Power System Protection
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Lecture No. 28
Power Swing

Welcome to Power System Protection course we are continuing with the Distance Relaying. This lecture is on Power Swing.

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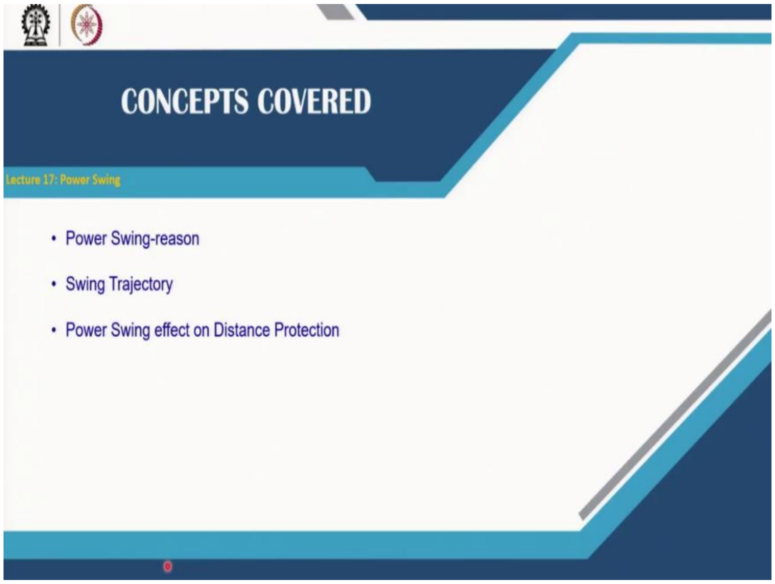

We will discuss on the reasons on Power Swing, Swing Trajectory during the Power Swing event and the effect of Power Swing on particularly Distance Relay.

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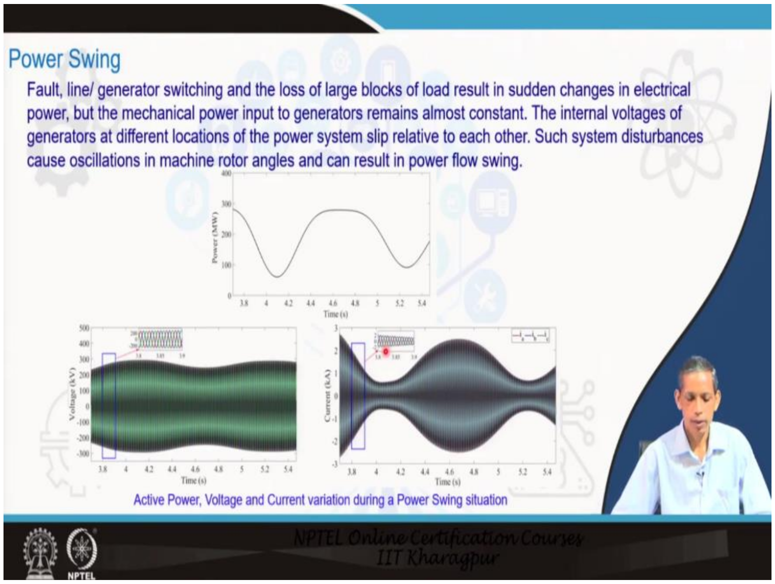

So, let us try to understand what you mean by Power Swing before going to the analysis aspect on the Distance link performance during power swing. Faults, generator or line switching, loss of large load result in power imbalance in the system and such sudden changes in electrical power when mechanical power remains almost unchanged. The internal voltages of generator at different locations slip related to each other. And that leads to oscillations in rotor angles which results in power flow swing both in real power and also in reactive powers.

So, if you see this real power perspective, this is a disturbance situation and we consider a swing has occurred and then the power against it oscillates like this with a very low frequency something like 1 Hz or so. At that situation as already mentioned here, this is the rotor angle issue the corresponding voltage and the current they also oscillate and effectively, the oscillation goes through certain envelope for both voltage and current.

So, the voltage magnitude and also the current magnitude vary. If you see this expanded version of this portion, this window, then, considering this to be a 50 Hz signal, you find a slow modulation in the magnitude. And in the same time, if you see this current also, there is very slow modulation of the current magnitude of the 50 Hz signal.

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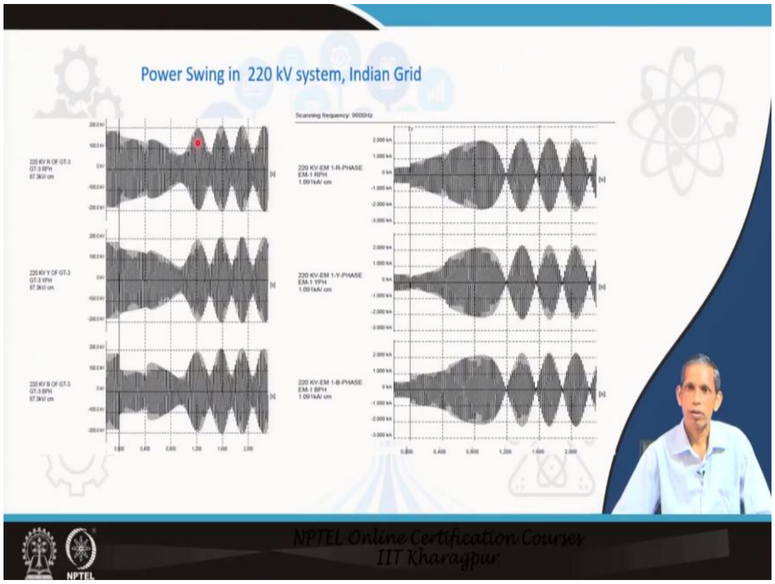

In a real event in a 220 kV system in India grid, if you see the left column is for 3 phases voltage oscillation and the right column is for the 3 phases current oscillation. So, what we see that in this case, the corresponding envelop, so there is a significant modulation in voltage and also in current. If you see the time axis, you see the current goes through a minimum value at this instant and at that instant the corresponding voltage goes to a maximum value. This is observed during power swing associated with power system, which happens to be due to unbalance in power due to the events like load switching, line switching, generator tripping or faults.

