Power System Protection and Switchgear

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Lecture 27
Protection of Transformers-II

Okay. So let us continue our discussion on the Transformer Protection.

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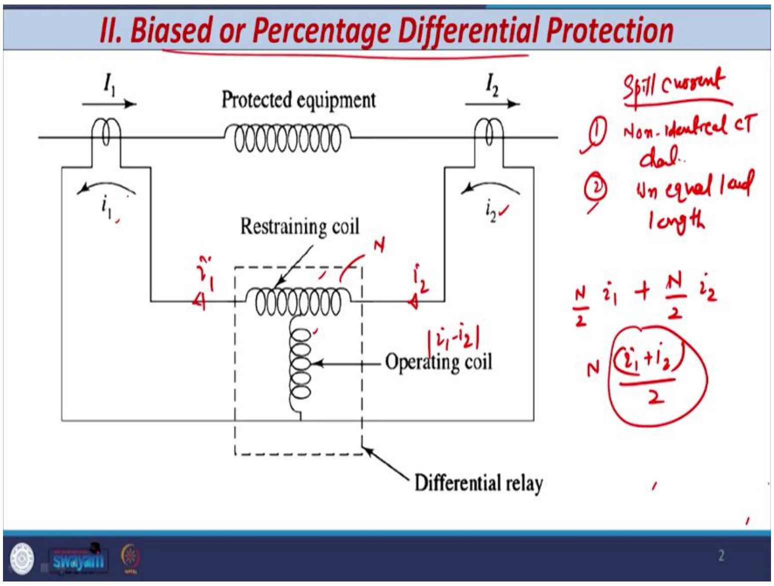

So we have discussed that earlier, that we can use the circulating current differential protection and in that circulating current differential protection, two problems are there. The first problem that is the problem of the spill current and this spill current that flows through the relay because of the non-identical, CT saturation characteristic and the second, that is the unequal lead length. And because of this two point, two problems, the differential current that flows through the relay and relay may mal-operate if we go for circulating current differential protection scheme.

So the remedy is to use the biased or percentage differential protection scheme. So in earlier case, circulating current differential protection scheme, the relay, this is the relay, right, it has only one coil that is known as the operating coil, through which the I1 minus I2 are the differential current flows.

Now is biased or percentage differential protection scheme, the another coil that is the known as the restraining coil is also connected. So the operating coil is connected at midpoint of restraining coil. So the current here that is I2 and this current that is I1, so the current through this operating coil still remain I1 minus I2, right, if I take absolute value. And if for the restraining coil has N number of turns, then the current flows for half of the turns that is the

I1 and the other current that flows through half of the turns of the restraining coil that is I2. So again, the value will be I1 plus I2 by 2.

So the current that flows through the restraining coil that is the average restraining current, if the average current, that is the I1 plus I2 by 2. So if we use this, then because of this two problems, non-identical CT saturation characteristic and the unequal lead lengths, I2 and I1 even though theyare not equal, unequal, and still spill current flows, then also this relay has two settings.

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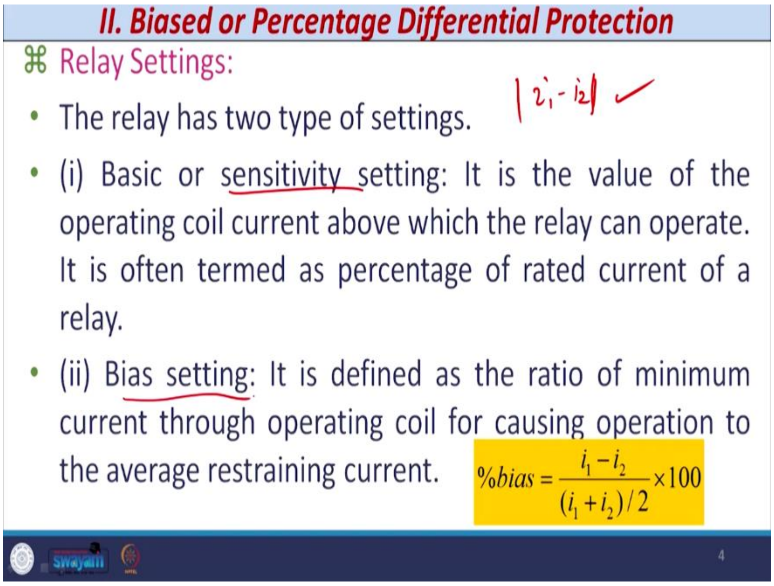

The first setting that is known as the busy setting or the sensitivity setting. So this basic setting or sensitivity setting that is given by I1 minus I2, so this is the current that flows through the operating coil of the relay, right. That is the bias differential relay. So this is the first setting that is known as the basic setting or the sensitivity setting, right.

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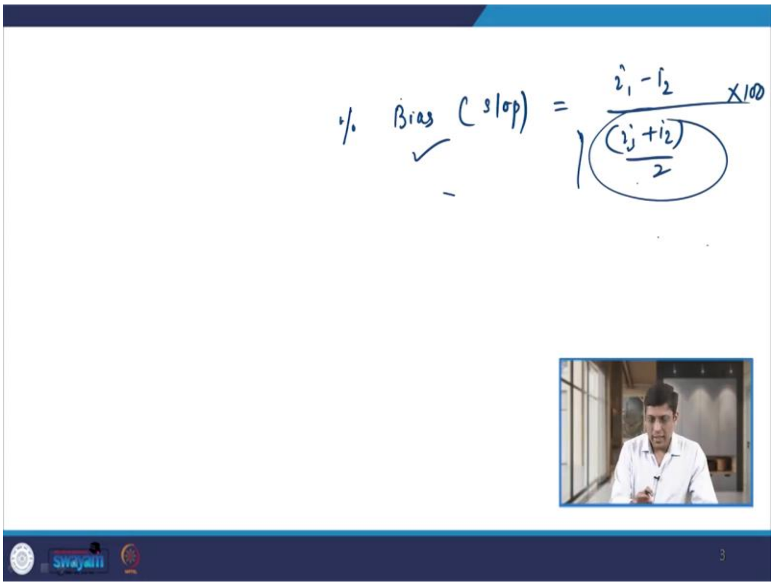

The second type of setting that is known as the bias setting. Sometimes this is also known as the percentage bias or sometimes it is also known as the slope setting. So the slope setting is given by the ratio of I1 minus I2 divided by I1 plus I2 by 2 into 100, so this you will get in percentage. So you can see that if in the case of circulating current differential protection, spill current I1 minus I2 flows because of two problems as we have discussed. In case of bias differential relay, even though differential current is there, spill current is there and this setting exceeds, but the percentage bias setting that is not going to exceed, because even though I1 minus I2 that is spill current flows, the denominator, you have the average restraining current, this also increases. So the percentage bias reduces.

So that means, if I consider the bias setting, then using this setting, whatever is the problems faced by the circulating current differential relay because of the non-identical CT saturation characteristic and the unequal lead lengths or because of the flow of spill current, this type of problem that can be avoided if I used biased or percentage differential protection scheme.

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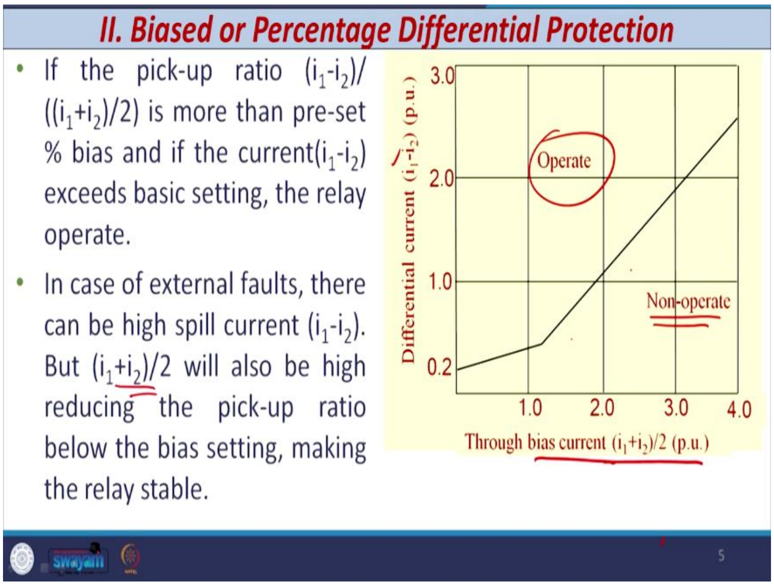

Now let us discuss what is the characteristic of biased differential relay. So the characteristic of this relay that is given or plotted considering on Y axis we can consider the differential current, that is I1 minus I2 and on X axis I will consider the bias current that is I1 plus I2 by 2. And you can see that the characteristic is like this, so any portion above this characteristic that is the operating region and the portion below this that is the blocking region.

Now when we consider any point, right, say the differential current flows or the spill current flows through the relay because of two reasons, then that point, because of increase in this value, restraining current that will again come or fall down somewhere here. So it is always in the blocking region or non-operating region, so relay does not operate and the mal-operation of the relay that can be avoided.

