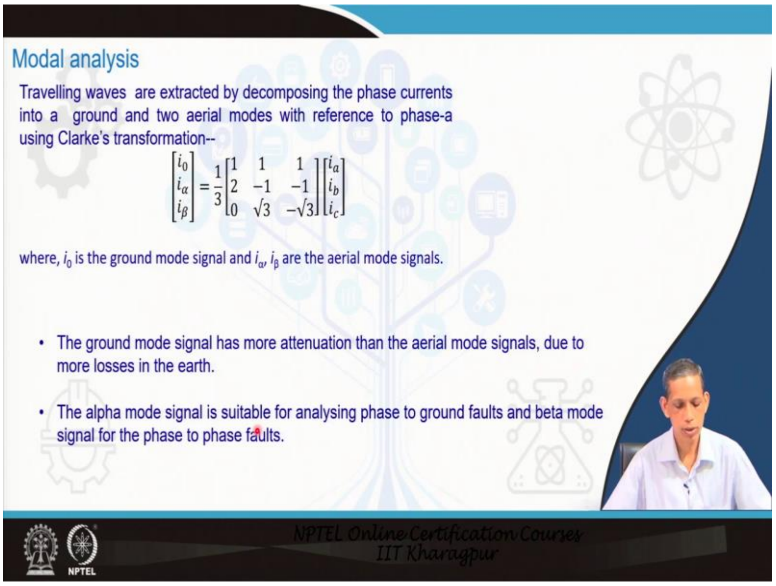

Now, on the perspective of how the corresponding traveling wave is being originated during fault or can be used for different protection applications. So, it is not straightforward like that, what we did in case of phasor based or sequence component-based protection schemes, where you talk about data sampling, acquisition of the data and then pass on to the one cycle DFT or any other filters to extract the fundamental and then use it for the different principles. Here, the corresponding from the signal. The signal contains also 50 Hz as you know, which is having a large component. Upon that, there will be superimposed with some high frequency component signal. This high frequency signal has to be extracted, which represents for this traveling wave perspective. Therefore, it requires different other techniques and all these things. So, we will try to figure out that. In case of extracting the sequence components from the fundamental or phasor based approach, we go for this transformation, the Fortescue's transformers 1, α, α^2 and so, you remember, that α corresponds to $1\angle 120^0$ angle. Now here, the modal analysis being widely used for usefulness of the traveling wave for different applications in terms of protection or fault location. The traveling waves are extracted by decomposing the phase currents into ground and 2 aerial modes with reference to phase-*a* using Clarke's transformation.

So, we have applied Clarke transformation to the ground mode and to aerial modes, i_α and i_β for the 2 aerial modes and i naught for the ground mode as you know. So, this is the transformation metrics for Clarke transformation matrices for the phase current i_a i_b i_c.

Therefore we got, considering phase-a reference, 3 components, i_0, i_α, i_β and this is for considering i_a as reference. Similarly, considering i_b, *b* phase as a reference, we will get another 3 components of i_0, i_α, i_β and for c also, as considering reference we will be getting another 3 components i_0, i_α, i_β. So, these 9 numbers of i_0, i_α, i_β will be useful information for different application for the traveling wave based approach. The ground mode signal has more attenuation than the aerial mode, because it travels through the ground associated and more losses in the earth. So, that is a problem, the signal strength decreases significantly with travel and therefore, that is not suitable for applications. The α-mode signal is suitable for analysis phase to ground faults and β-mode signal is for the phase-to-phase faults.

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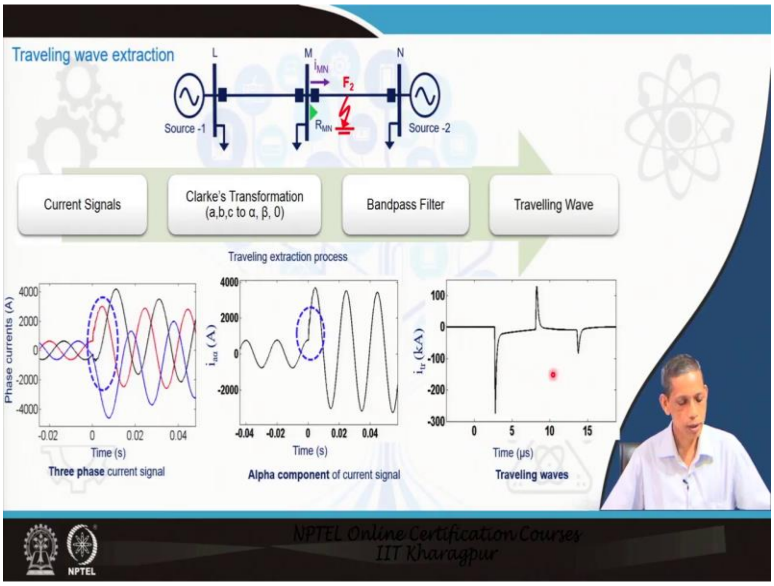

Now, how this, the corresponding traveling wave being extracted, so we like to see here. So here, suppose a relay happens to be there and fault happens to there, so the wave propagates from this side and goes to the side. Therefore, both voltage and current can be extracted, but we see current is being more widely used. The reason being that the associated transient in the CVT response as compared to the PT is not good for high frequency component, but CT response for high frequency component is pretty good. Therefore, in high voltage systems, where CVT is being used, the voltage signal becomes distorted for the high frequency component and traveling wave approach is not suitable there.

