Digital Protection of Power System
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Lecture 31
Digital Distance Relaying Scheme for Transmission Line - II

Hello friends. So, in the previous lecture, we have discussed about the need of distance relaying scheme. And then we have discussed that distance relay when it is used for the protection of long EHV and UHV lines this relay suffer or causes several issues. So, to avoid that there is a need to utilize digital distance relaying scheme.

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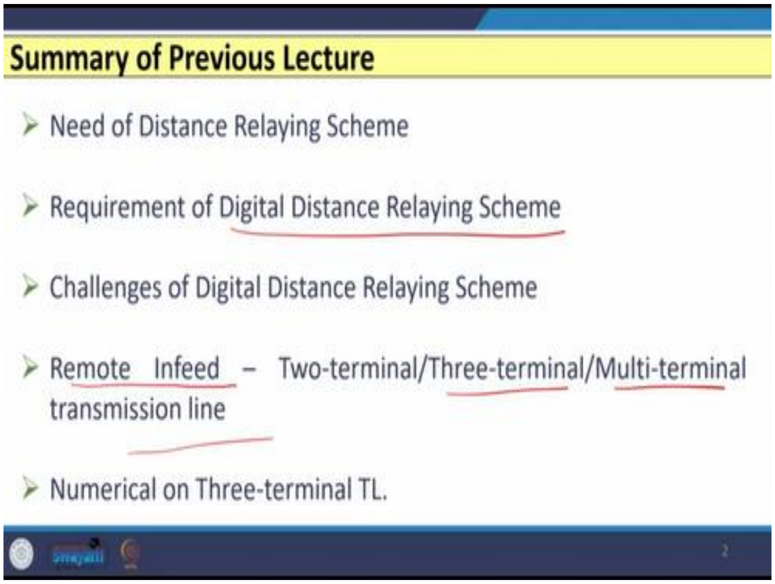

However, there are several challenges faced by digital distance relaying scheme also and out of that most of the two challenges are one is the remote infeed and in this we have discussed about the three terminal or multi terminal transmission line and the second is the series compensation.

So, out of these two issues, we have discussed the first one, that is what is the impact of remote infeed, when we consider three terminal or multi terminal transmission lines? So, basically reach of the distance relay is affected when there is a remote infeed or multiple infeeds are present and along with that, when the impact of fault resistances is consider the problem becomes more complex. We have also discussed one numericals on three terminal transmission lines.

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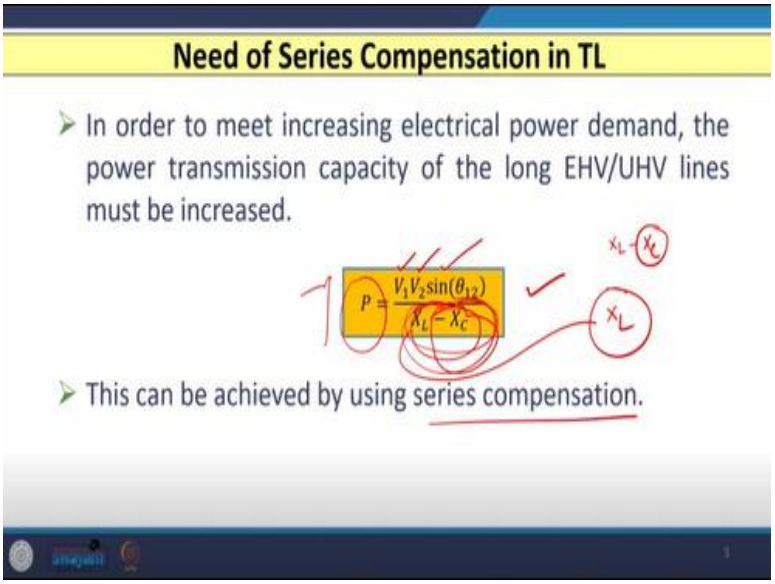

Now, let us discuss the second problem faced by digital distance relay that is the series compensation. So, we know that in order to meet the increasing electrical power demand, the power transmission capacity of long transmission line needs to be increased and this power to be transmitted by any transmission line that is governed by this equation.

$$P = \frac{V_1 V_2 \sin(\theta_{12})}{X_L - X_C}$$

So, when no series capacitor is connected in the transmission line, the transmission line acts as an uncompensated transmission line and only the value of X_L is there which is fixed there is no change in X_L. So, power to be transmitted mainly depends on the voltages at the sending end receiving end and sin of angle between these two voltages.

However, after the incorporation of several compensation device, if we use the series capacitor or maybe if we use the TCSC thyristorized control series capacitor, then in the denominator instead of X_L, we can have the X_L minus X_C where X_C is the capacitive reactance of the series capacitor, then we can definitely increase the power to be transmitted by the transmission line from sending end to the receiving end by reducing the denominator value.

So, if we wish to transmit more power, then definitely we have to incorporate series compensation. So, now our transmission line does not remain uncompensated line but it becomes series compensated transmission line.

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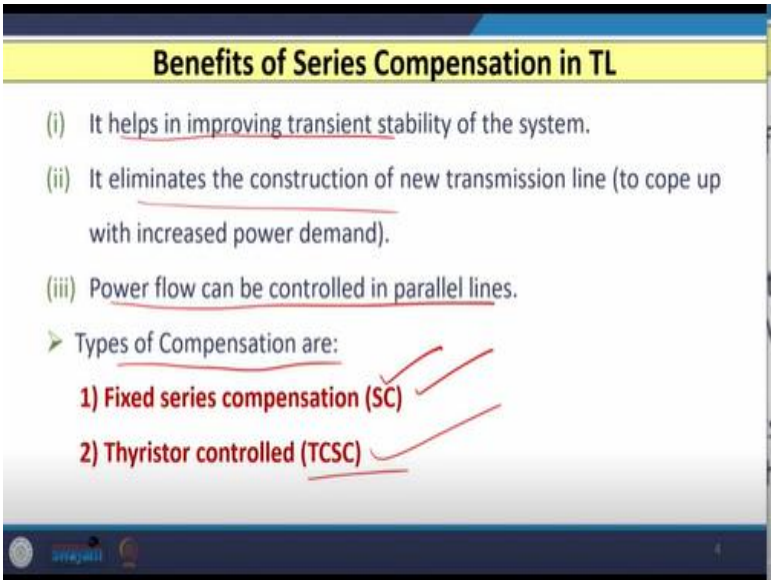

Now, if we incorporate series capacitor in the transmission line, then there are several benefits of that, the first benefit is that the incorporation or incorporating series capacitor helps in improving the transient stability of the system. It also eliminates the construction of new line because we know that the electricity demand is increasing day by day. And to cope up with this demand we need to install or erect a new transmission line instead of that we can improve the power transfer capability of the line by installing the compensation devices for example series capacitor.

The third advantage or benefit is the power flow can be controlled in parallel lines if installed series capacitor. So, let us see now, what are the different compensation devices we can install on the uncompensated transmission line? So, two types of compensation are possible. The first is the fixed series compensation known as SC or series capacitor. And second is the thyristor controlled series capacitor so that is known as TCSC. So, we will discuss one by one each.

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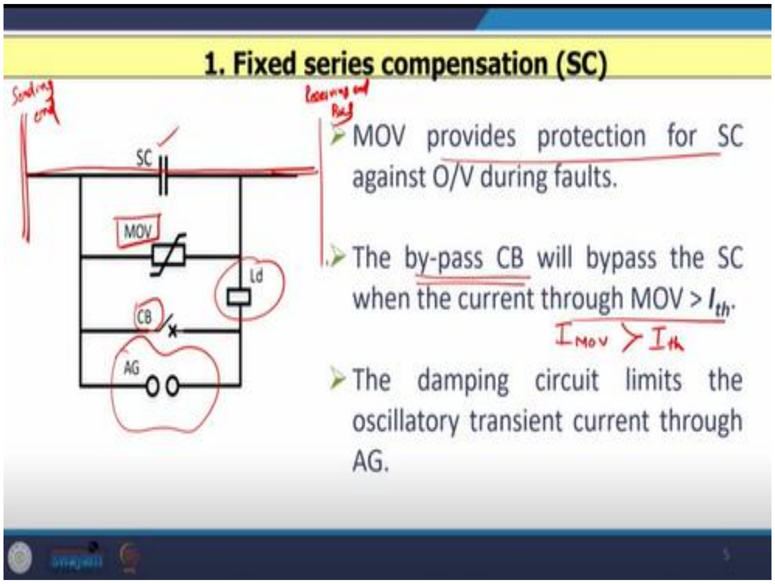

So, let us start our discussion by incorporating series capacitor in the transmission line. So, if we incorporate series capacitor in the transmission line, so you see this is my transmission line (as shown in above slide). So, let us say we have a sending end somewhere here, this is my sending end bus and here somewhere I have a receiving end bus (as shown in above slide). So, between this two that sending end or at receiving end anywhere or maybe in between, we can install this series capacitor.

Now, when we installed the series capacitor to protect the series capacitor against over voltages, we need a device, so that device is known as the metal oxide varistor or it is known as MOV. So, MOV provides protection for series capacitor against any over voltage which is going to occur or happen in case of fault. Now, MOV has certain capacity maybe in terms of joules or maybe it has some capacity up to which it can withstand certain voltages or energy. So, to avoid that, to protect the MOV, we need to incorporate some device and that device is known as circuit breaker.