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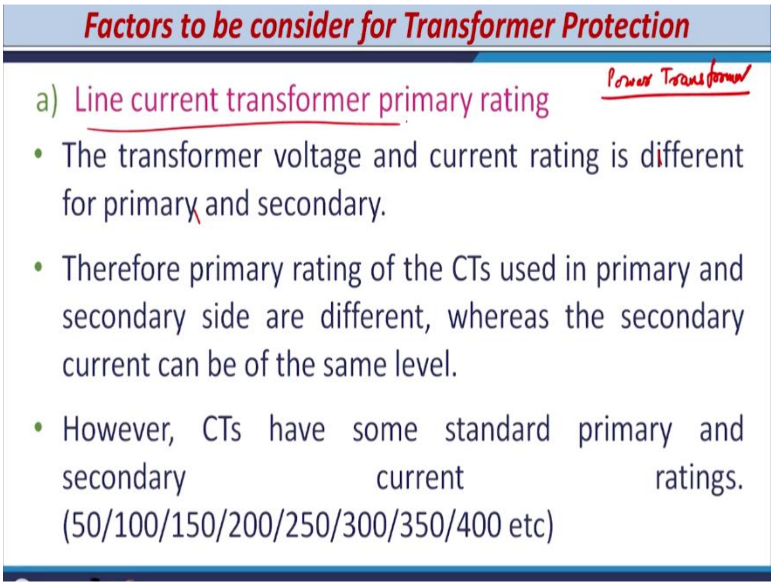

Before we apply this biased differential relay or any type of differential protection scheme to the transformer, power transformer, right, we are talking about the power transformer, then few points we need to consider. Let us see what are those points.

The first point that is the line charging transformer primary rating. Now we know that the transformer, voltage and current rating that is entirely different. So if I consider LV side and HV side, the currents are entirely different.

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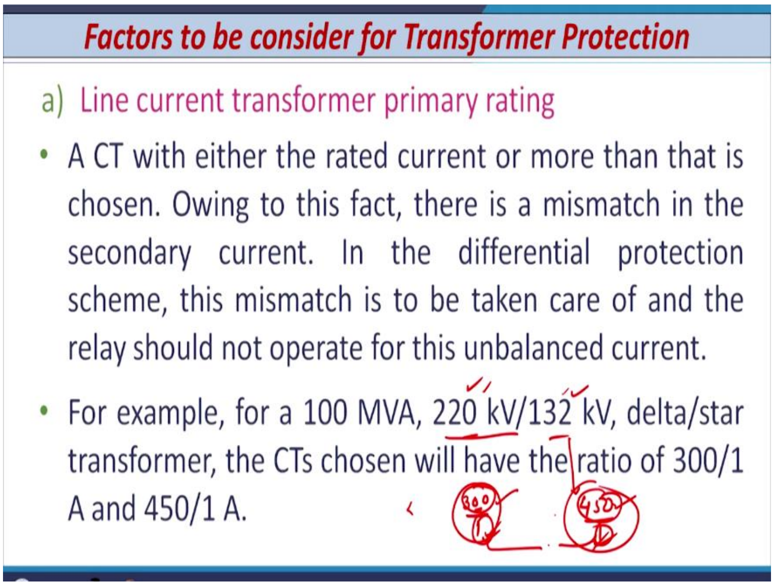

So whatever CT we use, then in that case, the CT ratio is also different. Why CT ratios are different because suppose for example, if I consider 220 kV by 132 kV delta star transformer, the MVA rating is 100, then the current on 220 kV side and 132 kV sider are different. Sowhatever CT ratio I have to consider or select on 220 kV side and 132 kV side, both are also entirely different.

For example, for 220 kV side, we have to consider the CT ratio that is 300 by 1 ampere for the CT located on 22 kV side and for the CT located on 132 kV side, the CT ratio I have to consider that is 450 by 1 ampere. So you can see the primary rating of both the CT1 and CT2 on each side of the transformer that is entirely different.

However, the secondary rating that is always same. It is always 1 ampere or 5 ampere. If the current is above 1,000 ampere primary side, then the secondary rating that is 5 ampere. If the primary current is less than 1,000 ampere then it is always 1 ampere. So that means the primary ratio is let us say below 1,000 by 1 ampere then you always go for CT secondary that is of 1 ampere and if it is more than 1,000 by 1 ampere ratio, then you will go for the 5 ampere CT secondary.

So this is very important and this point need to be consider when you consider the or when you apply the differential protection scheme in case of the power transformer. Why this is important? Because this primary rating that is different, even though secondaries are different, this two secondary currents are different and when you apply this two currents to the relay, differential current that always flows through the relay. So this need to be take care when you apply the differential protection in case of power transformer.

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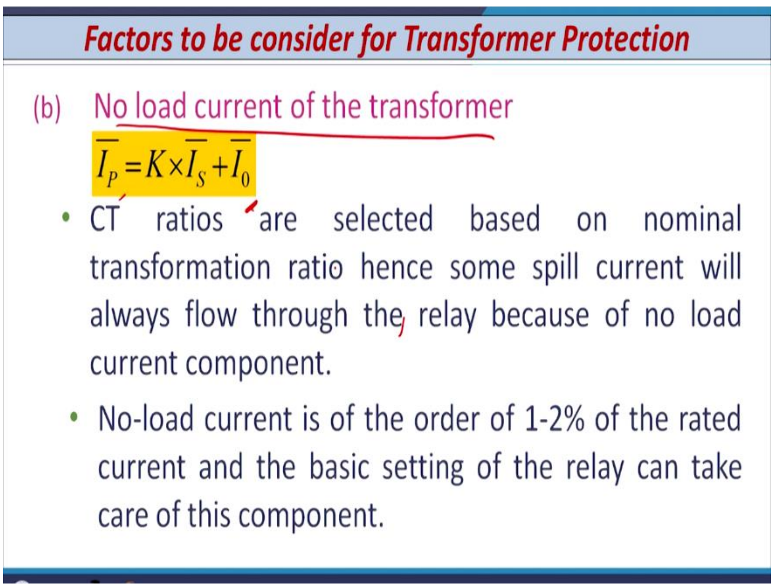

The second point we need to consider is the no-load current of the transformer. We know that the primary current of the transformer that is given by the IP, primary current, that is equal IS time some transformation ratio, K is the transformation ratio and the IS is the CT secondary current plus I not. So I not is the no-load current of the transformer that contains magnetising component as well as some loss component. The no-load current of the transformer that is roughly 1% to 2% of the full load current of the transformer.

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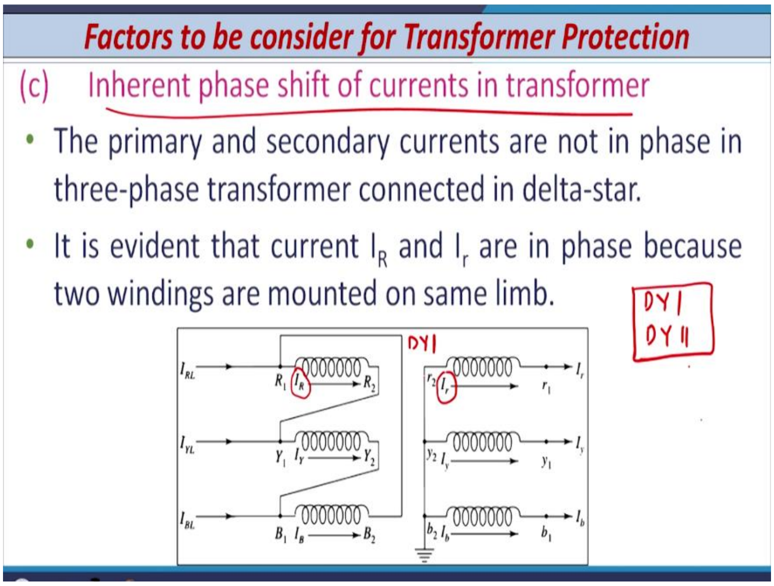

And when you decide the setting of the relay, then that relay is capable to take care of this point that is no-load current of the transformer. Let us discuss the third point we need to consider when we apply the differential protection scheme for the power transformer. So the third point that is known as the inherent phase shift exist in the power transformer.

Now when we consider the delta-star transformer and we know that in actual sub-station practical field, whatever transformer we use, power transformer that is either of DY-1 vector group or it is either DY-11 vector group. The other vector groups DY-7, DY-5 are not used, so we use only either DY-1 or DY-11. So here I have show the diagram for the DY-1 vector group. So this is for DY-1 vector group, delta-star transformer with the connection one.

Now when we consider this, you can this that this current capital IR and small ir this two currents are equal. Why? Because when you found the transformer, this two coils are again mounted on the same lane, so this capital IR and small ir both are same.

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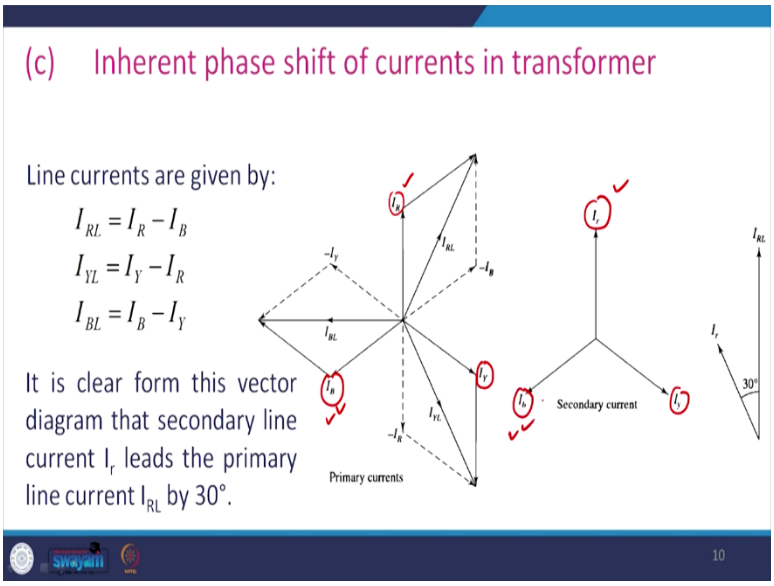

So if I draw the vector diagram, you can this small ir, iy and ib, both are, all are 120 degree apart and this ir that is in phase with capital IR, capital IY that is in phase with this, this is in phase with this Ir and IB that is in phase with the small ib, right. So this is very important.