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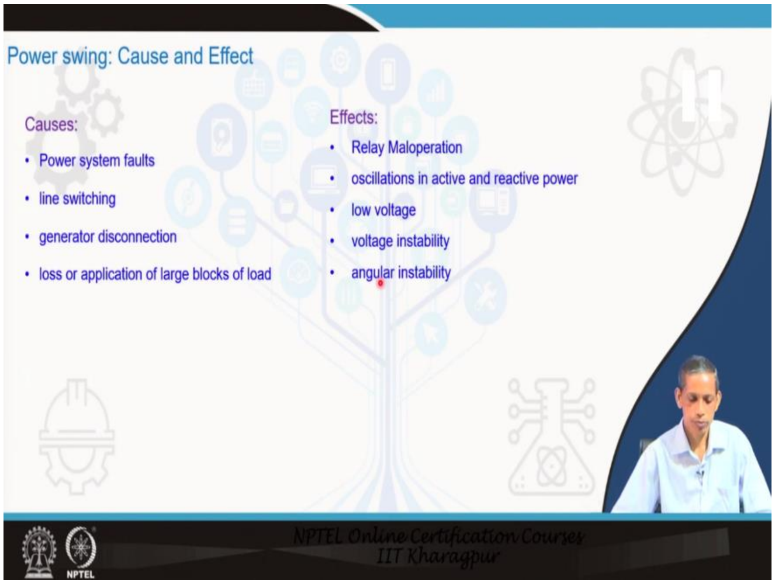

The reasons of power swing in a power system leads to difference in power like we are talking of electrical power versus mechanical power. This happens during power system faults which we are addressing in terms of protection; line switching, line is tripped due to some reason; generator disconnection, leading to short fall in generation; loss of large load, a bulk load is switched off meaning surplus generation. Now, the effects, it is of concern as this leads to chance of Relay mal-operation, which is our concern in the protection perspective.

Oscillations in both active and reactive power are observed and sometimes the voltage may also dip significantly, leading to voltage instability situation. And then we see that these oscillations may lead to angle instabilities in the system. But, our focus is on the protection perspective. So, we will confine to what are the effects of this power swing on protection issue.

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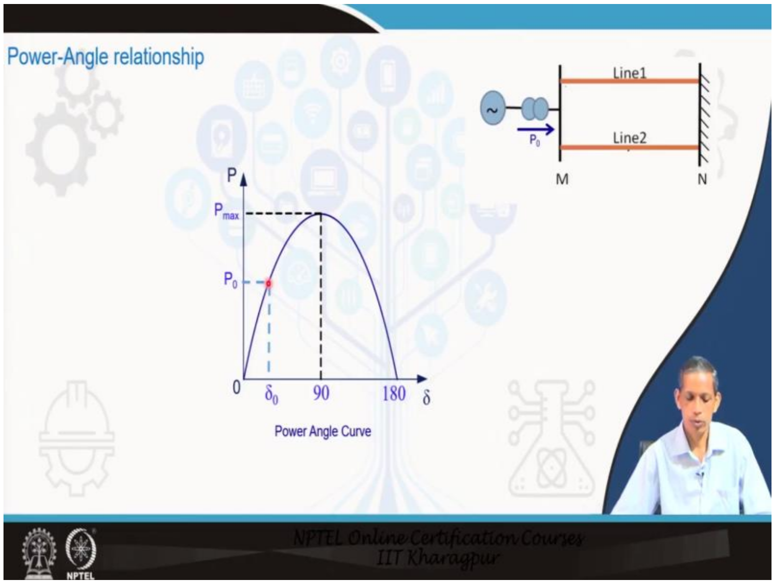

Now, let us try to understand how the corresponding power swing is originated in the system. So, this is an electric system with double circuit line feeding from a source and this is a grid side. So, you know related to the power angle curve $P\alpha\frac{V_1V_2}{X}sin\delta$, which is a very common relation. So, for a synchronous machine, corresponding P-δ curve is like. Suppose it is pushing P_0 to this system and therefore, the corresponding rotor angle is δ_0 from the P-δ curve.

When the angle in that relation of $P\alpha sin\delta$ reaches to 90^O it can push maximum power and so, this is operating at a stable point where the corresponding frequency maybe the nominal frequency, corresponding voltage maybe also stable voltage and the stable operating point at P_0.