Here it is known as by-pass circuit breaker because it is going to by-pass or divert the energy that is flowing through the MOV to protect the MOV, so that is known as by-pass capacitor. And this by-pass capacitor will bypass the series capacitor and MOV both when current through the MOV that is I_{MOV} that is current through the MOV is greater than some threshold value of current which is set depending upon the capacity of MOV.

Now, we know that by-pass circuit breaker is also there, it has some capacity. So, to protect the by-pass circuit breaker also, we need some another device which is known as air gap, it is also known as pear gap or air gap along with the damping circuit. So, this damping circuit limits the oscillatory transient current and the air gap is used to protect the by-pass circuit breaker.

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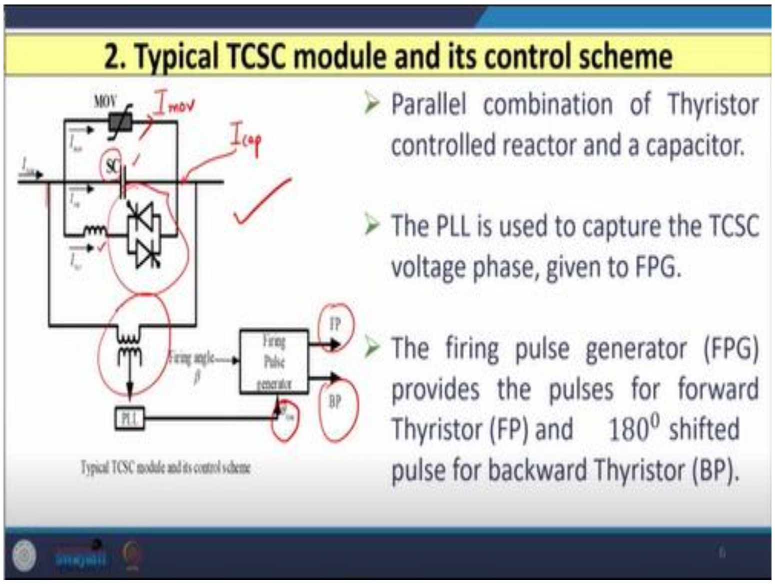

Now, if we consider the second compensation device that is the thyristorized controlled series capacitor and its control scheme then it looks like this. So, here you can see that we have a series capacitor SC which is there and current through this SC is known as I cap. So, that is I capacitor that is this current that is flowing through the series capacitor in parallel with that we have a MOV metal oxide varistor and we have discussed that MOV is used to protect the series capacitor against over voltage is during fault.

So, current through this MOV that is known as Imov and another thing is in parallel with series capacitor, we have one reactor and then we have another module of this that is known as thyristor and the whole circuit we have another one transformer and output of secondary of this transformer is connected to PLL block that is phase lock loop block and that is further connected to the FPG that is firing pulse generator circuit.

So, here we know that this PLL block that is phase lock loop block is used to capture the TCSC voltage phase and that value is that is theta TCSC that is given as an input to the firing pulse generator circuit, the firing pulse generator circuit provides the pulses that is required for this thyristor, so this firing pulse generator provides the two policies one is the forward pulse for one thyristor and another is the another pulse which is required for the backward thyristor and that is 180 degree out of phase.

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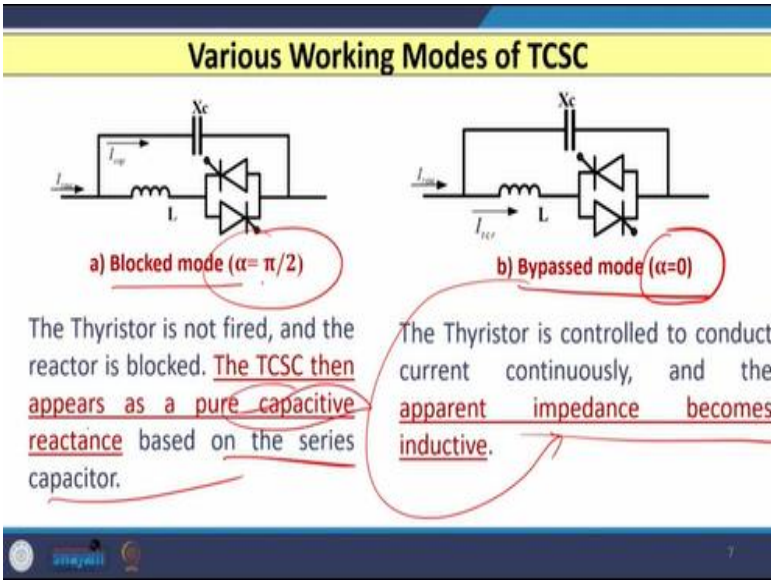

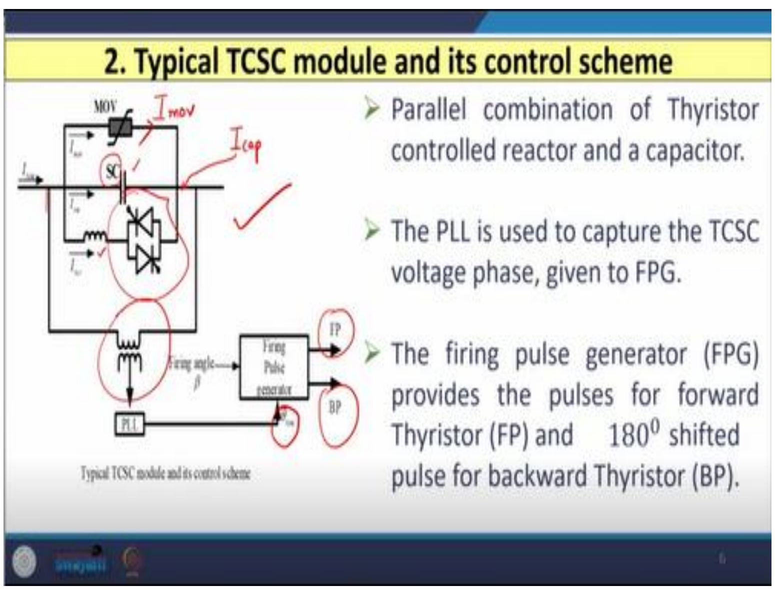

Now, there are four working modes of this typical TCSC module. So, let us see what are these four modes in which this TCSC can work? So, the first mode of this TCSC module is the blocking mode. So, in this mode, the value of alpha that is the alpha which is available here, that value of alpha is 90 degree or pi by 2. So the thyristor is not fired in this case when TCSC is working in blocking mode and the reactor is blocked. So, the TCSC appears as a purely capacitive reactance based on the series capacitor.

The second mode in which the TCSC may work that is the again, the by-pass mode in which the value of alpha that is 0 and the thyristor is controlled to conduct the current continuously and the apparent impedance become inductive only. So, in by-pass mode the apparent impedance is inductive whereas in blocking mode the apparent impedance is purely capacitive in nature.

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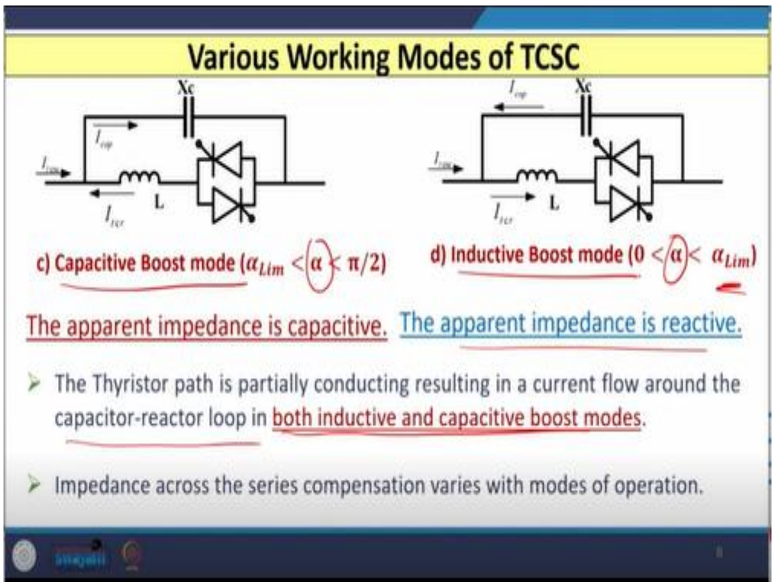

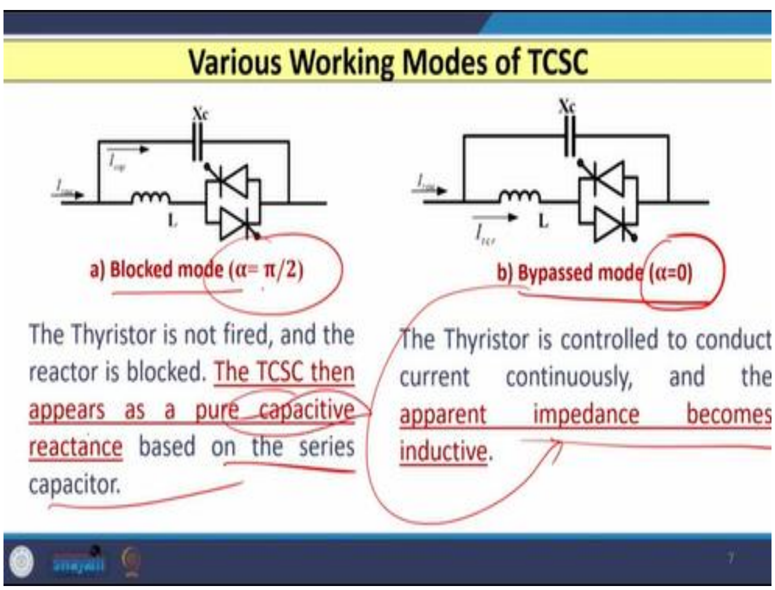

The third mode in which the TCSC module can work that is the capacity boost mode, where the value of alpha varies from alpha limit to the pi by 2 and the apparent impedance in this case is capacity and the fourth mode is the inductive boost mode, where the alpha varies between 0 and alpha limit and here the apparent impedance is reactive in nature.