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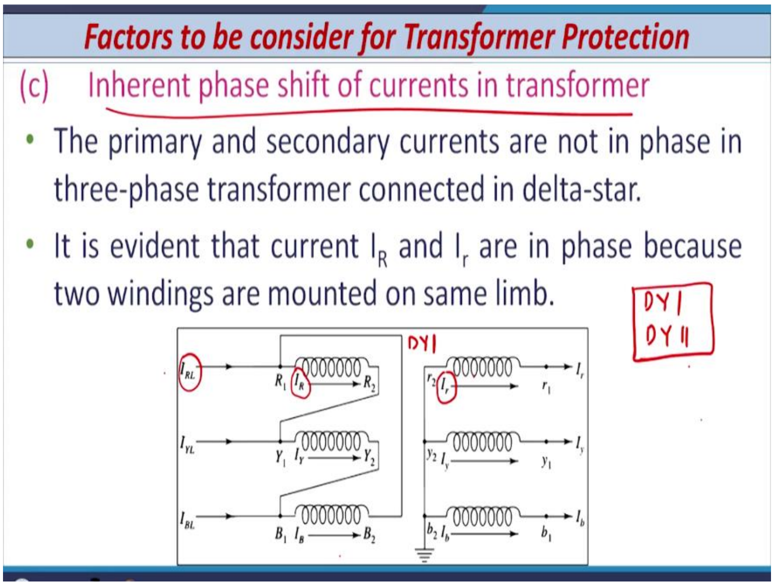

However, if I just look at this current, IRL, then this IRL is nothing but from this point if you mirror it is IR minus the current available from B phase that is IB. So this IRL that is nothing but the IR minus IB.

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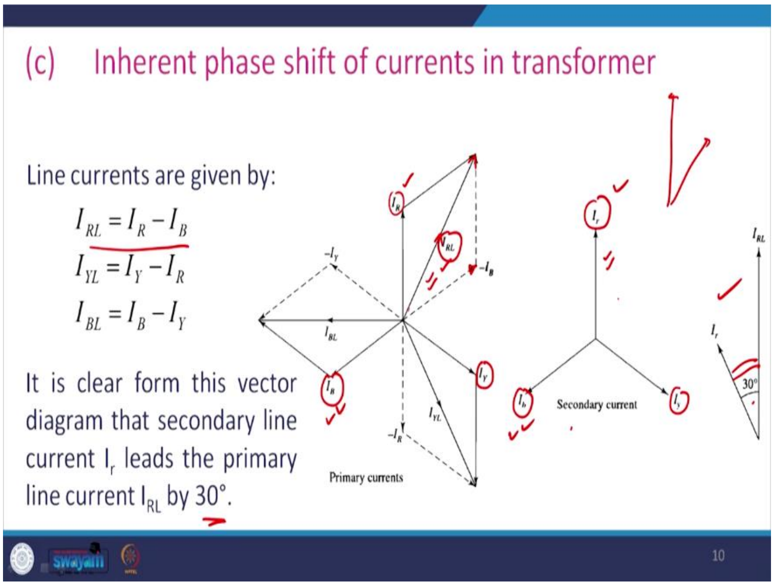

So if I draw a vector diagram for IRL, then it is IR minus IB, so your plus is IB is here so if I extend this, the your minus IB that is here. And if you add this to IR and minus IB then you will get the value of IRL that is here. So if I compare this IRL and this small ir, here this two points, then you can see that capital IRL and small ir there is a phase shift exist between these two. If I consider this diagram, considering the primary or the IRL as a reference value, then the secondary current IR always leads the primary current IRL by 30 degree, right, this is the 30 degree. So that's why or sometimes it is also known as 1 o'clock, right. So this type of connection is known as 1 o'clock connection, that's why the name given DY-1, right.

If I consider the DY-11 type of vector group, then the phase shift available that is the minus 30 degree and the available point that is somewhere like this, like 11 o'clock, that's why the connection name given, that is 11. And in this case, the secondary current IR lacks the primary current IRL by 30 degree that's why the minus 30 degree connection or 11 o'clock connection.

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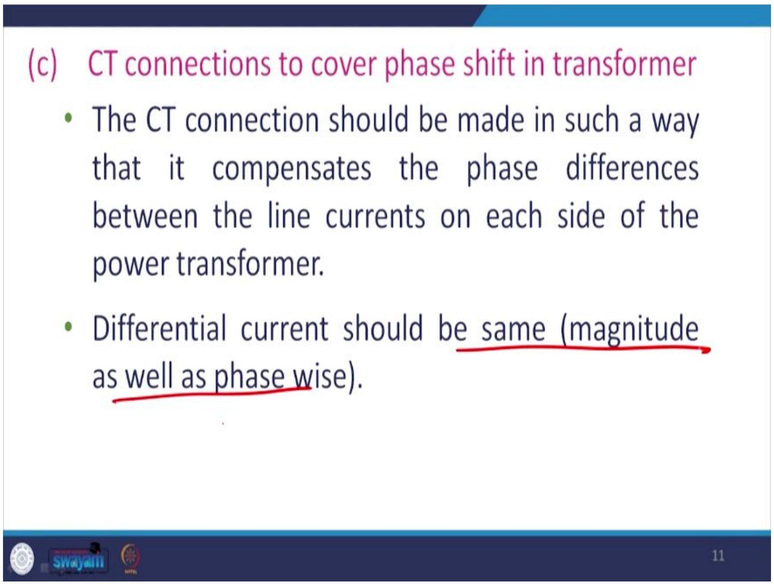

So whenever we give or whenever we apply differential protection scheme as differential relay to the transformer, delta-star transformer then as we have discussed that there is an inherent phase shift of 30 degree plus, minus, depending upon the vector group use, either 1 or 11. Whenever we apply the differential current or CT secondary current from LV side and CT secondary current from HV to the relay, the differential current always flow through the operating coil.

So this current, this two currents given to the relay that is equal in magnitude as well as in phase, so this is very important. Differential current should be same in magnitude as well as in phase. So we need to do some arrangement to compensate this phase shift inherent phase shift that exists in the delta-star transformer depending upon the vector group used, either DY-1 or DY-11.

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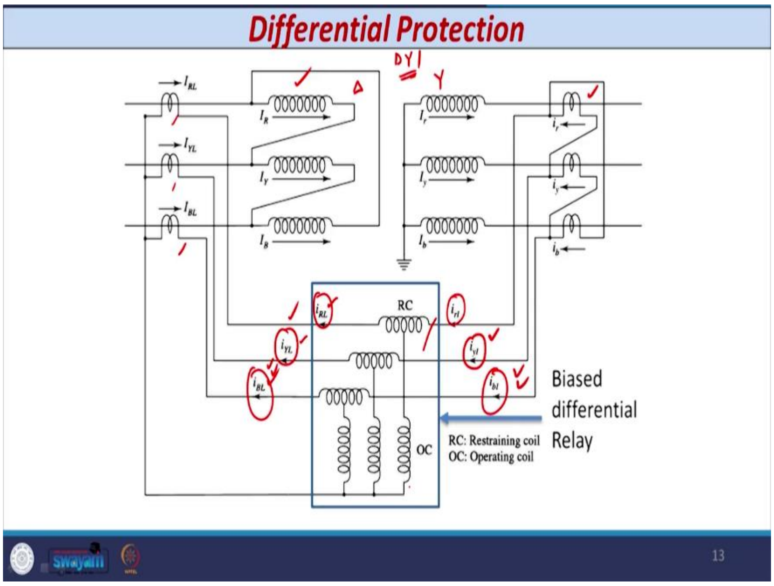

So how to avoid this? So to avoid this what we do is, this is your delta connected delta and this is star, right. This is again the DY delta-star connection. Now so the remedy to compensate the 30 degree phase shift, whatever delta side of the winding connection is there, whatever CT I use here, that CT I connect in star. And the star side, star winding of the transformer, whatever CT I use, that I connect in delta. So delta side, whatever CTs are used, line CTs are connected in star and on the star side the line CTs are connected in delta. Keep in mind, this delta should be same as your DY-1 like this, right.

So if you connect like this, then whatever phase shift is there that can be avoided. And whatever current, you can see that the primary current is IRL, IYL and IBL on delta side, so the secondary current 180 degree out of phase, that is IRL and IBL. This current should be equal to the current given on this side, that is IR, IY, IB, so small ir, iy and ib, this two currents, this current and this current should be same, this current and this current should be same, and the other, this current and this current should be same.

So this three currents are equal in magnitude as well as in phase, because this is the relay which has biased differential relay which has three operating coils and three restraining coil, one for each phase.

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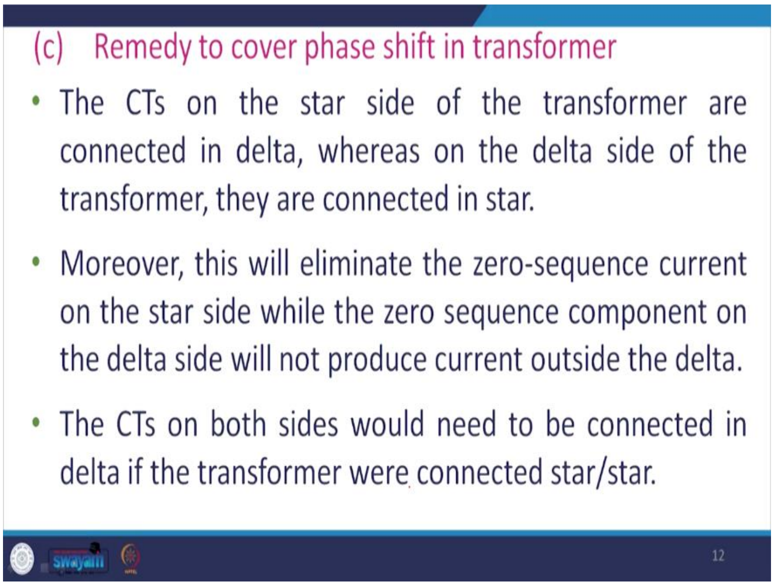

So that means if we go for any compensation then we have to connect the line CTs like this. Moreover, if we connect like this, then this is also going to eliminate the zero-sequence current on the star side, while the zero-sequence component on delta that is not produced outside the delta, it remains circulated inside the delta. On the other hand, if I use the star/star connection, then the CTs on both the side that should be connected in delta, but however, star/star connected vector group, normally we are not using, we use either DY-1 or DY-11.

