Power System Protection
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Lecture 34
Current Transformer - Part - II

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Welcome to NPTEL course on power system protection. We are continuing with current and voltage transformer in this lecture, we will address current transformer part 2, where we will see the transient performance of current transformer how to analyse it and then we will continue with the saturation aspect in current transformer and how does it affect in the output current and also the relay performance.

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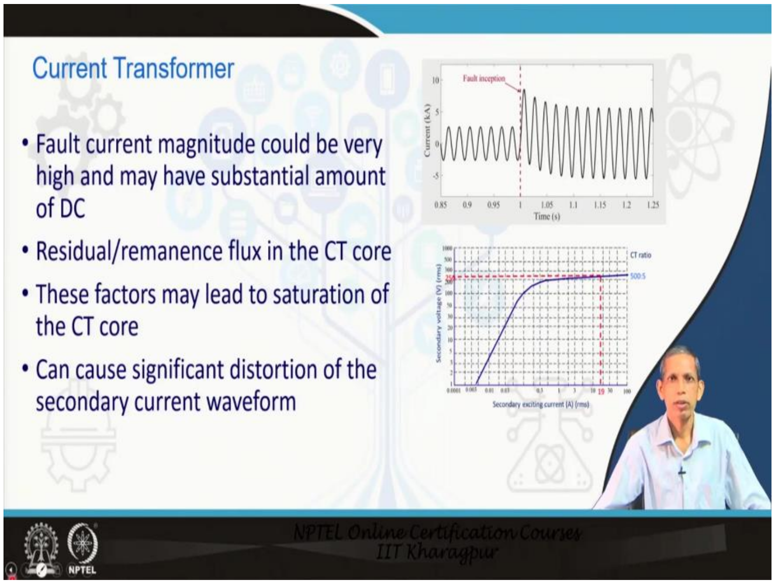

In the last class we are discussing about the steady state performance of current transformer. In this lecture will go for the transient performance of the current transformer. Fault goes through a transition process it the fault persists for long period it settles down to certain fault current, which is also very large amount. Before the fault current may be small. So, in this transition period how the corresponding CT respond to the situation that is of importance as the performance of the relay will depend upon that.

We see here that during the fault the corresponding current may be significantly high and also it may contain decaying DC and so. Further a CT may have residual flux in the magnetic core, this may lead to saturation and also may cause significant distortions in the secondary output.

In the last class also through an example, we see that if the burden impedance becomes more then the corresponding excitation current requirement I_M becomes large and it goes to the saturation region in the BH curve and once it happens to be saturated the error becomes significant as you have seen in this saturation as you know for any transformer the corresponding output is affected significantly. So, this lecture is to analyse such situation.

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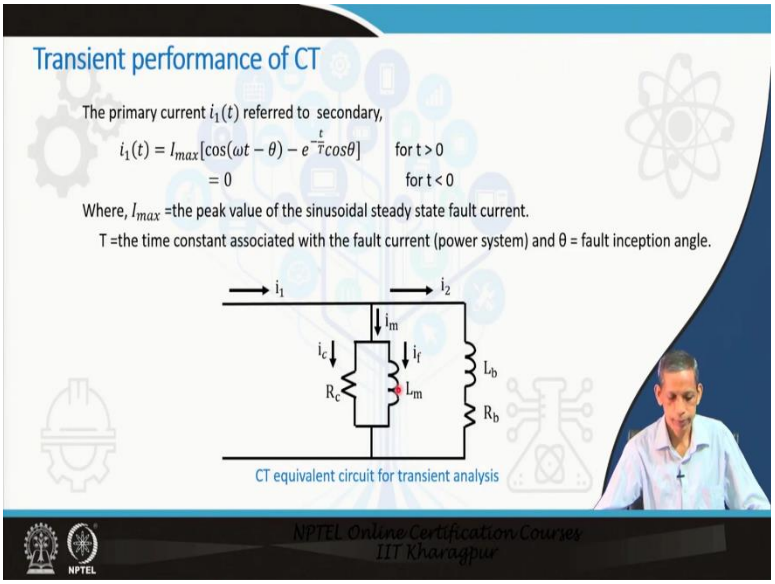