So, the thyristor path is partially conducting, which results in a current flow around the capacitor reactor loop in both inductive as well as capacity boost modes. So, the impedance across the series compensation varies depending upon in which mode TCSC module is working, if it is working in say first mode block mode that impedance is purely capacity if it is in by-pass mode it is inductive, if it is in capacity boost mode or inductive boost mode then it is both inductive and capacitive in nature. So, in what module or way that TCSC works, so impedance that is seen or apparent impedance seen by the relay that also varies.

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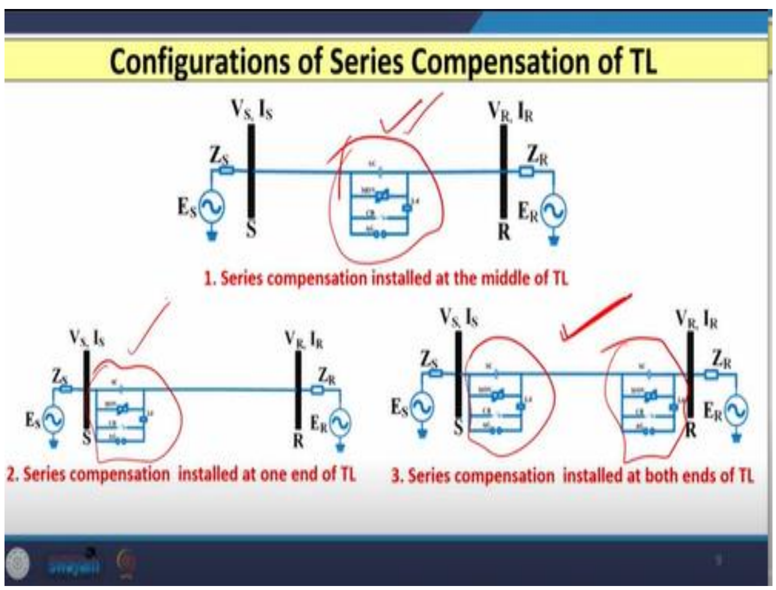

So, with this background, let us see what are the different configurations of series compensated transmission line? So, basically there are three configurations of series compensated transmission line, the first is the where the series capacitor with MOV and by-pass circuit breaker and others we are putting at the middle of the line. The second is we are installing the whole unit at the sending end and the third that is we are installing the whole unit at both sending as well as receiving end that is at both ends.

Now, in most of the utility this type of circuit where the module is installed at both hands that is very common, because if we wish to install this module at the middle of the substation, then again in middle of the line then again we need to build a separate substation here, which increases the cost that is why this configuration is very famous.

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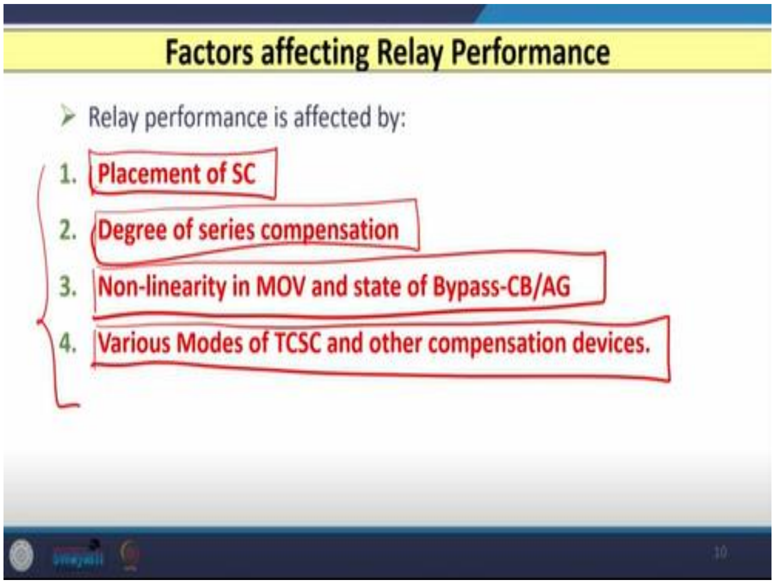

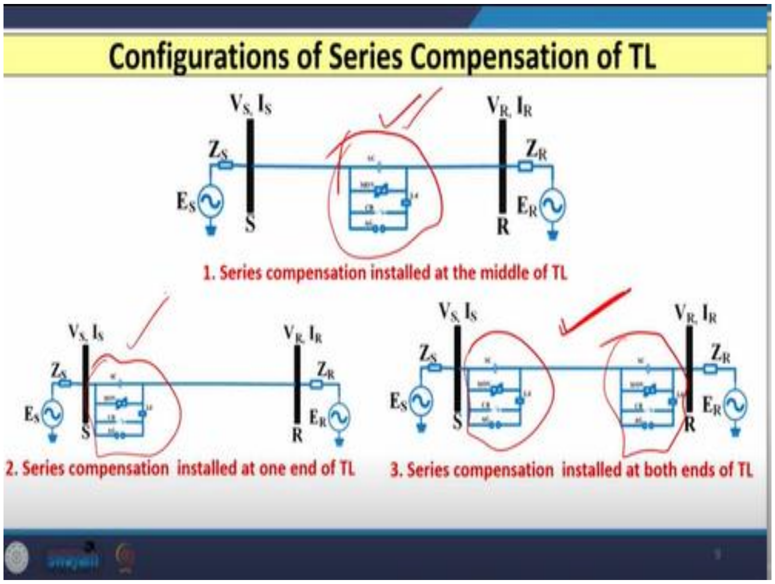

Now, when we consider the distance relay which is used for the protection of series compensated transmission line, then the performance of this relay is affected by several factors. The first factor is the placement of series capacitor as I told you, whether we are putting this at the middle or we are putting at the sending end only or we are putting at both end sending and receiving end depending upon that the performance of the relay or apparent impedance seen by the relay distance relay that also changes or affected.

The second is the degree of series compensation whether we are compensating 50 percent, 20 percent or 70 percent. So, depending upon the appearance impedance seen by the relay also varies. The third is the non-linearity introduced by metal oxide varistor and by-pass capacitor or air gap. So, because of this whether MOV is conducting or not, whether only series capacitor is conducting or whether both SC and MOV are bypassed.

So, there are various conditions are there, based on that the apparent impedance seen by the distance relay changes. The fourth thing is the various modes of TCSC and other compensation devices, so we know that there are four modes in which TCSC module works, so depending in each mode the apparent impedance seen by the relay that is entirely different.

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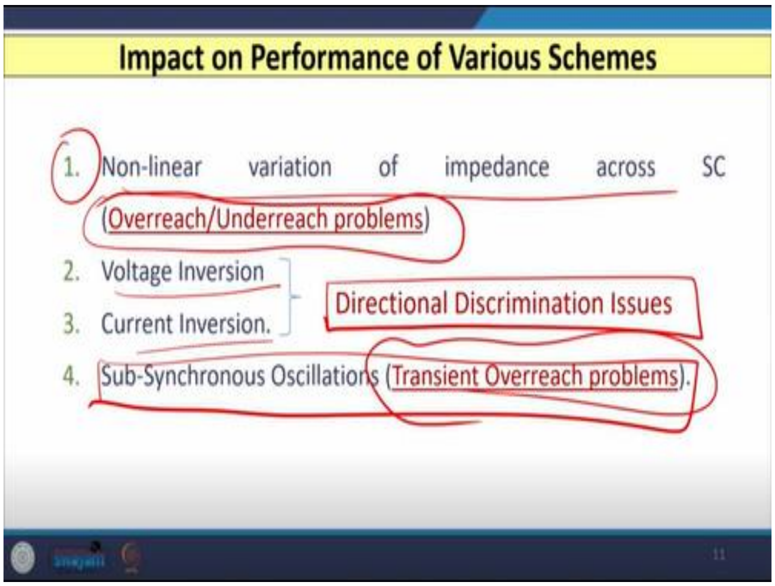

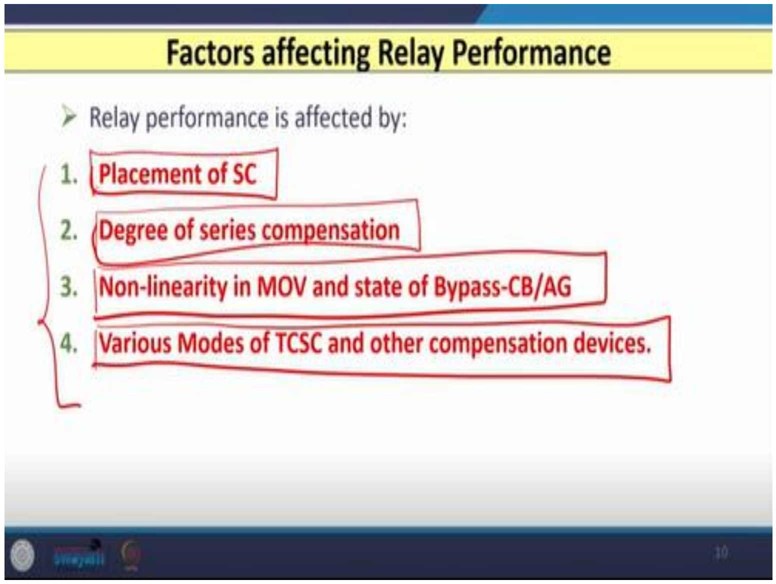

Now, let us see what are this impacts? Because we have discussed that these are the four major factors because of these the performance of the distance relays affected when it is used for the protection of series compensated transmission line.