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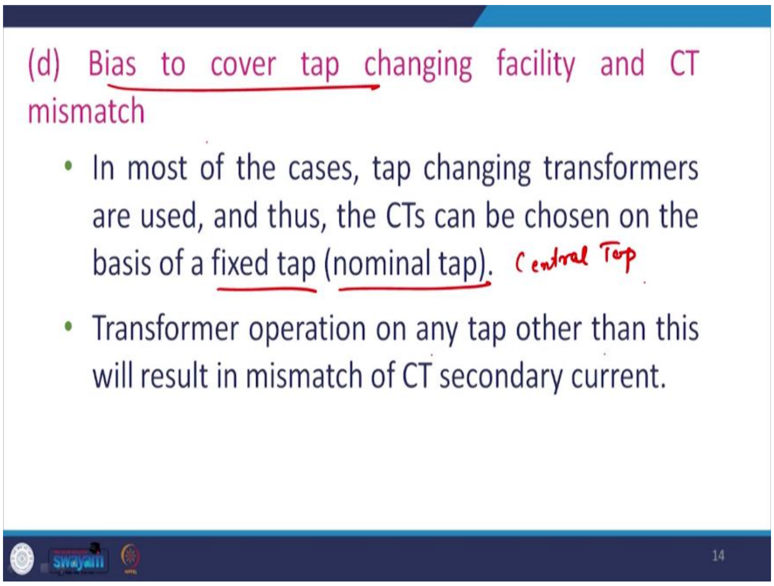

The next point that is or the next factor we need to consider that is a bias to cover the tap changing facility. We know that most of the power transformers are inherently contain the tap changing facility. So tap changing transformers are widely used and hence the CTs that can be chosen based on which tap, highest tap, nominal tap or the lowest tap. So normally when we decide the CT ratio, we decide the CT ratio based on the nominal tap or the fixed tap. This is normally the central tap, right.

So the transformers operation for any tap other than the nominal tap or the central tap, that means if we decide the CT ratio based on the nominal tap and then if I change the tap and put or use the highest tap, then in that case, because of the mismatch, some current that will always flow through the relay. So this current need to be compensated and this is known as again the spill current.

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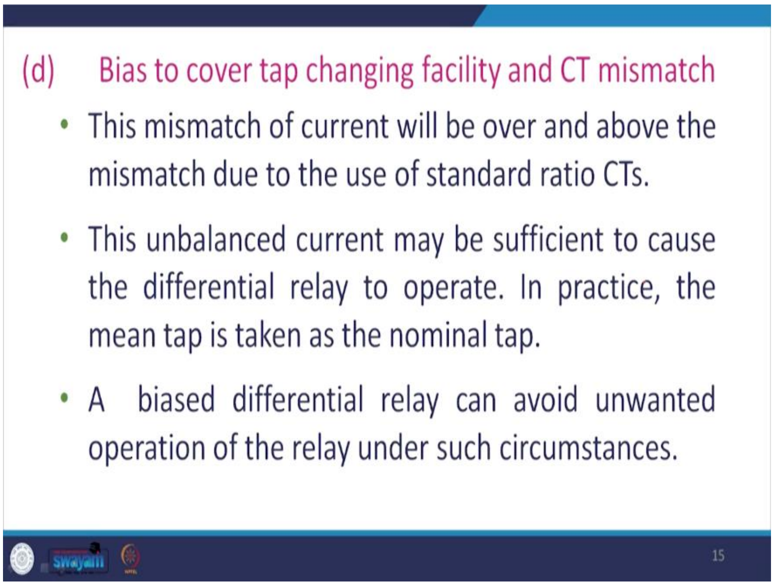

So the mismatch of the current that will over and above the mismatch because of the non-standard CT ratio or unequal lead length. So the unbalance current that maybe sufficient to cause the relay operation. So in practice there are two options, what is the remedy of this? The remedy is we can go for either bias differential relay, right, and bias differential relay, even though we use bias differential relay then this relay settings are decided based on the nominal tap. So we have to consider the worst case and then we decide the setting, particularly the bias setting of the differential relay.

But, however, we decide the setting based on worst case, then for other conditions, the sensitivity or the operation of the relay that is affected, right, it reduces the sensitivity.

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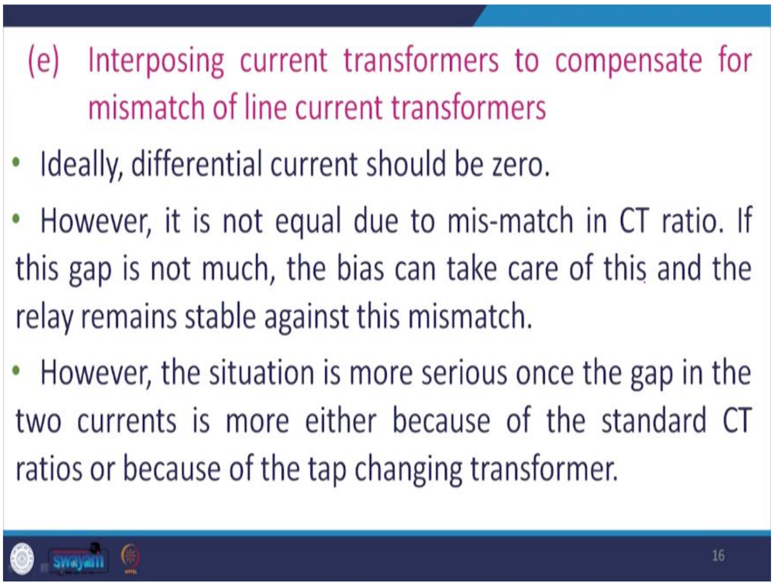

So the best option is we need to go for the adaptive setting. So we know that ideally the differential current should be zero, however, it is not zero because of the reasons as I have explained you, right, because of the tapping. So this situation is more serious. Now if we consider the difference in the mismatch that is lower than the bias, whatever percentage bias setting or slope setting, that can be easily take care of this.

But if the difference in the current because of tap change in tap, either highest tap or lowest tap, this difference is high, very high then the bias is not capable to take care of this. So in that case, we need to change the biased, percentage biased adaptively based on the change in the tappings of the transformer. So this is known as the adaptive setting.

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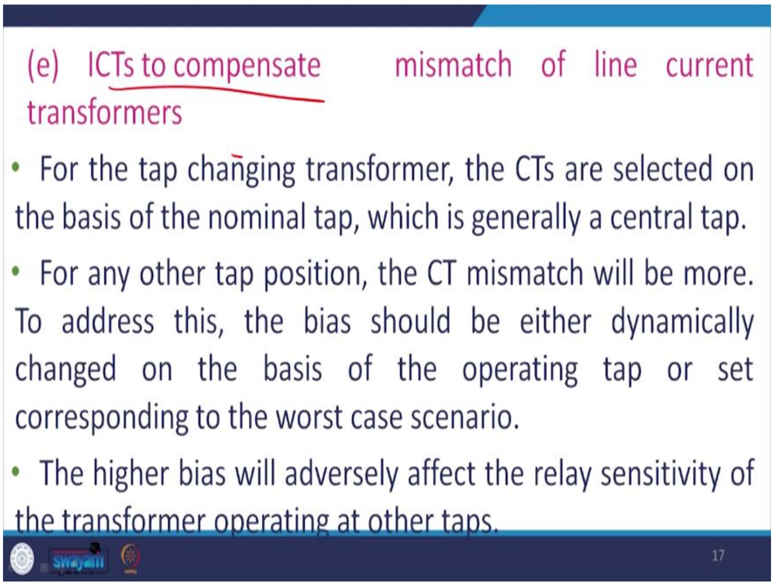

So sometimes, it maybe possible that whenever we use delta-star transformer, then as I told you delta side, we have to connect the line CTs in star and the star side we have to connect the line CTs in delta, so that the 30 degree phase shift can be easily compensated. However, sometimes in actual field, they do not connect both sides, delta side star CT and star side delta CT, they connect both side star/star. So in that case, you have to use the other option that is known as the interposing current transformer.

So interposing current transformers are again the non-standard CTs and this CTs are at low voltage. That means, if I wish to compensate the magnitude of current as well as phase shift at lower voltage, lower current, then we can go for the interposing current transformers.