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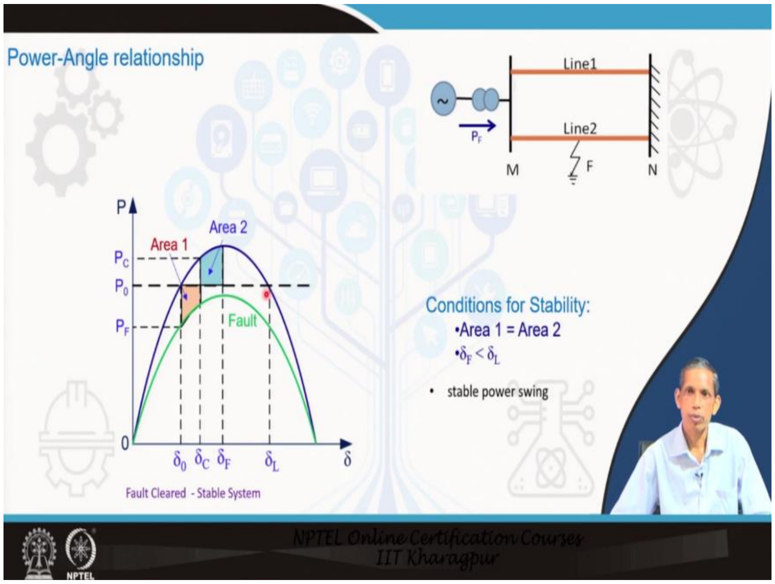

Now let us think of a situation in line 2, there is a fault and this fault is a temporary fault and after some time it vanishes of its own. In that situation if you go to the corresponding P-δ curve So, this upper curve, this curve is for the originally it was operating at this P_0 for this δ_0 and now suddenly at this point a follow up is to be they are in line 2. So, therefore, the power that can be pushed through this system from bus M to bus N that falls and therefore, it follows now, the corresponding $\frac{V_1V_2}{X}sin\delta$.

So, that $\frac{V_1V_2}{X}$ term now becomes smaller and that is the reason it goes now to another operating curve. So, it corresponding operating point during the fault initiation it becomes this point. So, that corresponds to P_F on this curve and that is where the P_F is pushing during the fault. Now, what happens for this operating point if you see the mechanical power which was corresponding to the P_0 remains unchanged in that period almost.

So, therefore, at this point the mechanical power is larger than the electrical power and therefore, we have a positive oscillation at this point. This positive oscillation makes the rotor angle increasing and it goes in upward into that direction on this curve. Now, at this point, suddenly the fault vanishes being a transient and then you can say that again the corresponding operating point shifts to the first curve and those therefore we can say reaches to this point.

But at this point, the electrical power suddenly is higher than the mechanical power for the system. So, therefore, the oscillation becomes a negative sign. This negative oscillation leads to now fall in velocity, but the velocity can still there in the positive value. So, therefore, it goes in the upward trend, with a negative oscillation and at this point the corresponding velocity vanishes and the corresponding machine rotor achieves the synchronous speed.

Now, at this point once you reaches the synchronous speed, but the oscillation being with a negative sign, so, it start you can say that going in the downward direction and then you can say that it goes to the downward, at P_0 again the electrical power becomes equals to the mechanical power, but the corresponding speed being smaller than the synchronous speed.

So, therefore, it goes in the further downward direction and in this position the mechanical power becomes further greater than the electrical power and that results in speeding up the alternator rotor. Then it goes a little downward hill till the corresponding rotor achieves the synchronous speed and again you can see that it comes the upward because of the mechanical power being more than the electrical power in this region.

So, finally, again it settles at P_0 point the original point or any shifting of the corresponding mechanical power and so, accordingly it will settle at a nearby point or so. The point what we see here that these you can see the point operating point on this curve. So, therefore, we say that it is going this way and that way and it works like that till the oscillation is damped out by the system damping and then settles at a particular point in this case again at P_0.

So, these change in the corresponding power change in power associated in nothing but that we mention at the corresponding power swing. So, there is what we say that in this case this is stable power swing situation oscillating of power around this P_0 and that leads to the power swing issue now, we know also the equal area criteria for the stability.

So, we said that these portion below these you can say that operating point this portion and above this considered second curve this portion is Area 1 which corresponds to here corresponds to this kinetic energy gained by the rotor and this is you can see there the kinetic energy loss by the rotor. So, this you can see it when they become equal we say this is stable situation and the corresponding alternator settles to a final value.

So, we say against that another condition that the corresponding final δ_F will be less than the corresponding δ_L. δ_L will consider the corresponding crossing point at this point. So, this is about the equilibrium criteria, which we know we can say that from stability perspective and so.

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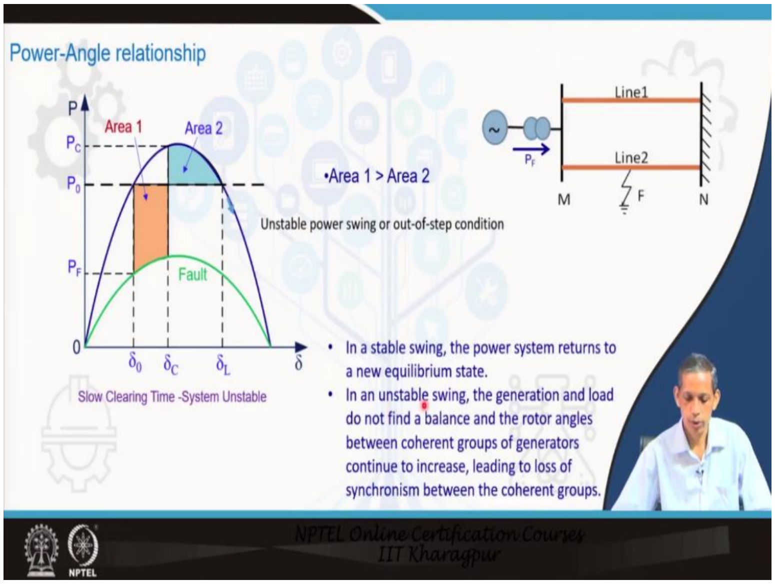

Now, let us go to the another situation on the same system some of the corresponding fault, which we have earlier discuss is clear by his own way when he says after but in a delayed time. Now, we see here what it means that it is operating at P_0 and then suddenly the fault happens to be there it goes what we have discussed earlier also. So, therefore you can say that because the oscillation is a positive oscillation moves forward.