So, the impact on the performance of different schemes let us say distance relay or digital relay or differential relay or any other relay mainly there are four impacts, the first is the non-linear variation of impedance across the series capacitor maybe because of a MOV or by-pass circuit breaker and because of that the major issue is overreach and under reaching of the distance relay. So, relay under reaches or overreaches is depending upon whether series capacitor is connected or it is bypassed completely.

The second and third issue that is voltage and current inversion and because of this because voltage seen by the relay reverses or the current that is flowing at the local and that reverses because of that the issue related to directional discrimination that is faced by the distance relay. So, whether the fault is forward or reverse the relay is not able to detect this sometimes the impedance seen by the relays negative also. So, this is also the another major issue faced by the distance relay.

The fourth important issue that is the sub-synchronous oscillations SSO and because of that, transient overreach problems, that is going to occur or faced by the distance relay, because in this case, the voltage and the current and what based on that whatever impedance is calculated and seen by the distance relay that is erroneous or that is also oscillatory in nature and because of that transient overreach issues are there.

Now, let us consider the first issue that is the if non-linear variation in impedance is there because of the series capacitor or maybe a MOV or by-pass circuit breaker, then let us see what issues are faced by the distance relay.

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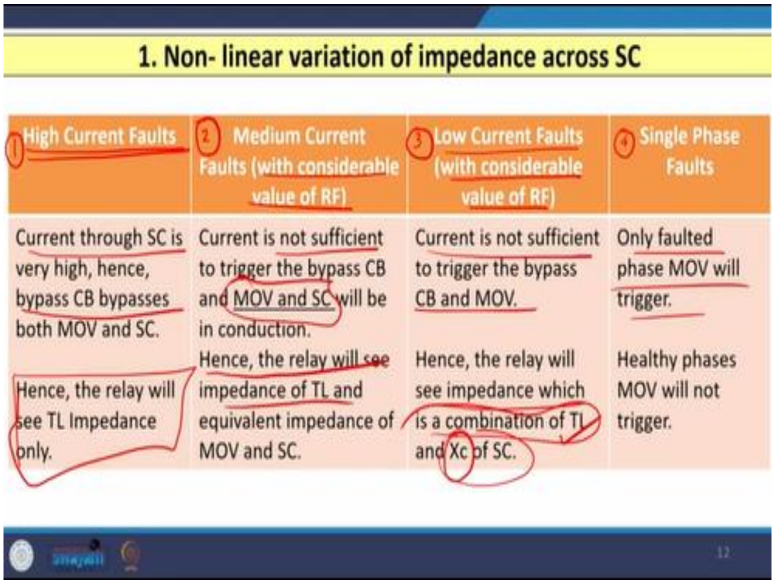

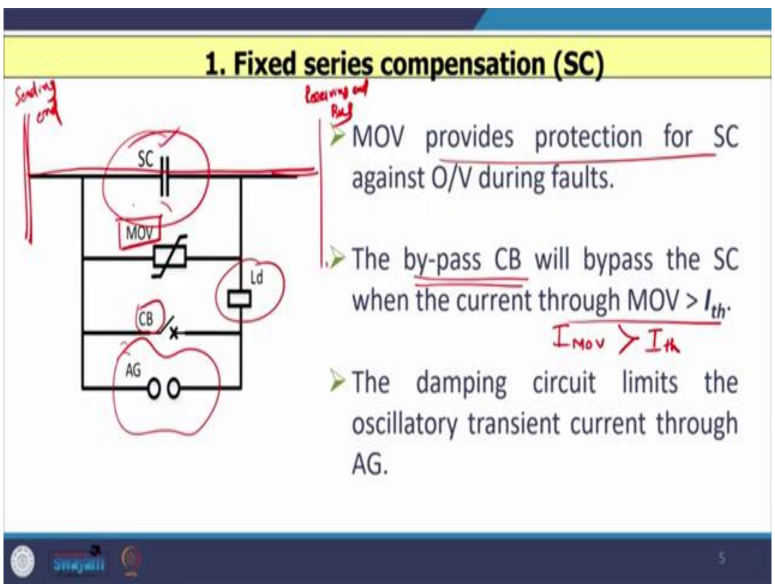

So, to understand that, let us consider four different conditions. The first condition is when the value of fault current is very high, let us say the three phase voltage short circuit occurs symmetrical fault occurs in that case, what would be the apparent impedance seen by the distance relay. So, when the magnitude of fault current is very high current through the series capacitor is very high and hence bypass circuit breaker bypass it both MOV as well as the series capacitor.

So, earlier you can see the module of this series capacitor, so here the series capacitor and MOV that will be completely by-passed. So, in this case your transmission line is as good as it is uncompensated transmission line. So, the relay will see the transmission line impedance only that is as good as uncompensated transmission line.

The second possibility is let us say the magnitude of fault current is moderate. So, medium fault currents are there with some considerable value of fault resistance is also there. So, in this case current is insufficient to trigger the bypass circuit breaker and MOV and the series capacitor will be in conduction. So, they are not bypassed they are there in the circuit they are available current flows through a MOV that is Imov and current flows through the SC series capacitor that is ISC both are there.

Hence the relay will see the impedance of transmission line as well as the equivalent impedance of the MOV and SC. So, the total net impedance that is transmission line impedance and the equivalent impedance of MOV and SC both because both are conducting. So, the entire equivalent impedance seen by the relay that is different in this case.

The third case is the magnitude of fault current is low current. So, with value of fault resistance is very high of the order of let us say 60, 70, 100,150 ohm. So, here in this case, the current is not sufficient to trigger the bypass circuit breaker and MOV. Hence, the relay will see the impedance which is a combination of the transmission line impedance and the Xc that is capacitive reactance of series capacitor. So, the equal and impedance which is a combination of transmission line impedance and Xc of SC series capacitor that is entirely different than the previous two cases.

And the fourth case that is the single phase fault that means the single line to ground faults which is going to occur in only one phase. So, only faulted phase MOV will be triggered whereas the healthy phase MOV will not be triggered. So, this will be important or particularly vital when we consider the single pole tripping facility or operation.

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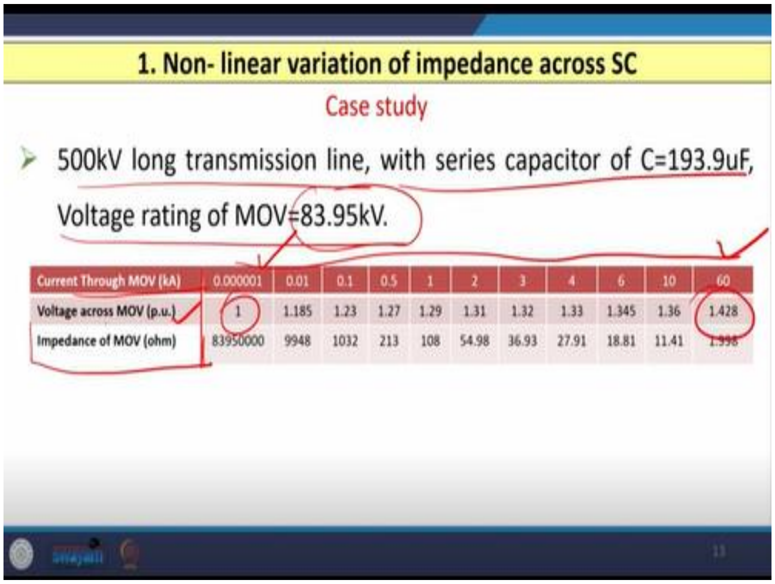

Now, to understand this, let us consider one case study. So, here we have considered a 500 kV long transmission line with series capacitor with C is equal to 193.9 microfarad with voltage rating of MOV that is 83.95 kV and here you can see in the table that we have shown the three values, one is the current through MOV in kilo ampere, these are the values varies from this value to this value up to 60 kilo ampere, voltage across the MOV in per unit that is also shown from 1 per unit to 1.428 per unit and impedance of MOV in ohm that is also shown from this to this value.