So, we will consider a CT model like this, what you have seen in the earlier lecture on the steady state part also i1 current is referred to the secondary, the i_2 current is goes to the relay that is the burden aspect and do have been magnetic current the i_m component divided into two parts the core loss component and the resistive path and the flux contribute component you can say that in the Lm part. Let us, consider a situation of the fault will act have the transient analysis for the CT performance. The primary current i_1 refer to the secondary can be expressed as

$$i_1(t) = I_{max}[\cos(\omega t - \theta) - e^{-\frac{t}{T}} cos\theta] \text{ For t > 0}$$

$$= 0 \text{ For t > 0}$$

Where, I_{max} is the peak value of the sinusoidal steady state fault current. T is the time constant associated with the fault current (power system) and θ is fault inception angle. Now, for this input signal to the CT, what is the corresponding output current of the CT that is the i_2 which goes into the relay that matters to us. So, for such an input, we apply to find out the corresponding output in the CT secondary for this I want what is the corresponding i_2.

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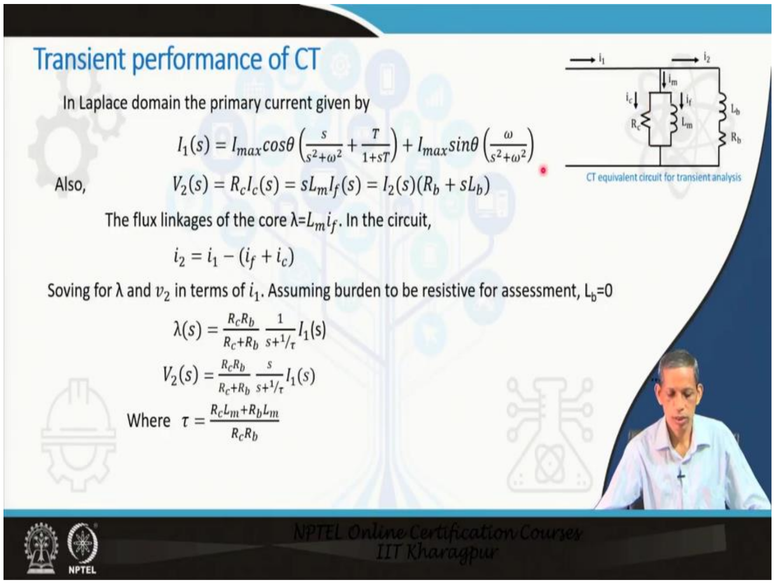

Now, we will take the Laplace transform of this current i_1.

$$I_1(s) = I_{max}cos\theta\left(\frac{s}{s^2+\omega^2}+\frac{T}{1+sT}\right)+I_{max}sin\theta\left(\frac{\omega}{s^2+\omega^2}\right)$$

and the voltage V_2 across the core of the CT is given by

$$V_2(s) = R_cI_c(s) = sL_mI_f(s) = I_2(s)(R_b+sL_b)$$

.The flux linkages (λ) of the core l is

$$\lambda=L_mi_f$$

Assuming burden to be resistive for assessment, L_b=0, relation for λ and v_2 in terms of i_1 is given by

$$\lambda(s) = \frac{R_cR_b}{R_c+R_b}\ \frac{1}{s+1/\tau}I_1(s)$$

$$V_2(s) = \frac{R_cR_b}{R_c+R_b}\ \frac{s}{s+1/\tau}I_1(s)$$

Where $\tau = \frac{R_cL_m+R_bL_m}{R_cR_b}$

So, this is a simplified thing we have considered to analyse you can say simplistic way, but more generic will be both L_b and R_b.