Now if you see as compared to the earlier example, this is the delayed one and then you can say it goes to the original curve and then it moves forward you can see that due to the oscillation being negative, but the velocity being still so you can see that positive. So, when it reaches to this point still if you see that the Area 2 is still smaller than the Area 1. So, this says that this is an unstable situation and it will go against that in there the corresponding rotor will go in a downhill area and leads to losing the synchronism in the system.

So in general, we say in a stable swing, the power system returns to a new equilibrium point and in an unstable swing, it will be swinging around this point and so in an unstable swing the generation and load do not find a balance at the rotor angles between the coherent groups of generators, group of generators which are coherent and continue to increase in that group leading to loss of synchronization between the coherent groups.

So, therefore, in an unstable situation the group of coherent enters may lose synchronism. So, that leads to these corresponding swing also classification into two aspects, one is the stable swing the other is unstable swing in this scenario.

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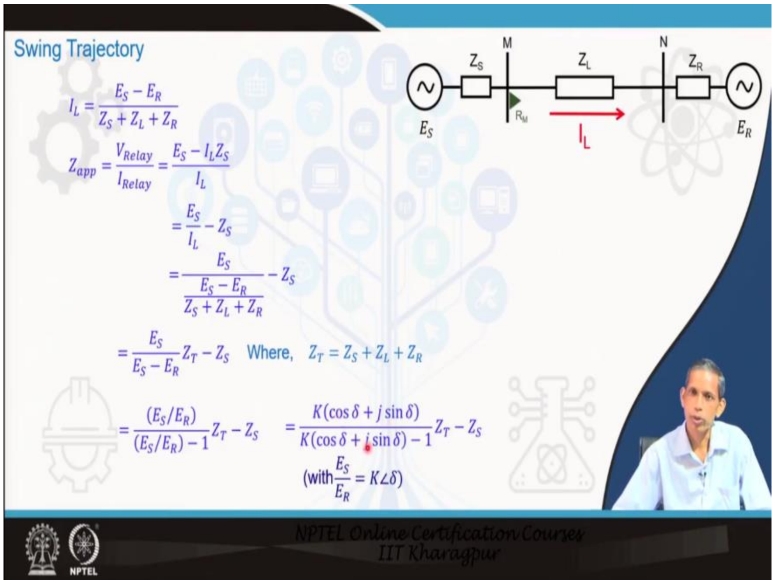

Now, we will say how the corresponding trajectory looks like in the impedance plan. Let us consider a 2-bus system equivalent system and we have this side a source with these impedance Z_s and this side source with impedance Z_r. An impedance being Z_l and the corresponding I_l is flowing during a normal condition in the system. So, $I_L = \frac{E_S - E_R}{Z_S + Z_L + Z_R}$.

So, during these situations being a balanced condition now, the apparent impedances seen by the distance relay will be in terms of any phase voltage by the corresponding phase current at the relay location. So, let us say this is our relay location. So, $Z_{app} = \frac{V_{Relay}}{I_{Relay}} = \frac{E_S - I_L Z_S}{I_L} = \frac{E_S}{I_L} - Z_S = \frac{E_S}{\frac{E_S - E_R}{Z_S + Z_L + Z_R}} - Z_S$.

So, if you do the algebraic manipulation then we get this step $\frac{E_S}{E_S - E_R} Z_T - Z_S$ where Z_T equals to the total impedance of this current path ($Z_T = Z_S + Z_L + Z_R$), the two source impedances equivalent source impedances plus the line impedance which you are considering between M and N.

So, this leads to $\frac{(E_S/E_R)}{(E_S/E_R)-1} Z_T - Z_S$and we substitute $\frac{E_S}{E_R} = K\angle\delta$ then, this part becomes equal to $\frac{K\angle\delta}{K\angle\delta - 1} Z_T - Z_S$. The corresponding $\angle\delta$ leads to $\cos\delta + j\sin\delta$ in both numerator and denominator.

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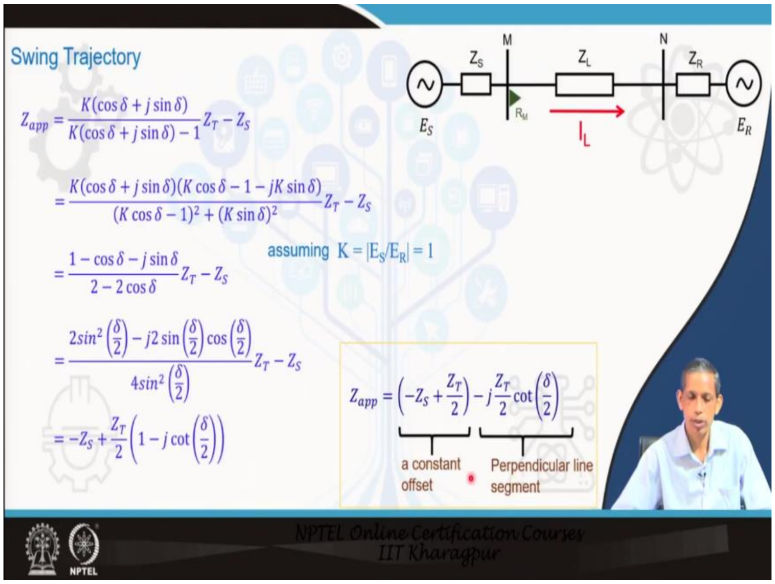