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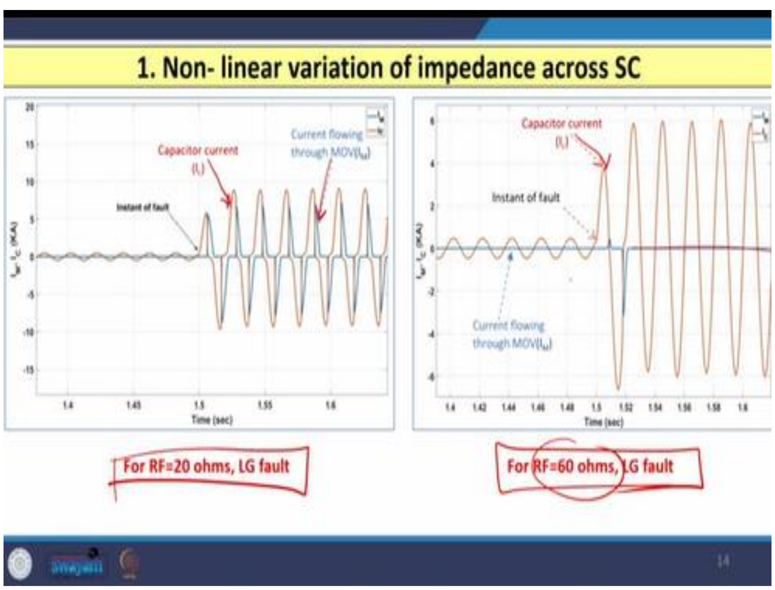

So, if I just find out the current in both the various cases assuming that the LG fault is there with fault resistance is very small let us say 20 Ohm, then you can see that here the current through the capacitor that is IC is shown here and current flowing through the MOV that is also shown in blue color. So, the MOV as well as series capacitor both are conducting. So, in this case both the currents are observed and the apparent impedance seen by relay that is entirely different.

Whereas, if I consider the LG fault with very high fault resistance, let us say 60 Ohm then in that case, you can see only the current through the capacitor is only there the current through the MOV which is shown by the blue which is not there, which is almost 0. So, MOV is not conducting only SC is there, so the equivalent impedance or apparent impedance seen by the relay this case that is entirely different than this case.

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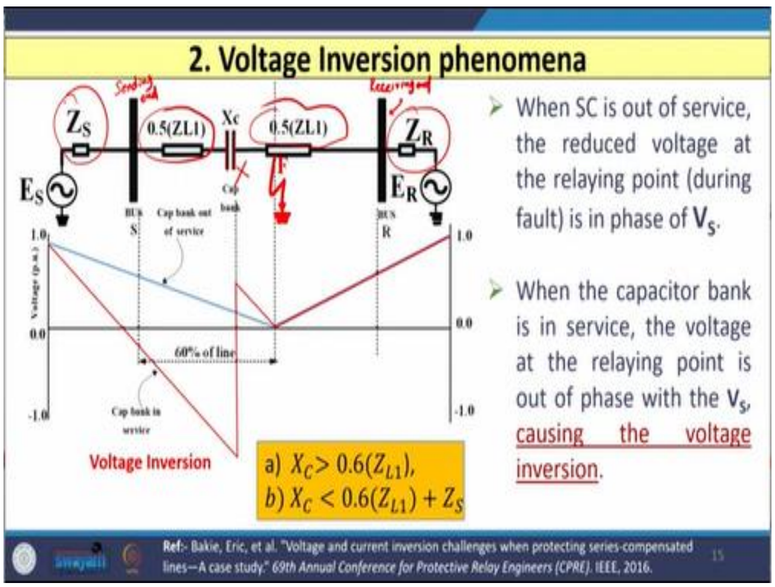

The second issue or the problem is the voltage inversion phenomena. So, here to understand this what we have done? I have shown two buses, one is the sending end bus and another is the receiving end bus and here you can see that I have shown one transmission line with the impedance ZL1 one and I have also shown one series capacitor with the value Xc and Xc plays exactly at the middle of the line.

So, on the left hand side of this Xc that means before the Xc the impedance of the line is 0.5 ZL1 and on the right hand side after the Xc the impedance of the line is again 0.5 ZL1 where ZL1 is the positive sequence impedance or the transmission line. The source impedance at sending end is ZS and the source impedance at the receiving end is the ZR.

Now, here when series capacitor is not there, it is not connected. So, series capacitor bank or module that is MOV, SC, by-pass circuit breaker all they are not connected they are out of service, then the voltage which is seen by the relay that is almost in phase with the supply voltage VS or ES.

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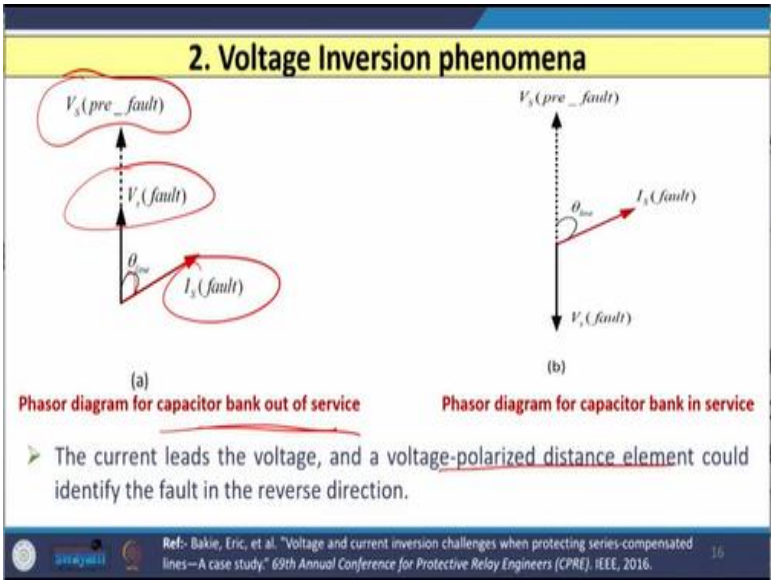

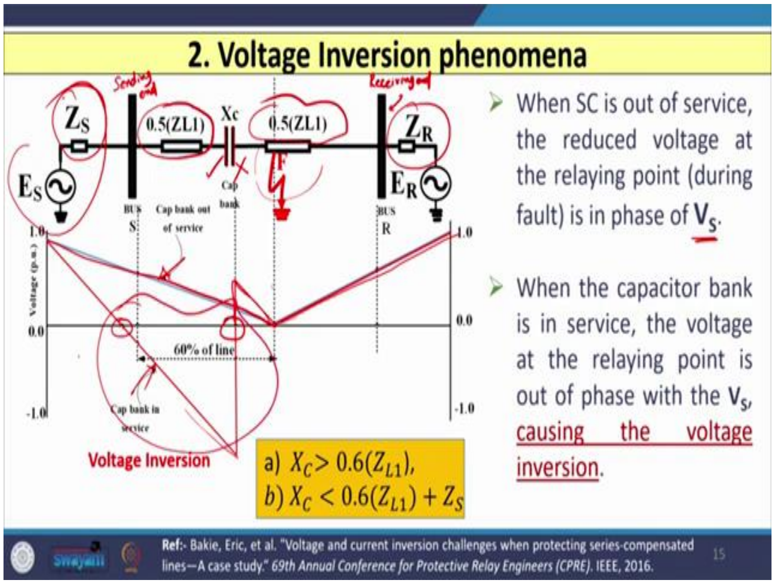

So, here in this case, you can see that the pre fault voltage when series capacitor bank is out of service it is not connected then the voltage that is almost same as the supply voltage. So, in that case the current that is here that is Is and you can see the angle between the Vs and Is that is theta line.

So, here when capacitor or series capacitor module is not connected, you can see that the voltage at every point from sending end to the receiving end is shown by this blue line. So, you can see that the voltage is decreasing here, there is a fault here. So, at fault point voltage becomes almost 0 and then again it increases. However, when capacitor bank is connected that means SC is there in the circuit with MOV, by-pass circuit breaker, air gap then in that case the voltage at the relaying point that is out of phase with the supply voltage.

So, you can see that, that at this point the red color voltage is the voltage when capacitor bank is in service and you see that after some point this voltage that goes in negative up to this point to this point and then after that is increases and again after the fault point it matches and increases with the as good as when the series capacitor module is not there. So, in this case, you can see that the phenomena known as voltage inversion takes place.

So, when voltage inversion is there, then the impedance seen are calculated by the relay that is also negative. And hence in that case the voltage-polarized distance element that could not identify the fault and that will identify the fault in reverse direction. It is not capable to identify the fault in forward direction, so voltage inversion phenomena is the phenomena which is faced by the most of the distance relay.

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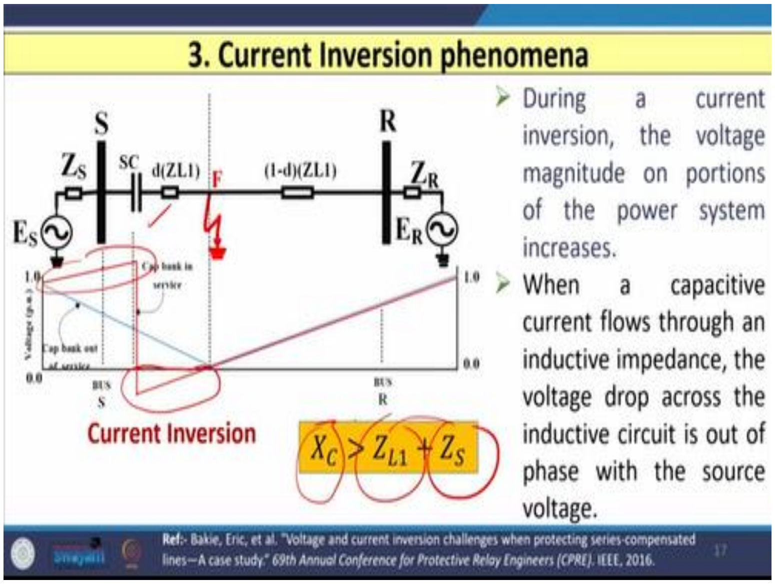

The third issue is the current inversion phenomena. So, during a current inversion the voltage magnitude on portion of the power system increases. So, you can see in earlier case when voltage inversion is there both the voltages whether the capacitor bank is there or not it reduces whereas, in the current inversion when capacitor bank is not connected, the voltage is shown by this blue line at each and every point throughout the line.