So, current information is more suitable in that case, because of the proper response from the CT. From the current signals we got the samples value to data acquisition process, and as already only mentioned this is high frequency component. Therefore, we have high sampling rate, typically MHz around whereas, we talk about some 3 5 kHz in case of normal phasor based approach. The Clarke transformation, α, β, 0 and then from phase-a phase-b phase-c to different phases to there, the bandpass filter carry forward to extract the high frequency component, because you have to reject the corresponding fundamental components and so.

Our purpose is not the fundamental perspective to extract this one and note that these portion, which is everything, because the traveling wave propagates in order to other end and again get reflected. Whereas we are talking here in terms of the s or ms, in terms of 1s or 20 ms and so.

Now, the corresponding phenomena, which is associated with a traveling wave is being this portion this small noisy portions and that reveals all the perspective. Therefore, our sampling rate is very high and also the scope of first relay decision. Now, after the i_α component, transformation on current signals, this becomes this and then, to extract the high frequency component after the decomposition to the alpha component with phase-a as reference.

Therefore, after the bandpass filter, the corresponding signal which obtained becomes this. So, what it reveals that, see here, this is the current signal, so then this is another one and this, so it means that there is reversal in current due to some reflection and it happens to be there.

So, this if you are talking about at any location at this point, availability of this one that means that the distance of separation between this and this, nothing but in terms of the microsecond, that reveals the corresponding time travel between fault point to the reflected point to the corresponding point and so. So, the corresponding traveling wave, which is being observed here reveals different information for relay application and one other thing you notice that because the associated system has a lossy system with resistance therefore, the corresponding wave also attenuates. After several reflections, it will be diminishing.

Therefore, the initial portion in the time axis is being mutual 2 3 something like that, the numbers of reflections will be available afterwards the strength diminishes significantly, therefore, the relay may not be able to see those changes or see those waves or extract those waves faithfully.

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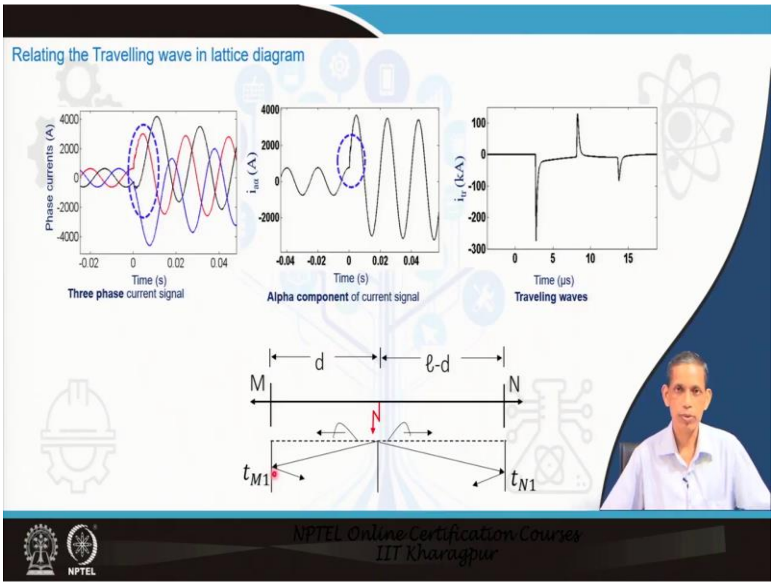

Now, same things here, what is being done, if we could try to correlate to consider to this traveling wave-based approach, a fault happens to be d and (1-d) pu distance away from this M and N side respectively. So, the wave travels from this side and to this side and then gets reflected here also at this bus, at the observation bus and gets reflected from this bus also and from the fault point again it will be reflected and again from the right-hand side also fault, reflected. So, if we are taking observations at M bus and N bus, then the corresponding waves will be available, this kind of traveling waves can be extracted and then if we correlate these corresponding waves from both the sides or at the local level, it can reveal different information for the fault position or so.