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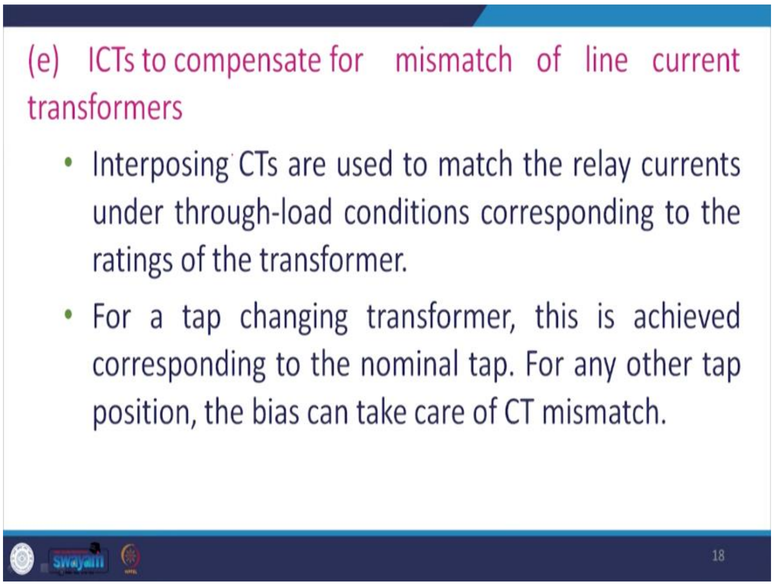

So, in this case, when we use the interposing current transformers it can easily compensate whatever is the mismatch in the magnitude as well as in the phase. So this type of CTs are always connected on the secondary side of original or actual current transformer. So on the secondary of CT you connect one more transformer that is known as the ICT and that is going to compensate the magnitude as well as the phase of the differential relay, so that the current is fed in each phase of the differential relay that is equal in magnitude as well as in phase.

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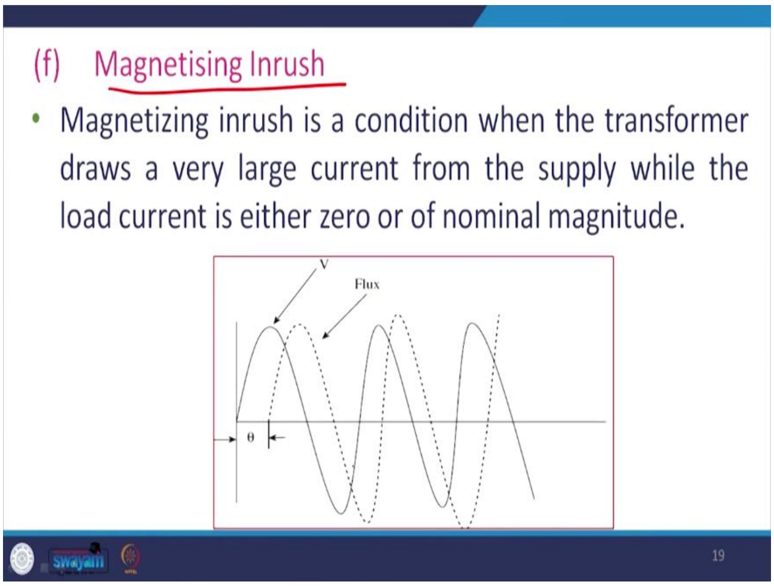

Now the next phenomena that is known as the Magnetising Inrush current. So Magnetising Inrush is a condition when the transformer draws a very large magnitude of current, while the load current is either zero or the nominal magnitude. That means when you energize the unloaded or lightly loaded power transformer, then the transformer draws a very high magnitude of current and that current is known as Inrush current.

Keep in mind, this Inrush current is not a fault. However, whenever the draws the current, Inrush current its magnitude is maybe 5 to 10 times to the full load current of the transformer. So whatever relay we connect, it treats such type of phenomena as a fault, but actually it is not a fault, because it is going to die down once the normal condition is established in the transformer.

Now to understand this phenomena, let us consider the voltage wave form between the voltage and flux with reference to time and the phase difference between this two that is seta, let us assume.

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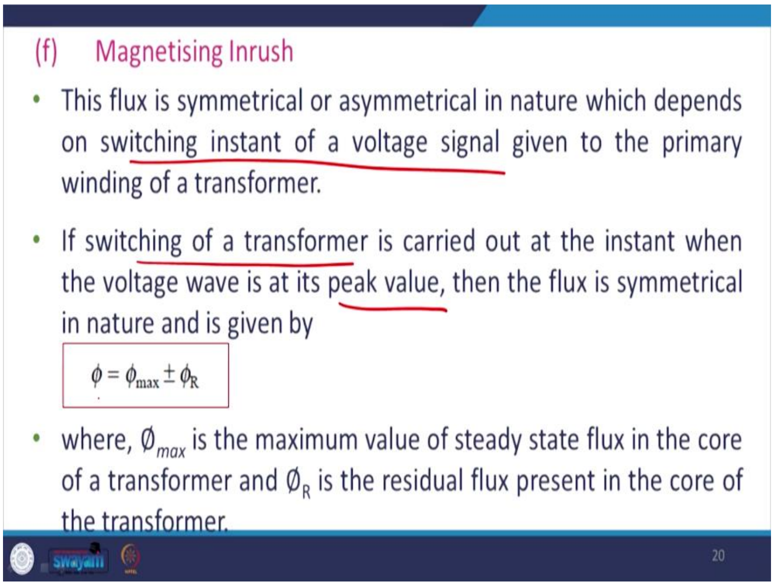

Now when the flux that is going to establish inside the core of the transformer, when you energize the unloaded or lightly loaded transformer, then this flux can be asymmetrical or symmetrical in nature. So whether the flux that is going to establish in the core of the power transformer that is symmetrical or asymmetrical in nature that depends on this reaching instant of the voltage signal, that means whatever this voltage signal I have shown at what instance you are energizing the transformer that is going to decide whether the flux that is going to establish in the core of the power transformer is symmetrical or asymmetrical.

If the switching of the transformer is carried out when the voltage wave is passing through its peak value, right, like this, here, its peak value, then the flux that is going to establish in the core of the transformer that is symmetrical in nature and it is given by phi, that is phi max plus or minus phi R, where phi max is the maximum value of steady state flux that is going to establish in the core of the transformer and phi R, that is nothing but the residual flux in the core of the transformer.

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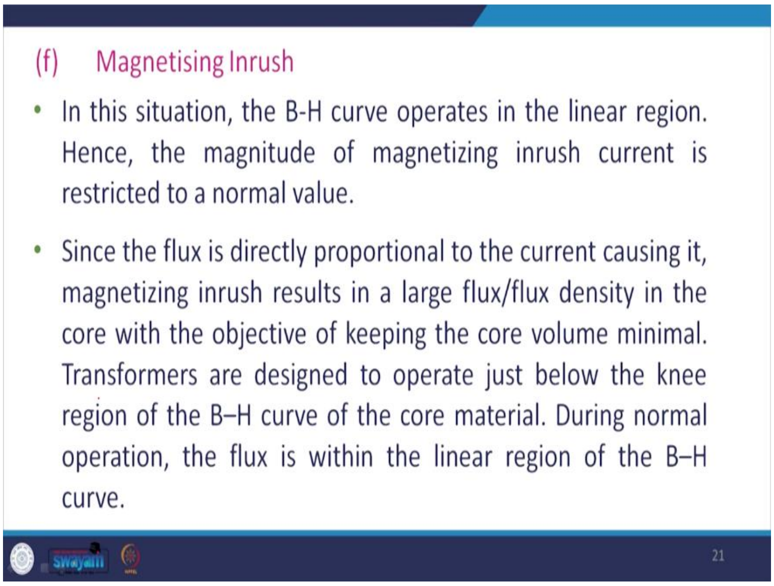

So in this situation what will happen as the flux is symmetrical in nature so B-H curve or whatever point that always operates in the linear region of the B-H curve and hence the magnitude of Inrush current that is restricted to a small value.

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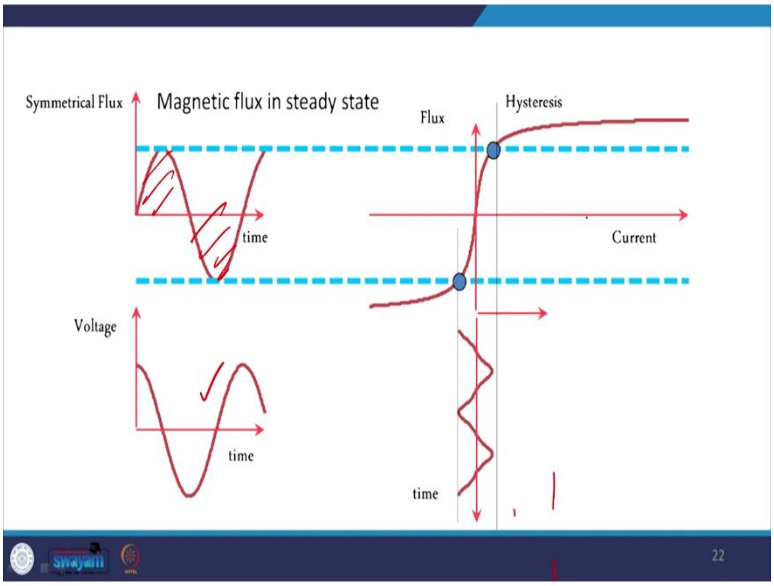

To understand this, if I consider that this is the voltage wave form and according to this, they establish flux that is symmetrical in nature, right, you can see, there is a symmetry in positive and negative halfway. So if I extend this point, blue dotted line, then you can see on Hysteresis curve, this points are always in the linear region of the B-H curve. So if I further extend downward, this two blue point, then you can see that the Inrush current, magnitude of current that is normal, that is not very high, right.