Whereas, when capacitor bank is connected, then this voltage it increases and then again reduces drastically, and in this case you can see the voltages that is again out of phase with reference to the previous one compared to the source impedance and in this case, this is going to happen particularly when the value of XC is greater than the ZL1 that is the positive sequence impedance of the line plus source impedance when the value of XC is greater than these two, then the current inversion phenomena takes place.

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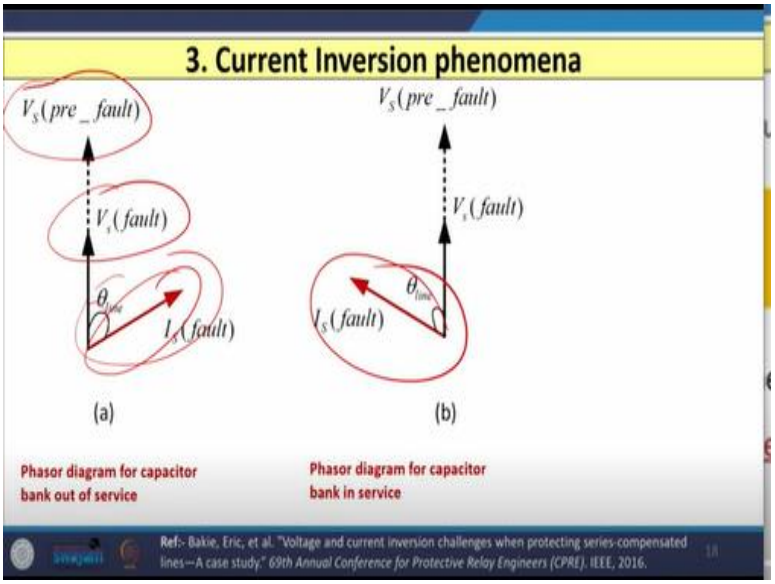

And if I draw the phasor diagram, then in that case when capacitor bank is out of service, you can see that the pre fault voltage and Vs both are in phase and your current is somewhere here and the theta line is here, but when the capacitor bank is available or connected in the line, then this Is reverses, because of these the apparent impedance seen by the relay that is again negative and hence the relay may not operate properly.

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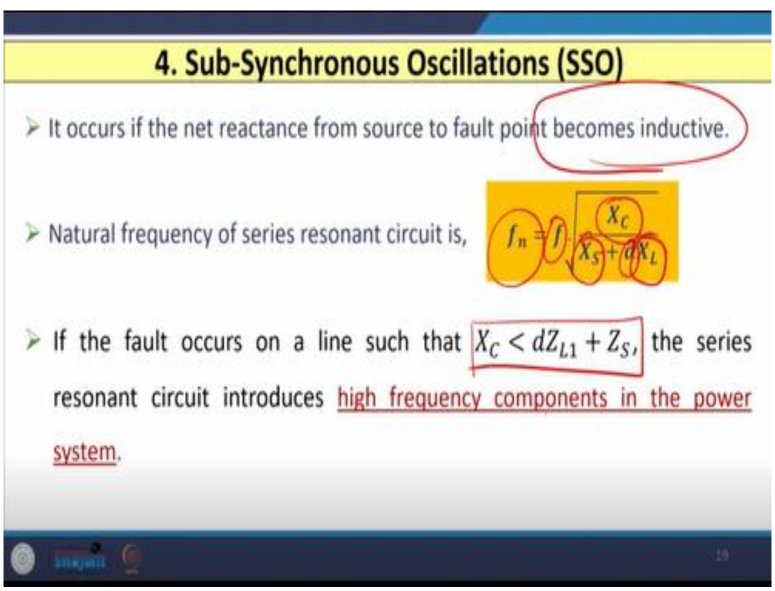

The fourth phenomena is known as sub-synchronous oscillations. So, this type of phenomena occurs when the net reactance from the source to the fault point that becomes the inductive So, natural frequency of series resonant circuit is given by a fn, which is nothing but the f that is the frequency into square root of XC that is the value of the series capacitor then XS is the reactance of the source d is the fall distance and XL is the inductive reactance of the transmission line. So, if the fault occur in a line in such a way that when XC is less than the dZL1 plus ZS then the series resonant circuit introduces high frequency component in the power system network.

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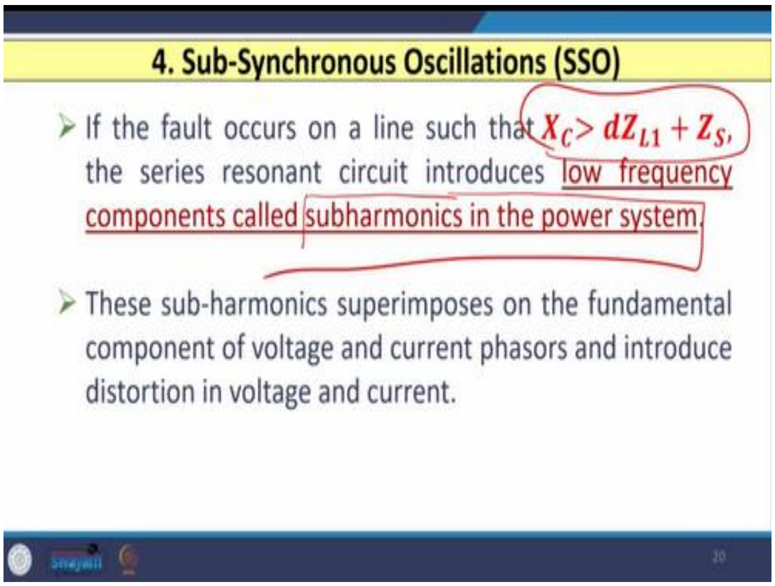

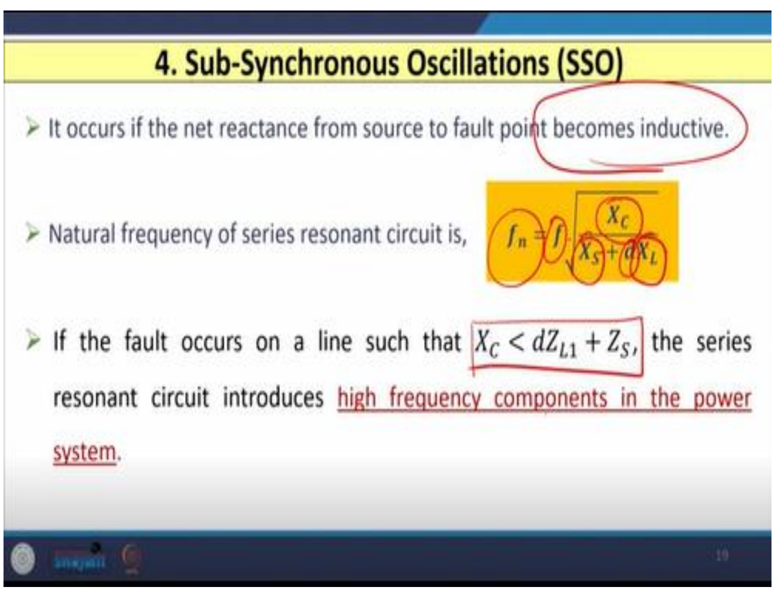

On the other hand, if the reverse is the case that means, when, here high frequency components are introduced when XC is less than this dZL1 plus ZS, but is reverse is the case when XC is greater than dZL1 plus ZS then this are going to introduce a low frequency component in the network which is widely known as sub harmonics in the power system. So, this sub-harmonic superimposes on the fundamental component of voltage and current phasors and introduces distortion in the voltage and current signals.

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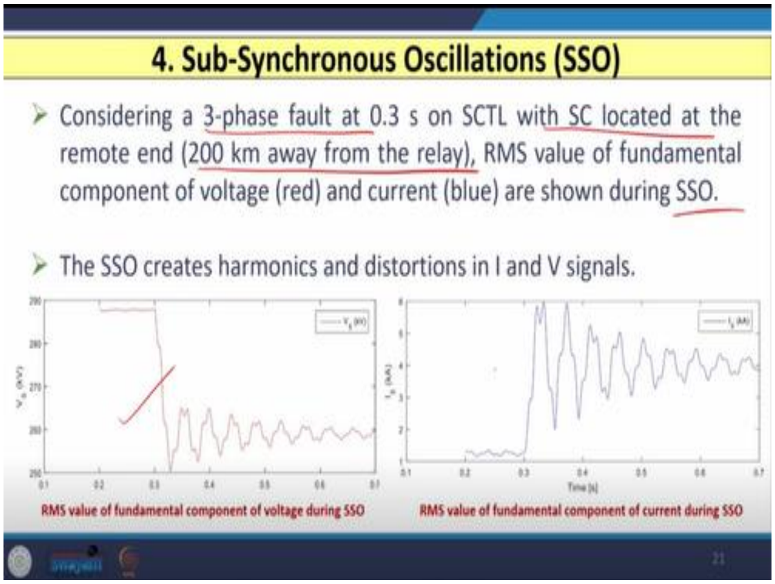

So, to understand this, let us consider a 3-phase fault which is going to occur at 0.3 second on series compensated transmission line with series capacitor is located at the remote end, which is 200 kilometer far away from the sending end. And in that case, if I capture the fundamental component of voltage and currents during this, sub-synchronous oscillations conditions, then you can see that the voltage and currents are observed here and you can see they are oscillating.