We take the same relations for the Z_{app} what we have derived in the earlier slide. Now, if we expand this one in this sense, you can see that the imaginary part and you would like to multiply the corresponding conjugate part to consider that to make this part denominator part real. So, we got the relation with the Z_T Z_S remaining as it was now if you see consider if you say consider $K = |E_S/E_R| = 1$. So, what do I mean by that the internal voltage of the two sources having the same amount of voltage. So, that is pretty practical also, they will be around 1.

So, if you consider to have a study and if you substitute all K value to be 1 then you get the relations to be $\frac{1 - \cos\delta - j\sin\delta}{2 - 2\cos\delta} Z_T - Z_S$ subject to K equals to 1. This leads to $= \frac{2\sin^2\left(\frac{\delta}{2}\right) - j2\sin\left(\frac{\delta}{2}\right)\cos\left(\frac{\delta}{2}\right)}{4\sin^2\left(\frac{\delta}{2}\right)} Z_T - Z_S - Z_S + \frac{Z_T}{2}\left(1 - j\cot\left(\frac{\delta}{2}\right)\right)$. So, we see that from this term this is Z_{app} as seen by this relay during that δ angle as obtained by the corresponding internal voltage between E_S and E_R. So, we say that becomes equals to this part has a constant part $-Z_S + \frac{Z_T}{2}$ and $-j\frac{Z_T}{2}cot\left(\frac{\delta}{2}\right)$.

So, we can see that these parts is a constant term and this is a variation term during power swing, because we say that the δ goes on changing and during the power swing on that the earlier slide we discuss on the on the powering characteristics. So, that least you can say the δ angle goes and changing this part also goes on changing and again that is with a j operator. So, it is perpendicular to what is being in there in the term kind of thing.

But that leads to the variation, variation of impedance as seen by the apparent impedance upon the fixed term $-Z_S + \frac{Z_T}{2}$. So, that means that the apparent impedance seen by the relay during power swing is not a fixed one it is a variable one.

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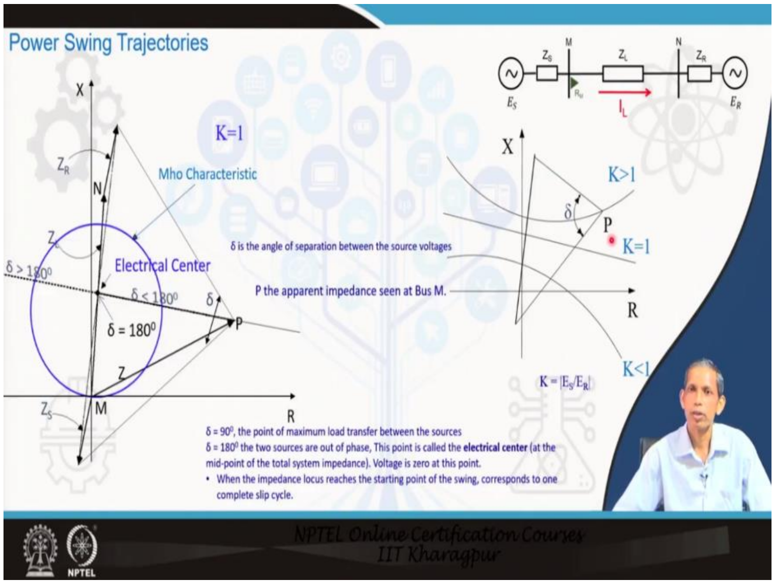

So, this that is why I say these variation of Z_i gives us a trajectory and that against that trajectory we talk about power swing trajectory. Now, we have considered K equals to 1 while that is = $|E_S/E_R|=1$ and then it gets let us consider a mho relay for that to consider realy at R_M now, this you can see that M here and then this real axis and the corresponding imaginary axis.

So, this you can say the impedance this part is Z_S and this is line impedance M to N and then N at this point this endpoint is Z_R, this side impedance. So, this side source impedance equivalent source impedance. So, these all the 3 impedance constitute the Z_T and if draw considered line straighten from here to here to connect to these extreme points.

Now, P is the operating point at a particular situation and the corresponding apparent impedance seen by the corresponding bus M is nothing but these Z_M to the apparent impedance seen by the relay. The δ angle between the two internal voltages this side and that said the E_S and E_R corresponds to this angle here and we have considered K equals to 1.

Now, what happens you see here when the δ angle now the corresponding P point operating point goes on changing during power swing because δ varies. So, when the corresponding δ goes on increasing and reaches to 90^O turn on the period duck at 90^O it reaches the maximum power transfer point. From P-δ, at 90^O the operating point with maximum load power happens to be there. Now, when this δ goes on increasing you see are these K equals to 1.

So, this this, this you can see the line and this line are nothing but the impedances from P to the corresponding P to that E_R side and this is P to consider it to E_S side. So, these you can say the magnitude of this line and the length of this line and this line will be same. So, therefore, the path have that to the operating point will be on this path and then you can say the least to when the corresponding angle goes on increasing beyond 90^O and it reaches to 180^O where at this point. So, this point you can say that is at 180^O.