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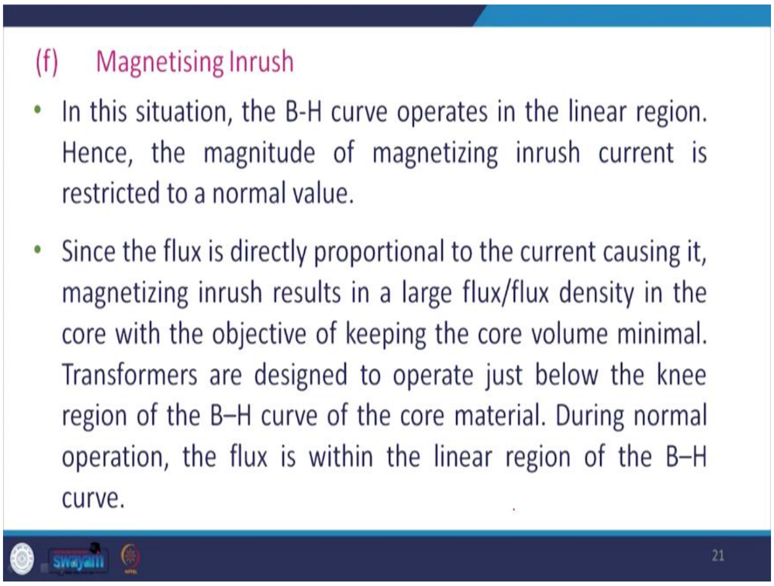

And you can see that whenever the flux that is as much it's going to establish in the core of the transformer that is directly proportional to the current, right. So Magnetising Inrush results in a large flux value or flux density in the core of the transformer. At this point of time, the core volume of the transformer that remains minimal.

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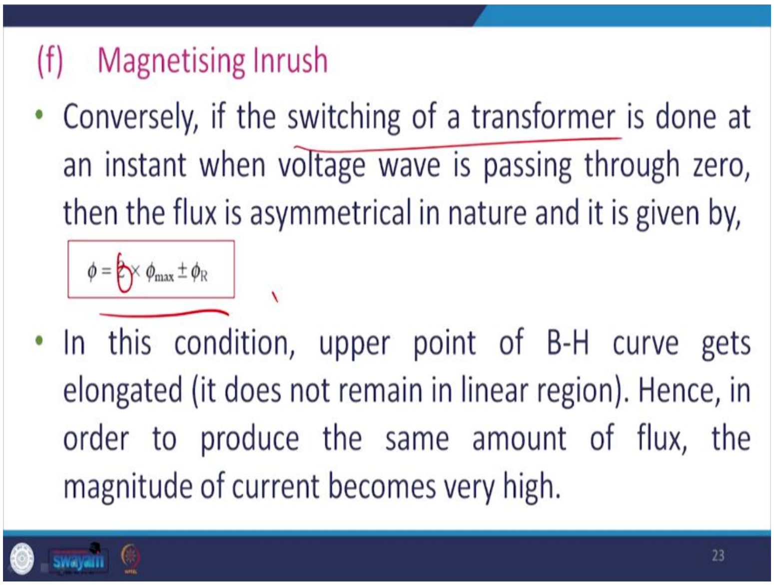

So whenever transformers are designed to operate, they have to design in such a way that it always operate below the knee point. So if point x is that value, transformer enters the saturation region and it is not in the linear region of the B-H curve but it is in the non-linear region of the B-H curve.

Now conversely, if the switching of the transformer is done when the supply voltage is passing through its zero value, then whatever flux that is going to establish that is asymmetrical in nature and that is given by again the same equation, but the tube that comes in picture. So in this case, the upper point of the B-H curve that gets elongated, it does not remain in the linear region of the B-H curve and hence in order to produce the same amount of flux, the magnitude of current that becomes very high.

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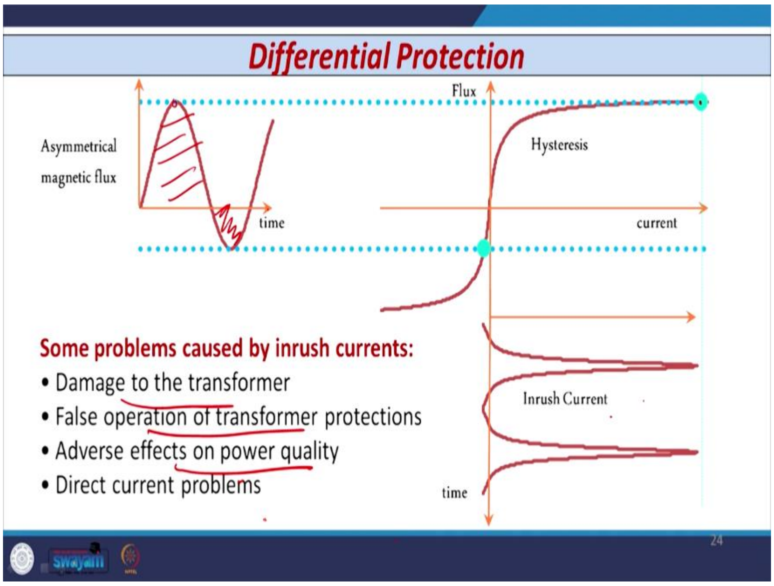

So you can see that here I have shown the asymmetrical flux, right, and because of this, this point that comes somewhere here and if you – it is not in the linear region of the B-H curve, so if you extend this two green point, then the magnitude of current to produce the same value of flux that is very high and this current is known as the Inrush current. The magnitude of this current is almost 10 to 12 times the full load current of the transformer and because of this Inrush current, this is going to damage the transformer, because of this there are fair chances of mal-operation of the differential relay because differential relay treats this phenomena as a fault. It is also going to keep adverse effect on the power quality and it also produces the DC component.

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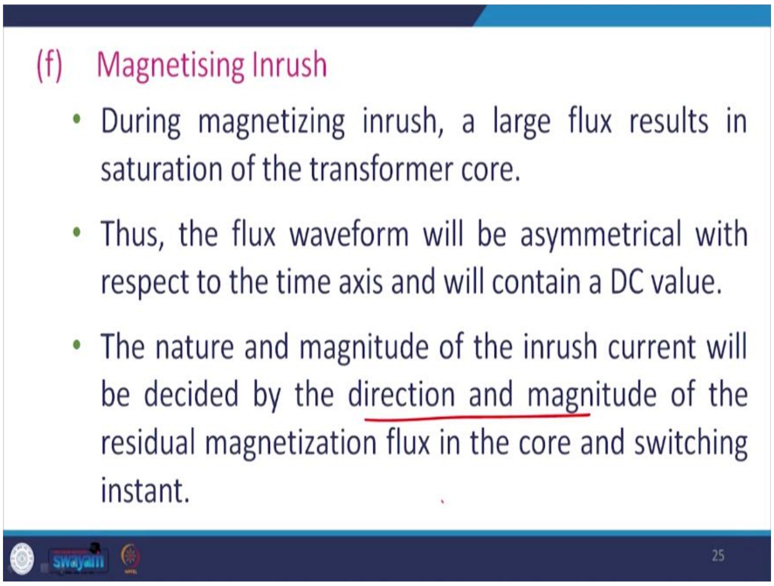

This is because the flux produce is asymmetrical in nature, so this asymmetrical flux contains the decaying DC component. So the nature and magnitude of Inrush current, how much value it attains that depends on the direction and the magnitude of the residual magnetisation flux in the core and the switching instant. That means at what instant of voltage you are energizing the transformer.

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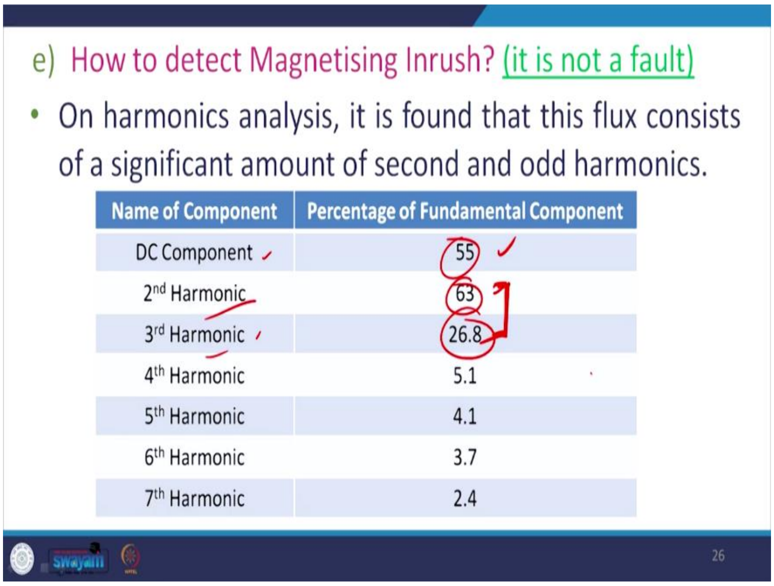

Now how to avoid this? How do detect this? Because Inrush is not a fault. So if I go for harmonic analysis of the flux wave-shape, then it is found that the DC component with reference to the percentage of fundamental component, that is 55 times, the second harmonic is 63 times and third harmonic that is almost 26.8 times. The other harmonics goes on reducing with reference to the percentage of fundamental component. So if I detect this two component, right, or the DC component then I can easily identify the Inrush pattern or Inrush point and hence, we can block the operation of the relay.

So in normal practice, what they are doing is, they normally monitor the second and third, second harmonic component. So if second harmonic component exceeds say 20% then the operation of the relay is blocked, indicating that it is an Inrush phenomena it is not a fault.

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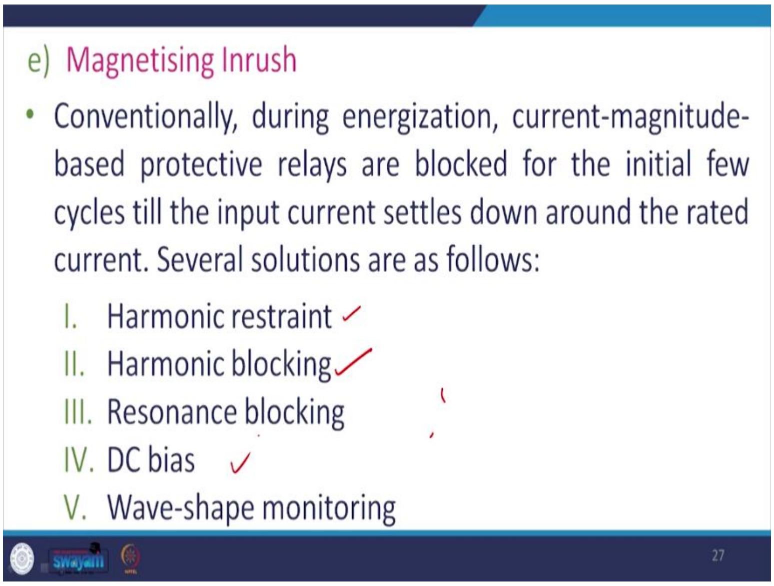

So different techniques are available. This techniques are harmonic restraint technique, harmonic blocking technique, DC biasing technique as the DC component is also significant and sometime, wave-shape monitoring technique is also available.