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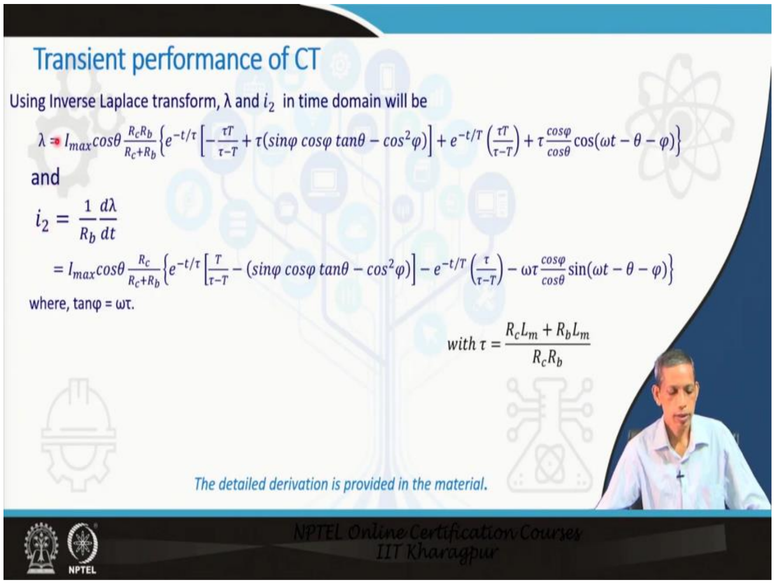

Now, from this, we like to solve the corresponding λ and V_2 in terms of time domain and then we proceed. So, using the inverse Laplace transform from those two expressions. We can find λ and i_1 i_2 and in terms of i_1. So, λ comes out to be

$$\lambda(t) = I_{max}cos\theta \frac{R_cR_b}{R_c+R_b}\left\{e^{-t/\tau}\left[-\frac{\tau T}{\tau-T}+\tau(sin\varphi\ cos\varphi\ tan\theta - cos^2\varphi)\right]+e^{-t/T}\left(\frac{\tau T}{\tau-T}\right) + \tau\frac{cos\varphi}{cos\theta}\cos(\omega t-\theta-\varphi)\right\}$$

where, tanϕ = ωτ. In this expression in this expression, τ is the time constant of the equivalent circuit of the CT and capital T is the time constant related with the system side that corresponds to i_1.

Then i_2 which we have defined by the previous expression as

$$i_2(t) = \frac{1}{R_b}\frac{d\lambda}{dt}$$

Can be written as

$$i_2(t) = I_{max} cos\theta \frac{R_c}{R_c + R_b} \left\{ e^{-t/\tau} \left[\frac{T}{\tau - T} - (sin\varphi\, cos\varphi\, tan\theta - cos^2\varphi) \right] - e^{-t/T} \left(\frac{\tau}{\tau - T} \right) - \omega\tau \frac{cos\varphi}{cos\theta} \sin(\omega t - \theta - \varphi) \right\}$$

So, this you can say that derivation detail derivation will provide also material how to achieve to this λ and i_2. The expressions here is not the same what i_1 contains there are additional terms here and this term like we are talking about the ϕ aspect and then the corresponding exponential terms are coming into picture and also the corresponding tau the time constant related you can say that that depends upon the parameters of the CT.

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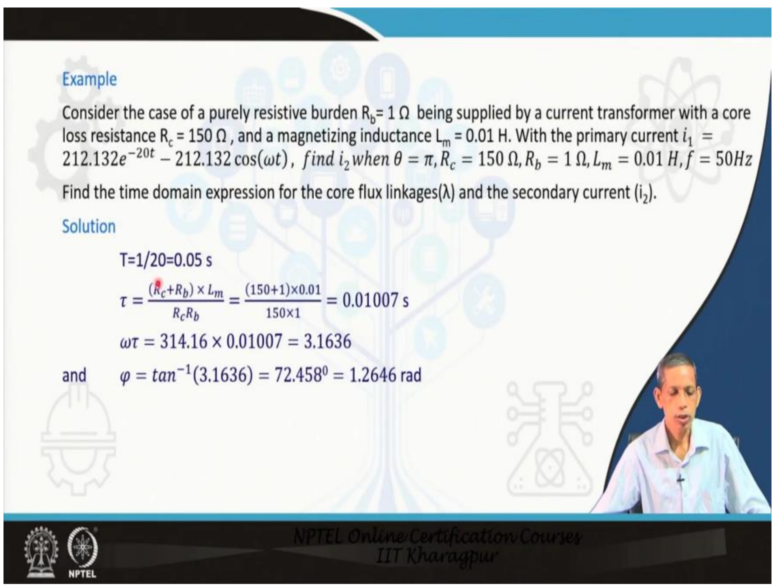

So how this corresponding how the corresponding i_2 is in terms of i_1 we will try to figure out through an example and clarify on this one more.