So, at this point these 2 sides you consider two sources are out of it and the voltage becomes 0 and this point considered 180^O corresponds to the electrical voltage as mentioned as electrical center of the system corresponding to these events the relay which we are analyzing. One more thing that the, the when the impedance locus because the C you are considered the P point moves on then the corresponding impedance goes on changing and that impedance is nothing but the seen impedance by the relay.

So, when it reaches to this point, the impedance is on the line and that is minimum impedance seen by the relay. So, we see here however, it is not necessary that the operating point will go on normally like this if you remember the corresponding δ angle, which in the unstable situation and stable situation in case of stable the δ angle is limited and in case of unstable it goes on moving forward losing the synchronism.

So, in case of stable swing the δ is limited. So, it may traverse some path and again comes back, it may come back again and in case of unstable swing it will goes on increasing. So, that mean that means that you can say that the corresponding stable swing case, it may not reach to the corresponding electrical center. Now, what you see here when the impedance locus reaches to the starting point, there is a considered to a stable situation again consider a starting point then the corresponding return complete to consider that trajectory is called the one complete side slip cycle.

Now, furthermore, we consider assume that the K equals to 1 now, let us assume that K may not be 1, either K greater than 1 or K less than 1 or K consider the $|E_S/E_R|$. So, that means that in this case we consider with K greater than 1 it follow the trajectory like this, this is taken from that relation Z_{app} relations in terms of K and δ we are expressed in the earlier slide and when K greater than 1 the corresponding is that trajectory path becomes this.

And note that, when K equals exactly 1, then the corresponding trajectory path for the power swing during the power swing oscillation we come to this as seen by the apparent impedance seen by the relay R end. So, and the corresponding δ whether this is on K greater than 1 the corresponding δ this side and this side you can say impedance this line is nothing but the line which you have expressed for this straight line connecting from this end to the end that you can select So, the corresponding operating point P and this operating point may shift from this way oscillate on this trajectory depending upon the K value.

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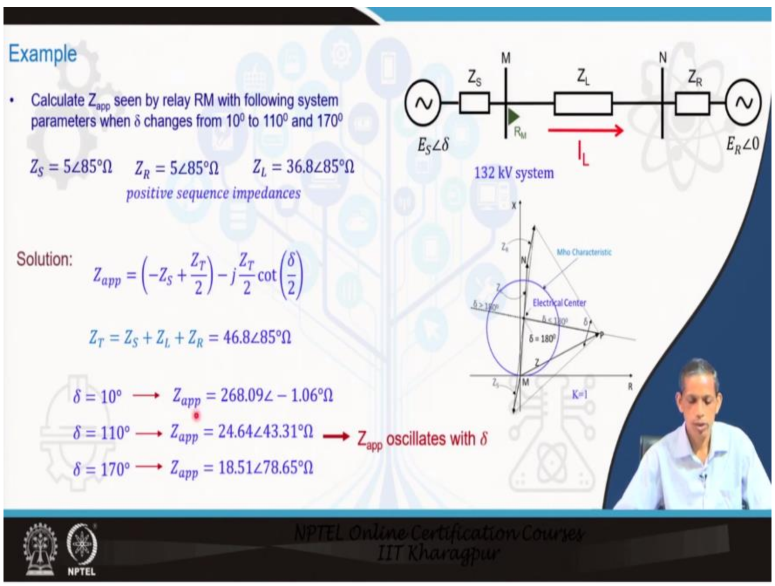

Now, let us see an example what we have narrated in the earlier discussion. So, this system and then we have a system parameter 132 kV systems, we have system parameters given Z_S impedance, system parameters impedance Z_R and Z_L. Now, we have to calculate the Z_{app} seen by the relay RM with the following system parameters when δ changes from 10^O to 110^O and 170^O and so.

So, for different values of δ how the corresponding Z apparent seen by seen by the relay will let to consider get those points in terms of this. So, let us we assuming that that K equals to 1 in this case, so, $Z_{app} = \left(-Z_S + \frac{Z_T}{2}\right) - j\frac{Z_T}{2}cot\left(\frac{\delta}{2}\right)$. This is the variable part and this is the constant part, for the Z_T the total impedance of this part for the current.

So, $Z_S + Z_L + Z_R$ data are given is substituted data then you go to the Z_T to $46.8\angle 85°\Omega$. Now, in this relation you substitute the corresponding Z_T, Z_S and then the δ. For δ= 10^O, $Z_{app} = 268.09\angle -$

$1.06°\Omega$ somewhat larger in magnitude with an angle; when δ= 110^O, it means δ is going towards this one then this impedance decreases and then we are getting $Z_{app} = 24.64\angle 43.31°\Omega$, a substantial decrement in impedance.

When δ becomes 170^O, close to the electrical center there is 180^O point then you get the corresponding $Z_{app} = 18.51\angle 78.65°\Omega$ further decrement in magnitude. So, it is coming closer to the electrical center and at electrical center it will having the minimum path the minimum apparent impedance seen by the relay at RM. So, this clearly shows that the apparent impedance seen by the relay oscillates, if it is a stable swing and it goes on consider changing from higher value to a small value. So, that is the observations we made from this example, for this system.