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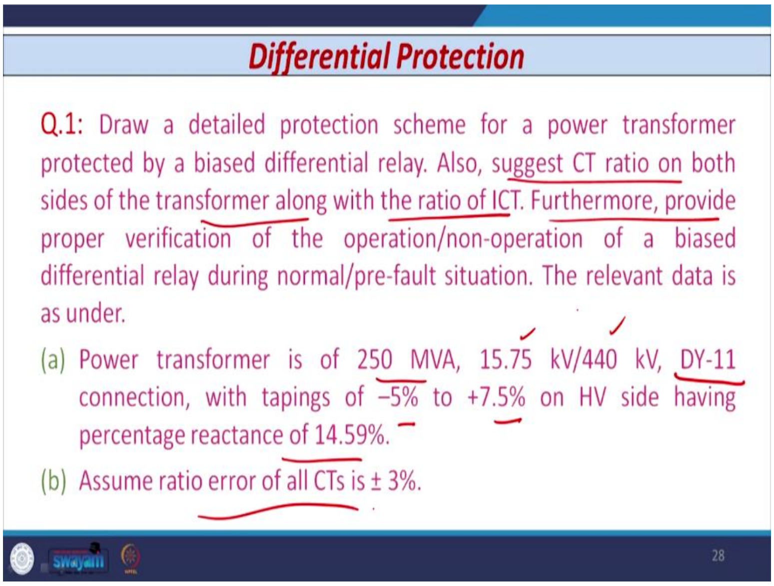

Now let us consider one example. So in this example, you need to draw protection scheme for a power transformer that contains biased differential relay. You need to suggest suitable CT ratio on both side of the transformer, along with you need to suggest the ratio of interposing current transformer that is ICT also. Furthermore, to provide the proper verification, you need to also say that whether the bias differential relay will operate in normal condition or pre-fault condition or not.

The data are the power transformer rating is given 250 MVA, 15.75 by 440 kV, it is DY-11 type transformer, it is a tap changing transformer, so tappings are provided from minus 5% to plus to 7.5% on HV side. The reactance is the 14.59% and you need to assume this ratio error of all the CTs that is plus or minus 3%. That means normal CT as well as interposing current transformer, that is ICT also.

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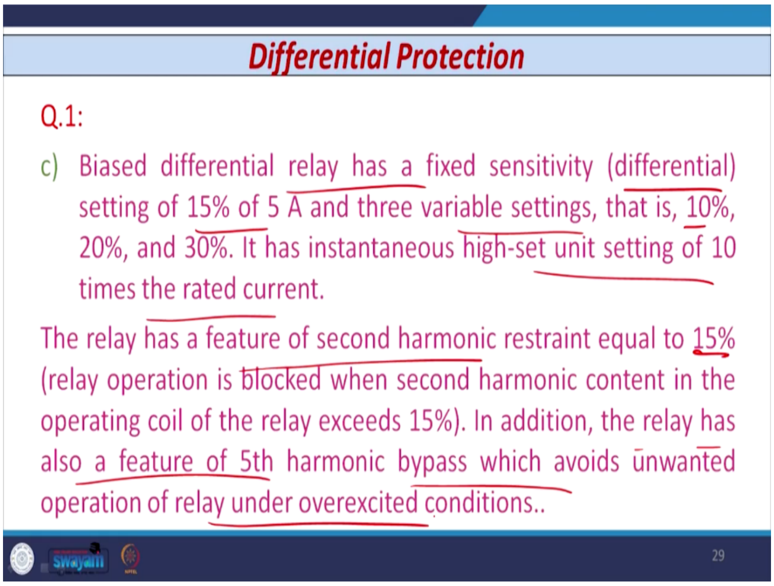

The bias differential relay that is connected, it has two setting, one is the sensitivity setting that is 15% of 5 ampere, it has three variable settings, 10, 20 and 30. And the second setting that is the bias setting also provided. It has also the high-set instantaneous setting which is 10 times the rated current or the full load current of the transformer. The relay is equipped with second harmonic restraint feature that is if it exceeds 15%, the operation of relay is blocked and the relay has also a feature of 5th harmonic bypass which avoids unwanted operation of transformer in case of overexcited condition.

So overexcited condition is a special type of phenomena that occurs in the transformer when the voltage is high above nominal value and the value of flux that is below the nominal value. So V by F flux, this ratio increases and this is not a fault but it is just overexcited condition and relay has to discriminate between fault and overexcited condition also.

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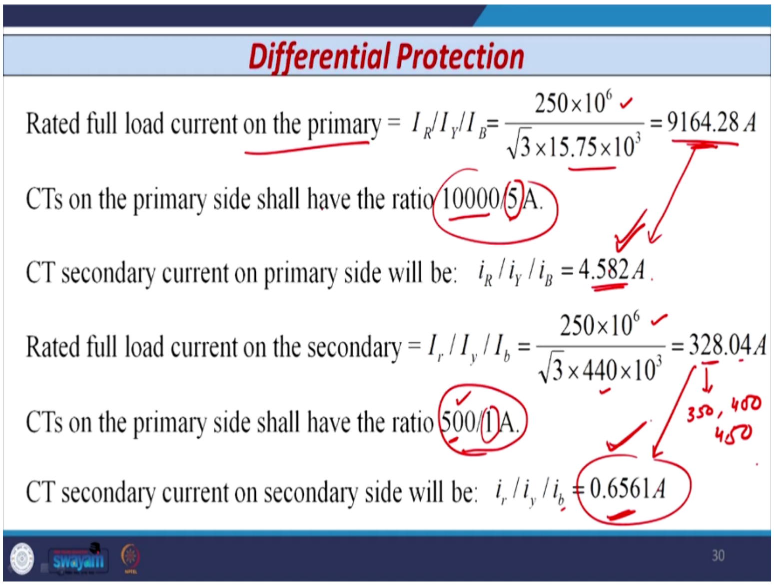

So, in this case, let us first find out the full load current of the transformer on primary side. So the rating 250 into 10 raise to 6 by root 3 into 15.75 kV, so current comes out to be 9,164 ampere. So I select 10,000 ampere by 5 ampere I have selected 5 ampere CT secondary, because this current is more than 1,000 ampere. If I use this CT ratio and if I transferred this current on secondary side, then the current comes out to be the 4.582 ampere. So 9,164.28 multiple by 5 divided by 10,000, so your current comes out to be 4.582.

Similarly, if I find out rated current on secondary side, then that is 250 into 10 raised to 6 divide by 440 kV, so the current is 328 ampere. I can select 500 ampere by 1 ampere CT, I have selected 1 ampere secondary because this current is less than 1,000 ampere. Here you can go for 350 ampere also, 400 ampere also, 450 ampere also, because CTs standard CTs are available in the multiple of 50s, but I have selected deliberately 500 ampere looking into the future load growth. If I transfer this current on secondary side, using the CT ratio, then the current is 0.6561 ampere. So 328.04 multiply by 1 divide by 500, so it comes out to be this current.

Keep in mind, this current and this current are not equal, right, because this two currents are not equal, you have to give this current to the differential relay and whenever you give magnitude as well as phase wise, this two currents are equal. So that’s why we have to introduce the interposing current transformer.

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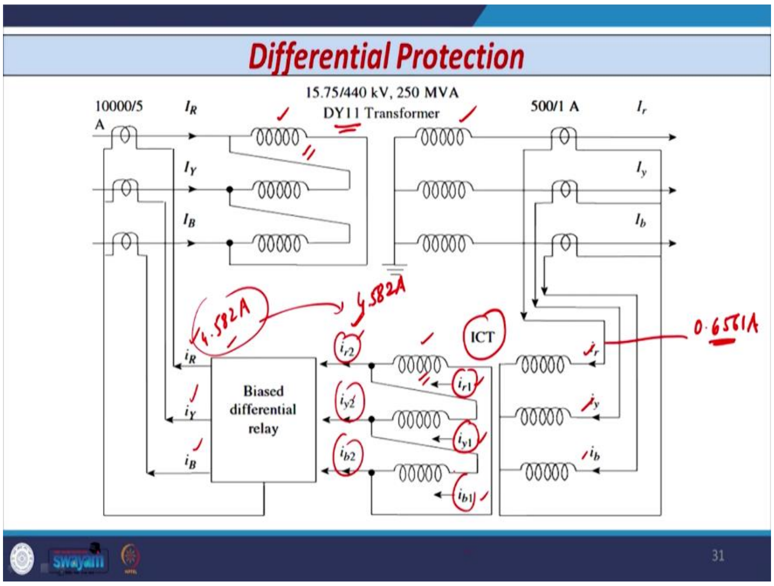

So this is the schematic diagram you have to draw. This is your delta-star transformer with DY-11 feature. This is delta connect winding, this is star winding. On delta side, I have connected three line CTs in star and on star side also, I have connected in star. Even though we have discussed earlier that delta should be, this should be connected in star, this CTs should be connected in delta, but I have not used because I have used the interposing current transformer.