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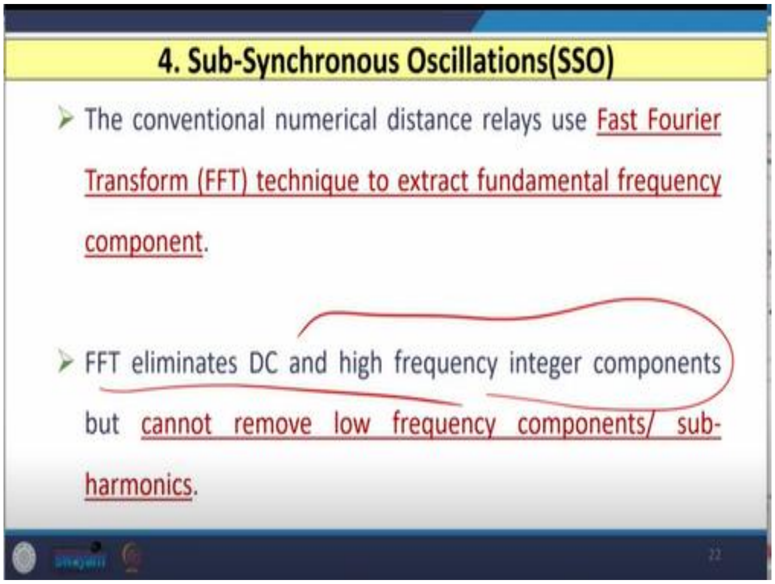

So, because of that whatever is the apparent impedance seen by the relay that is also oscillating in nature. So, in this case, the conventional numerical distance relays normally use fast Fourier transform techniques to extract the fundamental frequency components. So, this is basically phasor estimation techniques though FFT eliminates decaying DC component and high frequency integer components, but this is not capable to remove low frequency component or sub-harmonics.

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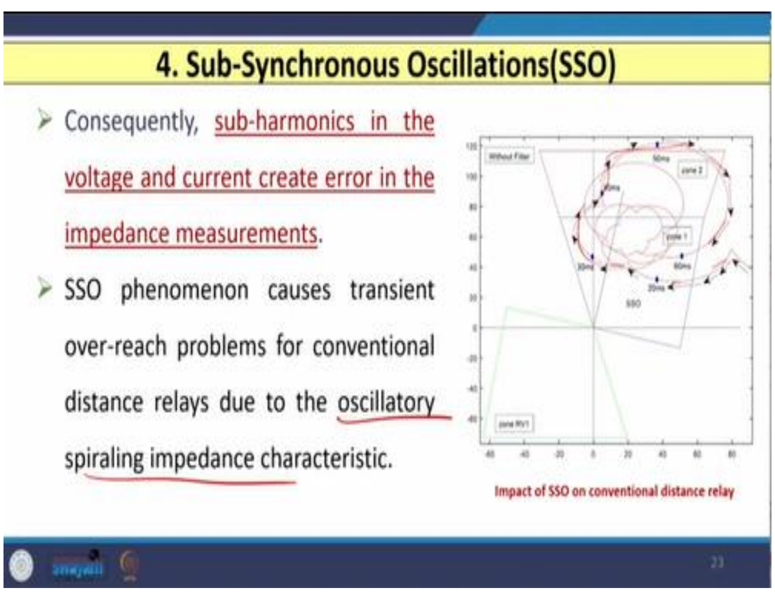

So, because of that the sub-harmonics in the voltage and current create the error in the impedance measurement. So, particularly you can see that in this case the impedance seen by the relay that is oscillatory spiraling impedance type of characteristic. So, you can see here I have shown on RX plane when the impedance enters here at 20 milliseconds then 30 to 40, 50 and then again it is oscillating in nature. So, whatever is the impedance seen by the relay that is not fixed and hence relay may mal operate.

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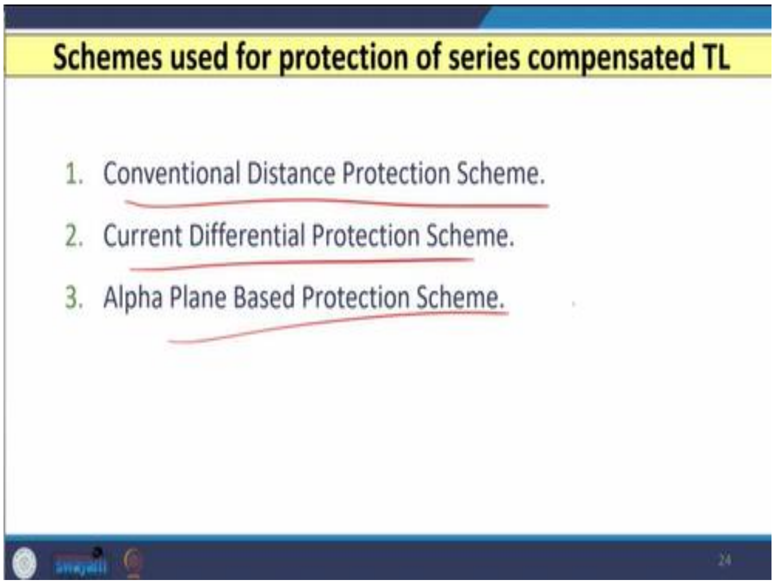

Now, to avoid this for all the four phenomenas that is the current voltage inversion, the non-linearity introduced because of MOV and XC series capacitor and the last one that is the sub-synchronous oscillations which are introduced because when XC value is greater than the dZL1 plus ZS. To avoid that normally three types of schemes are used one is the conventional digital distance relaying scheme, another is the differential scheme and another is the alpha plane scheme.

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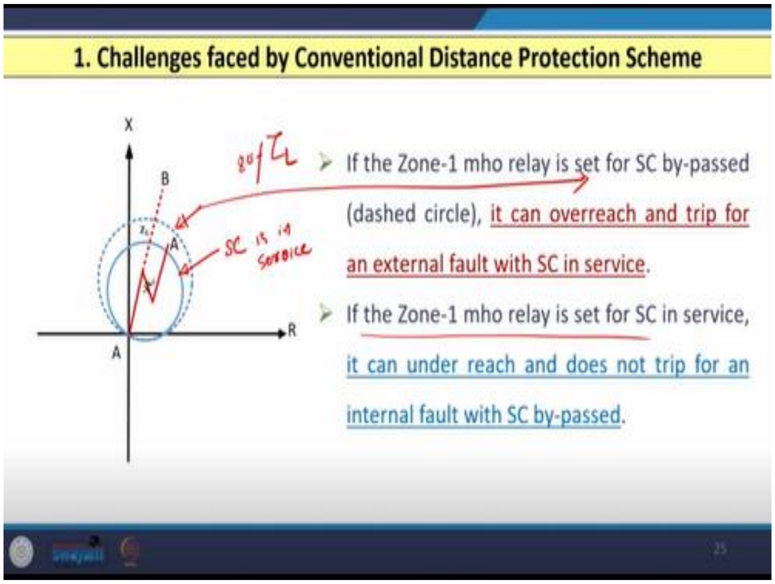

Now, if I consider the conventional distance protection scheme, then the setting of this scheme is difficult when I consider or when I apply for the protection of series compensated transmission line, because you can see the first zone characteristic of this conventional distance relay is shown here. Now, if zone-1 of this mho type characteristic is set normally, which is 80 percent of the ZL if it is set assuming that SC module is not connected it is by-passed, then this will overreach and trip in case of external fault when SC is in service. So, one case that is overreaching is there.

Second, let us say set the first zone of relay when SC is by-pass then why not we set the relay when SC is there. So, if we set the zone-1 of the relay, when SC is in service, so this is dot hard circle this one when SC is in service and this is there when SC is not in service. So, if we set the relevant SC is in service, then you are relay under reach and does not initiate a trip in case of internal fault when SC is by-passed. So, the conventional distance relay faces challenges in terms of overreaching in case of external fault and under reaching in case of internal fault and it is difficult to set the relay whether we set when SC is by-passed or we set when SC is there.