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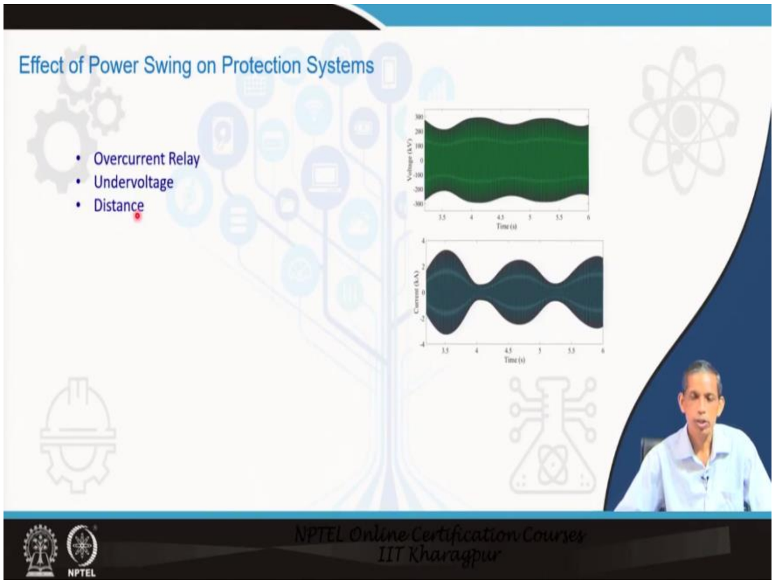

Now, the effect of power swing on protection systems, so, we know we can say that the voltage varies in magnitude and also the current magnitude depending upon the amount of disturbance created by the fault or generator tripping or so. So, if that become significant, the depth of this oscillation will be also significant. In that case what will happen simple we say that the current magnitude becomes significant at this point that may result in tripping of the over current the instantaneous and it is more than the pickup it will trip even though this is not a fault situation.

So, therefore, we can call it as a unwanted tripping or malfunction of the mal operation of the relay over current relay. If it is IDMT relay, the time is a factor within the stipulated time of this IDMT related time if it happens to be there a chance it will trip otherwise in most of the cases it will not happen so. So, in case of voltage if the corresponding under voltage situation then there is a chance you can say that the under voltage will also go for it unwanted tripping even though it is not a fault.

Distance relay is also vulnerable, because we see the Z_{app} goes on changing sometimes from high value from the load area to the low value considered when the δ goes on increasing. So, that may lead to consider distance also vulnerable. So, our focus is here on distances will go we consider that how the corresponding power swing affects the distance relay performance.

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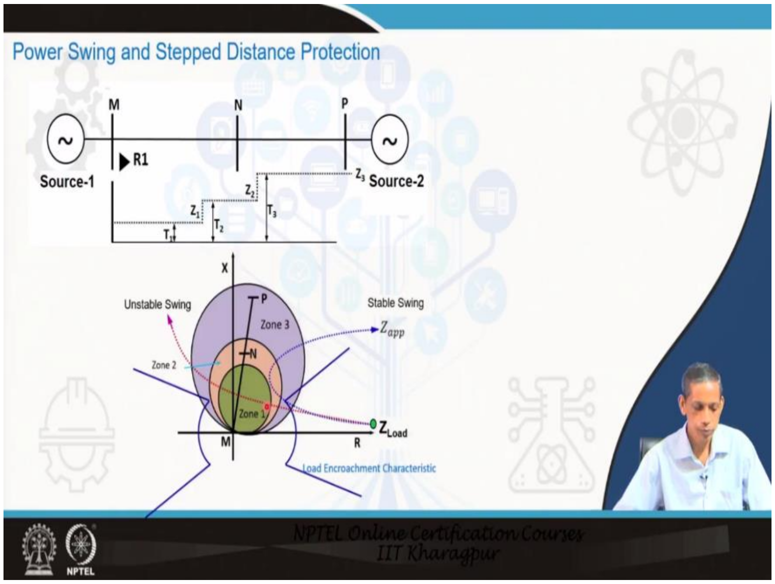

Now, let us consider a 3 bus system and we have we can say that R1 relay we are observing and these R1 relay is having 3 zones. Zone 1 instantaneous, no intentional delay, Zone 2 with some time delay and you can see that we have Zone 3 with certain further time delay something like 1 second or so, we have already discussed in the earlier lectures. So, these are the 3 Zones, Zone 1, Zone 2 and Zone 3 with mho relay characteristics for understanding associated with that you can see that we have a the load encroachment characteristics.

Now, let us consider at one point the corresponding operating point we can see that the system at a loading concern Z_L here what is being seen by the relay R1. So, first example, if you see here let a disturbance happens to be in the system so, somewhere then there is swing observed that swing you can may go for a stable swing; if a stable swing happens to be there it might trace it traverses a path like this.

You note that it goes on δ goes on increasing, Z apparent goes on decreasing and because δ reaches to a final value and then it again it goes on decreasing δ. So, therefore, the corresponding apparent impedence also goes on increasing and that is what you can say in a stable swing observe you can see a trajectory like this maybe very closer or so.

Now, whereas, in case of unstable swing from the load point, it traverses you can say that a path like this δ goes on progressing and progressing it goes beyond 180^O also and 180^O electrical center it has a minimum you get to the impedance and then you can say that at this point and then you can say it goes further you could say in case of the δ also that sense.

So, this you can say that clear considered 180^O the unstable power swing situation and so. So, what we see here from this swing results in apparent impendence to be significantly low, and it may enter into the Zone 3, Zone 2 worse near with Zone 1 also. Note that Zone 1 considered has no delay part, but Zone 2 and Zone 3 they are associated delays. Now, if the corresponding trajectory remains for that period, it gets there in Zone 2 or Zone 3 then Zone 2, Zone 3 may also malfunction and if it enters to Zone 1, then there is a chance of tripping.