So you can see that on the delta side, this three currents are known that is four point, you can see how much, 4.582 ampere. And this currents, you have calculated that is 0.6561 ampere. So this current, that is 0.6561 ampere. So this two currents are not equal, so by sum means we have to do some arrangements so that this two currents are equal and for that, we have utilized the interposing current transformer with one side winding that is star connected, right. So CT secondary are founded by 5 ampere, that is directly connected to this, so this currents that is same.

On the other side, the other winding of the ICT that is delta connected, so this delta connection is similar to this delta connection, you can see. And the currents, this current through this winding is IR-1, IY-1, IB-1 and the current available that is IR-2, IY-2 and IB-2. So let us find out this two currents. So now see, this currents is 4.582 ampere, so obviously this currents that, this three currents are also same as 4.582 ampere, because we need to decide ratio of ICT which is not given. So this currents that is also 4.582 and then the current given to the bias differential relay that is equal. So if I find out the current, if this currents are 4.582 ampere, then obviously this current, we can easily find out.

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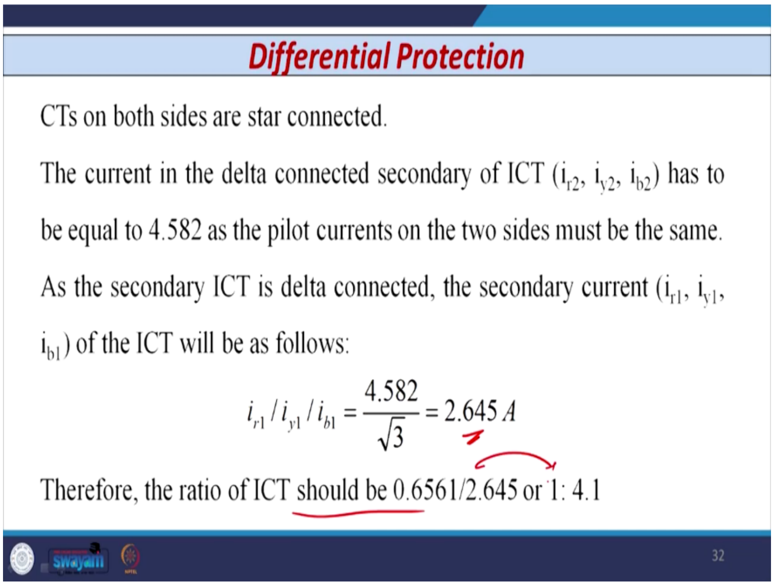

So this IR-1, IY-1, IB-1 that is nothing but the 4.582 divide by root 3, so this comes out to be 2.645 ampere. So the ratio of ICT should be 0.6561 divide by 2.645 or if I convert it then it should be one raised to 4.1.

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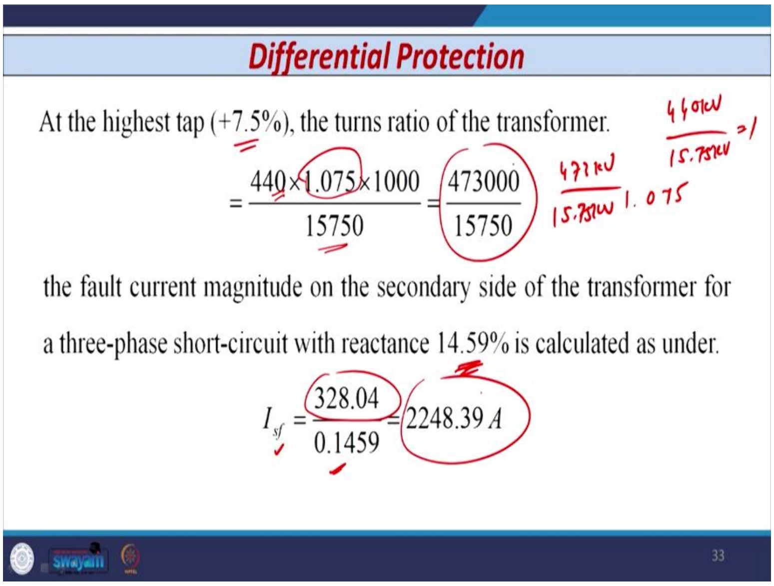

So if I consider this CT ratio that is 1 raised to 4.1 and if I consider the highest tapping, that is plus 7.5% then with this, let us find out what is the ratio. So the normal ratio is 440 kV by 15.75 kV. If I multiply this, if I consider 440 kV by 15.75 kV as the one value then at tap plus

7.5% the value comes out to be 1.075. So if I multiply this with 1.075, then the ratio comes out to be 473 kV by 15.75 kV.

So on the secondary side of the transformer, the reactance value is given, so what is the fault current on the secondary side of the transformer, this current we have already calculated, full load current on secondary side of the transformer divide by this. So the fault current on secondary side that is 2248 ampere.

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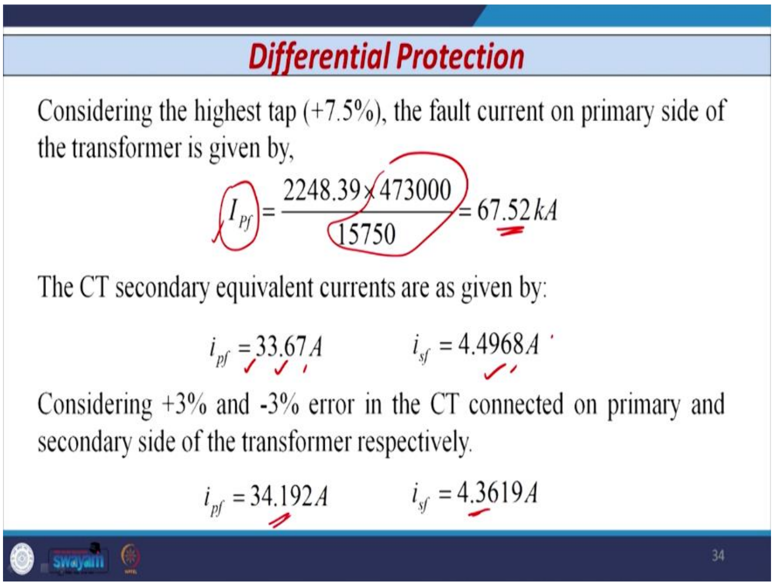

If I use this, that is 473 kV by 15.75 kV and if I find out the fault current on primary side by multiplying this current with the 473 kV by 15.75 kV then the current comes out to be this value.

If I transfer this current, ipf 67 kilo ampere and isf that is 2248 ampere, if I transfer this two currents on secondary side using CT ratio 10,000 by 5 and 500 by 1, then the current comes out to be this two values. Now we have to consider ratio error in the CT. So if I consider the worst case, primary side plus 3% ratio error, secondary side minus 3% ratio error, so I consider plus 3% here minus 3% here, the current comes out to be like this value.

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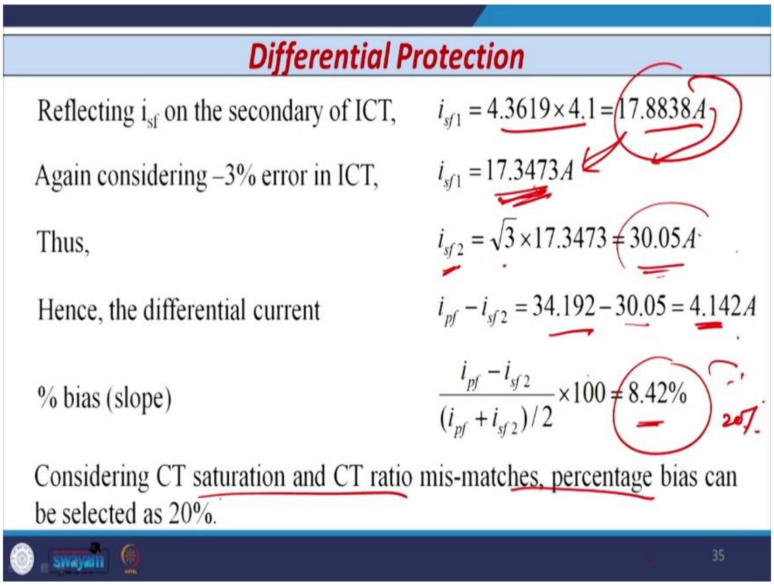

So further, now we have to consider this current that is the isf. This currents are available somewhere here, right. So when I consider this isf, then if I multiply with the ratio of ict, there is just 4.1, then the value of current comes out to be this value. If I further consider minus 3% error in this, then the value comes out to be this value. And this value is where, this value is somewhere, right. And if I multiply this value to find out the isf 2, then I have to multiply this value with root 3, so its value comes out to be 13.05 ampere.

So in previous case, the value is 34 ampere primary side CT secondary and on this side, the value is this. So if I take the difference of this two current, then 34.192 minus 30.02 so differential current is 4.142 ampere. And the percentage bias, if I use this value then it comes to our be 8.42%.

Now see the setting which is already given inside in the data, if you refer the data, then the data, the setting that is given is bias differential relay as a fixed setting that is 15% of 5 ampere. So if I take 15% of 5 ampere then you will get value. And the other setting that is given 10%, 20% and 30%. So with this you can see that, I can select this bias setting as 10%, but considering the CT saturation and mismatch, I can go for the higher setting that is 20%, right. So this we can consider 20% and this value, you can see that it is 15% of 5 ampere if you take, then this value is also comparable.

So this is all about how we can calculate the, how we can apply the differential protection in the transformer and how we can calculate the CT ratio, ICT ratio and how we can equalize the current side to the differential relay in magnitude as well as phase wise.

So in this session, we have discussed the different factors to be considered while we'll apply the differential protection scheme to the transformer. We started with the tappings, we also consider the Magnetising Inrush phenomena and some other factors also, and then we have solved the example. Thank you.