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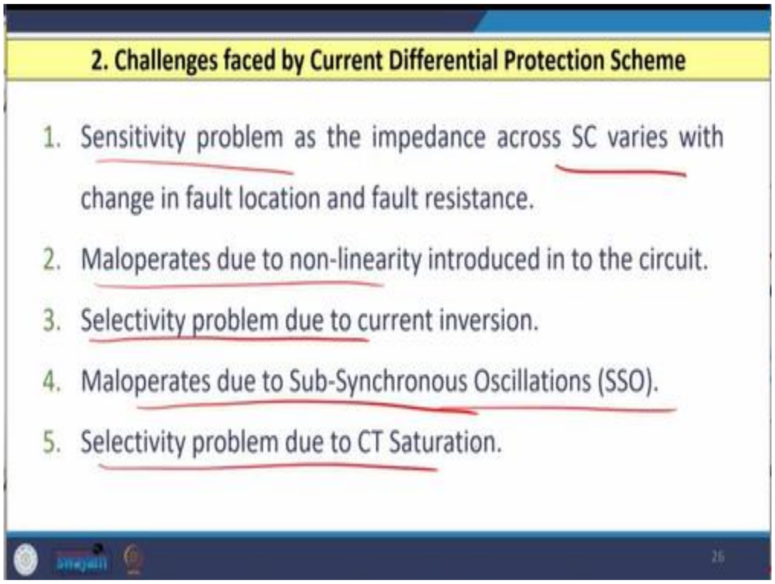

Now, instead of that, if I use current differential protection scheme, then this scheme faces several challenges. The challenge major challenges are the first one is the sensitivity issue. As the impedance across the series capacitor varies because of the change in fault location and fault resistance. This type of scheme may maloperate, because of non- linearity introduced by the MOV, SC and by-pass circuit breaker. It also has a selectivity problem due to current inversion. This type of relay may maloperate in case of sub-synchronous oscillations and selectivity problem because of CT saturation especially in case of external or heavy through fault.

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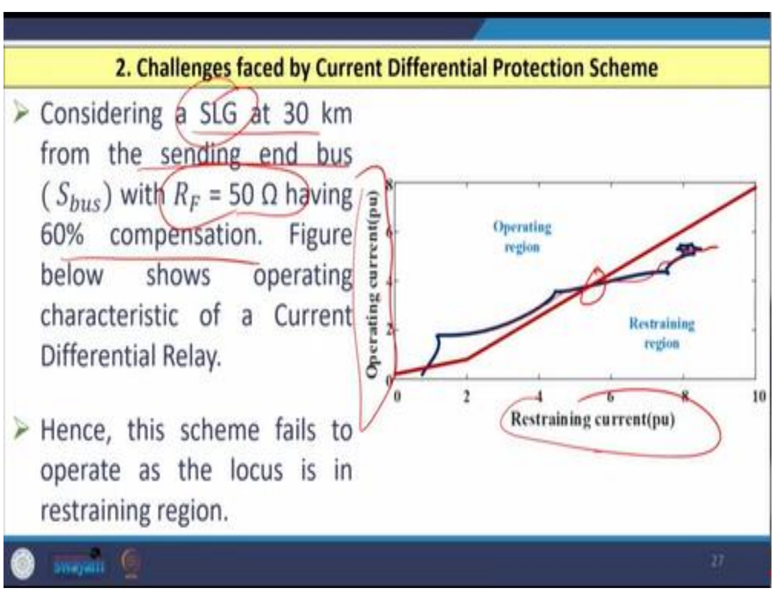

To understand this, let us consider a single line to ground fault at 30 kilometer from the sending end bus with RF is equal to 50 ohm with 60 percent compensation. So, here the output of the current differential relay shown in terms of operating characteristic where the restraining current I have shown on x-axis and operating current I have shown on y-axis. So, here you can see that initially the locus is in operating region because it is a single line to ground fault with 50 Ohm fault resistance 60 percent compensation, but after this point, it will enter into the restraining region and hence relay is not able to identify this as a fault.

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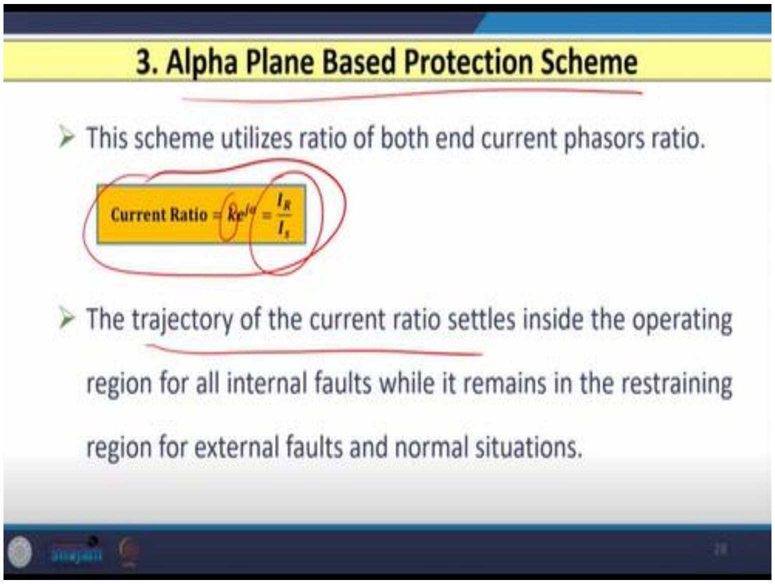

So, to avoid this we have to go or select another scheme and the recent scheme is based on alpha plane. So, this type of scheme utilizes the ratio of both end current phasors and that is given by this current ratio is equal to k some constant e raise to j alpha, which is nothing but the receiving and current phasor divided by sending end current phasor. So, the trajectory of this current ratio settles inside the operating region for all internal faults were at it remains in the restraining region for all external faults and in normal conditions.

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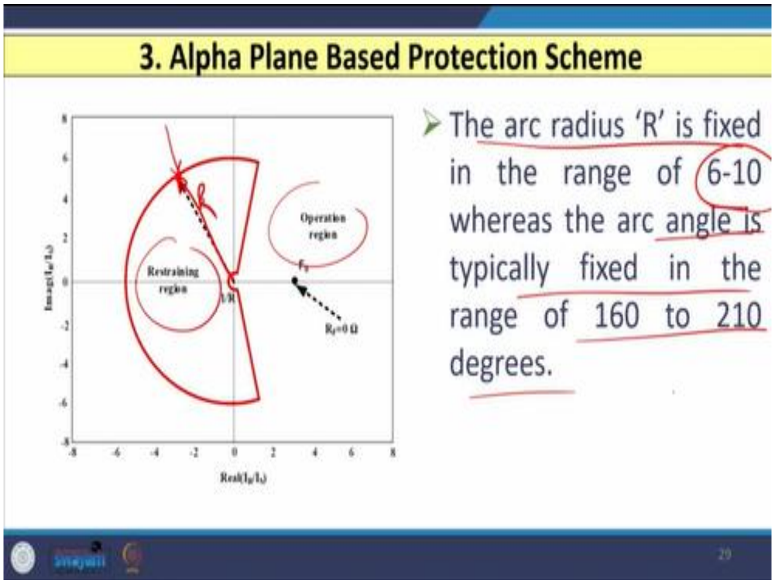

So, here the alpha plane characteristic looks like this. And here you can see that any point inside this alpha plane that is your restraining region any point that is outside of this alpha plane that is your operating region. Now, the question comes how to decide the radius of this alpha plane. So, the arc radius is fixed in the range of 6 to 10 whereas, the arc angle is typically fixed in the range of 160 to 200 degree.

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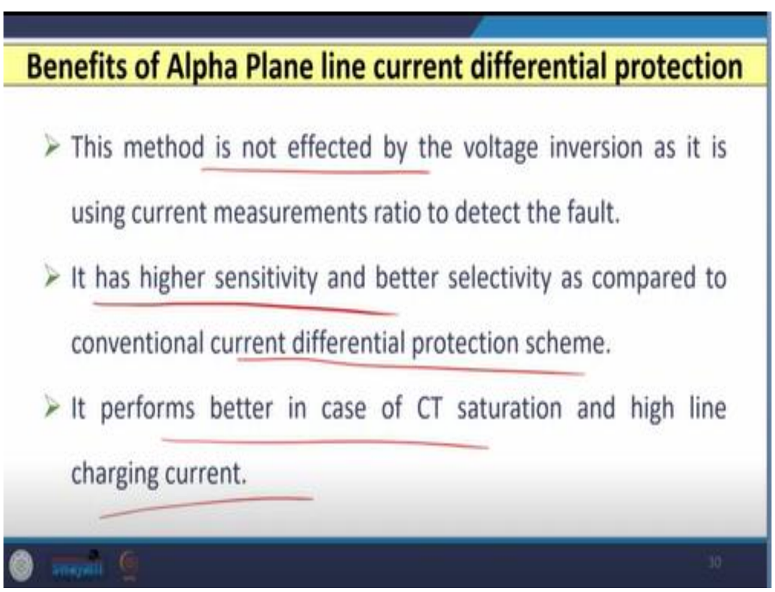

So, there are certain benefits of the alpha plane line current differential protection scheme. The reason is this method is not affected by the voltage inversion phenomena because it works on current principle it is based on the ratio of two current phasors, so voltage inversion phenomena is not there.

This type of scheme has higher sensitivity and better selectivity compared to the current differential protection scheme. And this type of scheme performs better in case of CT saturation and high line charging currents that is why nowadays most of the utility, they use alpha plane based scheme particularly when it is installed for series compensated transmission lines.

So, here we have discussed the three different types of schemes, one is the conventional distance related scheme, second is the current differential protection scheme. And third is the alpha plane based scheme. And we have discussed the performance of these schemes based on four important things.

First is the under reaching and overreaching of the distance relay because of the non-linearity introduced by MOV, by-pass circuit breaker and the air gap and the series capacitor and the second is the current inversion the third is the voltage inversion and fourth is the SSO. So, based on that we have discussed the important issues or challenges faced by the three schemes used for the protection of series compensated transmission line. Thank you.