So, that means that that means that if you see this perspective, because in the system disturbances are common large systems like Indian grid, very often you will find some disturbances small amount small magnitude or a larger magnitude that when lead to swing frequently in that synchronized situations, then the corresponding apparent seen by relays will be varying. So, at times they may I can say that into the apparent and the corresponding trajectory of the relay.

But if you see you can see that very likely it will vary with a high probability it may enter into Zone 3 with a lesser probability it will enter to Zone 2 and with a further lesser probability it will go to Zone 1.

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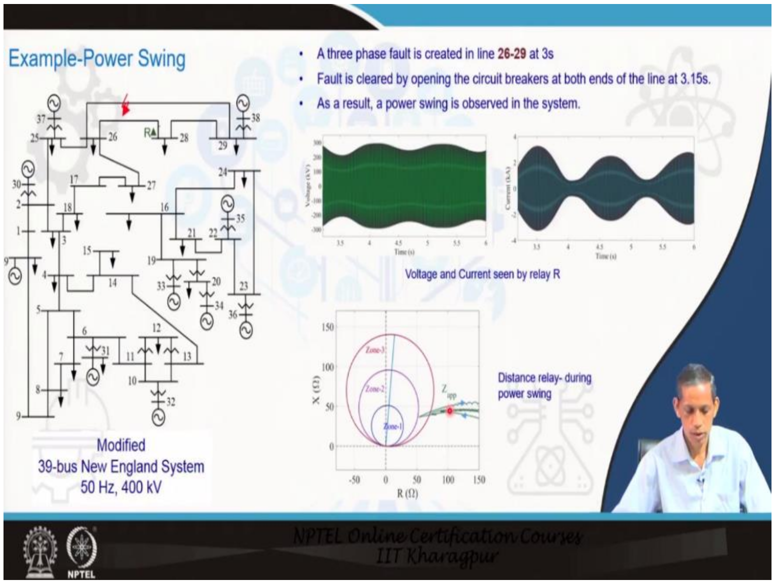

Now take one example power swing for this 39 Bus New England 50 Hz 400 kV system. So, a simulated to consider for this, fault in this line, line 26 to 29. And we are observing this relay R. So, fault at 3 second you created and the fault is clear by opening the circuit breaker at both the ends here and here at 3.15 second after 150 millisecond the fault is clear. As a result the power swing is observed in the system.

This line is out, but we are observing at least you can see that line for this line 28 to 26 relay at this and this and these were corresponding voltage observer the relay considered during that power swing after the clearing fault happens to be voltage and current appears to be like this. So, at the time the corresponding Zone 1 Zone 2 and Zone 3 setting for this relays shown here in mho characteristics and you observed the corresponding consider the these you consider a period of oscillations and all these things, which happens to be stable consider swing, because you see here the corresponding trajectory of the Z apparent goes enter here to Zone 3 and again comes again goes and again comes like that, it goes on changing.

So, we see here considered there are a few cycles shown here on the slip cycle shown here consider this one but during the swing cases.

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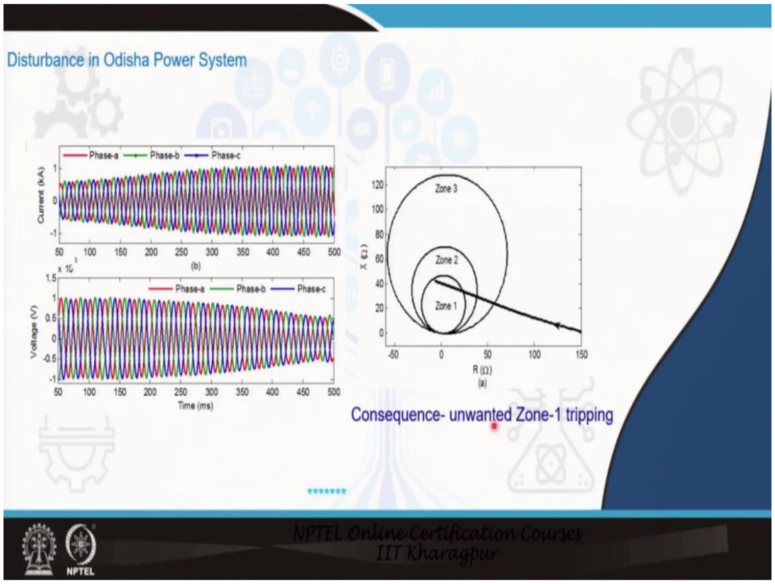

This is a practical example in the Indian Power in Odisha Power System. So, if you see you can see that here, this is the relay collected data, so, the corresponding current and voltages are shown here you can see that plot and then what happened in this case, if we go consider to the trajectory plot the sequence their voltage and current trajectory for the Zone 1, Zone 2, Zone 3, it enters to the Zone 1 and therefore, considered in that event the corresponding consequence there was that the Zone 1 tripped unwantedly and which is not desirable.

It note that you can say that unwanted tripping rates to consider it further loading of other lines and may lead to it cascading events and eventually leading to large scale disturbance in the system. And most of the large scale disturbance analysis revealed that power swing is a important factor which leads to malfunction of the relays. So, in this lecture, we learnt on power swing, the reasons how that is being originated and we see that what is the corresponding what is it about this stable swing and unstable swing.

And how the corresponding apparent impedance changes during the power swing that equation and others examples also we see, and we see that there is chance of vulnerability of this distance relay on the operation distance relay performance during the power swing situation. Thank you