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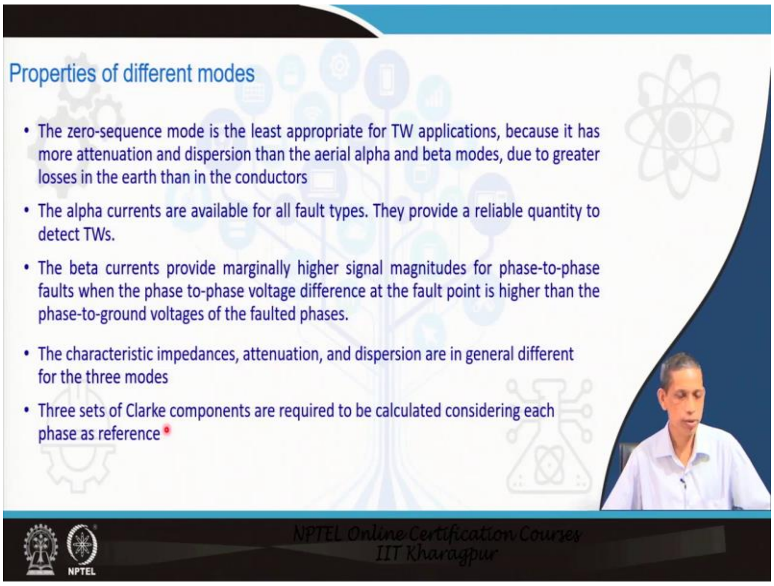

So, there are different properties of this modes that 0, α and β that we are talking about. So, the zero-sequence mode kind of thing is least appropriate for traveling application because it has more attenuation, dispersion and so. α - β modes are less, having less loss as compared to zero sequence approach.

The alpha currents are available for all type types of fault. They provide a reliable quantity to detect traveling waves. For the beta currents, they provide marginally higher signal magnitude for a phase-to-phase fault. So, both can be used for better applications into the protections.

The characteristic impedance attenuation and dispersions are in general different for the 3 modes, they are different again for the 3 modes. 3 sets of Clarke components as I mentioned for the, with reference to *a*, *b* and c can be acquired differently and that is why it is more calculation intensive and that too we require in this business should, I am say that should be completed in the μs or so, because of the fastness of the traveling wave perspective.

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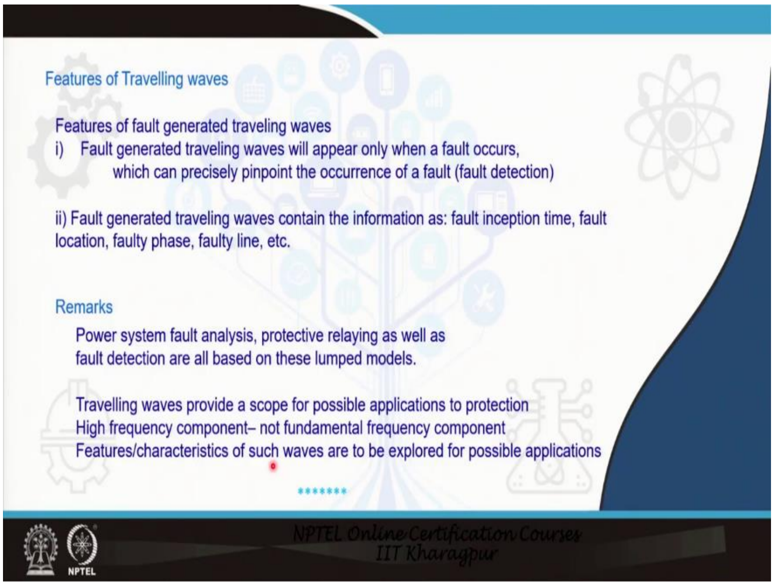

Features of traveling waves on that perspective, fault generated traveling waves will appear only when a fault occurs. We can discriminate between fault and a load change and so, which can precisely pinpoint the occurrence of a fault or it can use for the fault detection. Furthermore, fault generated traveling waves contain the information as fault inception time, fault location, where it has originated. We said that Bewley's lattice diagram can be correlated to that.

So, the traveling time of the wave is indicative of location of the fault. Faulted phase can be identified also, because where we got the, with respect to the reference C and all these things, where you got the corresponding significant amount of traveling wave that will be indicative of that and we can identify the faulted line in the double circuit line or multi-circuit system.

So, different features available or different features or characteristics available from there can be useful for different applications. In, overall, we say that power system fault analysis, which we have carried out in earlier lectures and all these things protective relaying as well as fault detections are based on lumped models, our analysis was lumped models, sequence component analysis. But in actuality, for proper modelling of the systems, we require the distributed model and traveling wave is based on the distributed model of the thing. Therefore, this is more accurate in that perspective. High frequency component, non-fundamental frequency component. So, we have to extract to get the high frequency traveling wave this one with a high sampling rate and the corresponding fundamental component and other components are to be eliminated from there. Feature characteristics of such waves are to be explored for possible applications.

So, the information which should be extracted from such waves is different the way you proceeded based on the fundamental component or the phasor-based component. We will see in the next lecture on different applications of traveling waves or protection perspective. Thank you.