Example: Consider the case of a purely resistive burden R_b= 1 Ω being supplied by a current transformer with a core loss resistance R_c = 150 Ω , and a magnetizing inductance L_m = 0.01 H. With the primary current $i_1 = 212.132e^{-20t} - 212.132\cos(\omega t)$, Find i_2 when θ = π R_c= 150Ω, Rb=1Ω, L_m = 0.01H, f=50Hz also find the time domain expression for the core flux linkages (λ) and the secondary current (i_2).

Solution

$$T=1/20=0.05 \text{ s}$$

$$\tau = \frac{(R_c+R_b)\times L_m}{R_c R_b} = \frac{(150+1)\times 0.01}{150\times 1} = 0.01007 \text{ s}$$

$$\omega\tau = 314.16 \times 0.01007 = 3.1636$$

and $\varphi = tan^{-1}(3.1636) = 72.4580 = 1.2646$ rad

The expression for λ becomes

$$\lambda = I_{max} cos\theta \frac{R_c R_b}{R_c + R_b}\left\{e^{-t/\tau}\left[-\frac{\tau T}{\tau - T} + \tau(sin\varphi\, cos\varphi\, tan\theta - cos^2\varphi)\right] + e^{-t/T}\left(\frac{\tau T}{\tau - T}\right) + \tau\frac{cos\varphi}{cos\theta}\cos(\omega t - \theta - \varphi)\right\}$$

$$= 212.132 cos\pi \frac{150x1}{(150+1)}\left\{e^{-t/0.01007}\left[-\frac{0.01007\times 0.05}{0.01007 - 0.05} + 0.01007(\sin(1.2646)\cos(1.2646)\, tan\pi - cos^2(1.2646))\right] + e^{-t/0.05}\frac{0.01007\times 0.05}{0.01007 - 0.05} + 0.01007\frac{\cos(1.2646)}{cos\pi}\cos(\omega t - \pi - 1.2646)\right\}$$

$$= -2.464 e^{-99.3t} + 2.657 e^{-20t} + 0.639\cos(314.16t - 4.406)$$

i_2 becomes

$$i_2 = I_{max} cos\theta \frac{R_c}{R_c + R_b}\left\{e^{-t/\tau}\left[\frac{T}{\tau - T} - (sin\varphi\, cos\varphi\, tan\theta - cos^2\varphi)\right] - e^{-t/T}\left(\frac{\tau}{\tau - T}\right) - \omega\tau\frac{cos\varphi}{cos\theta}\sin(\omega t - \theta - \varphi)\right\}$$

$$= 244.7235 e^{-99.3t} - 53.143 e^{-20t} - 200.952\sin(314.16t - 4.406)$$

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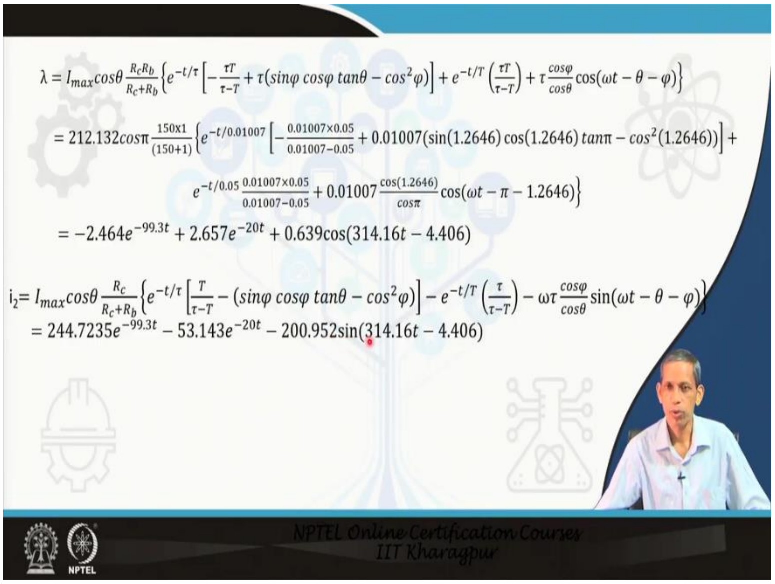

So you see you can say that this expression of i_2 is different in terms of the with respect to i_1 that means that the i_2 now defers in terms of the characteristic output with respect to i_1.

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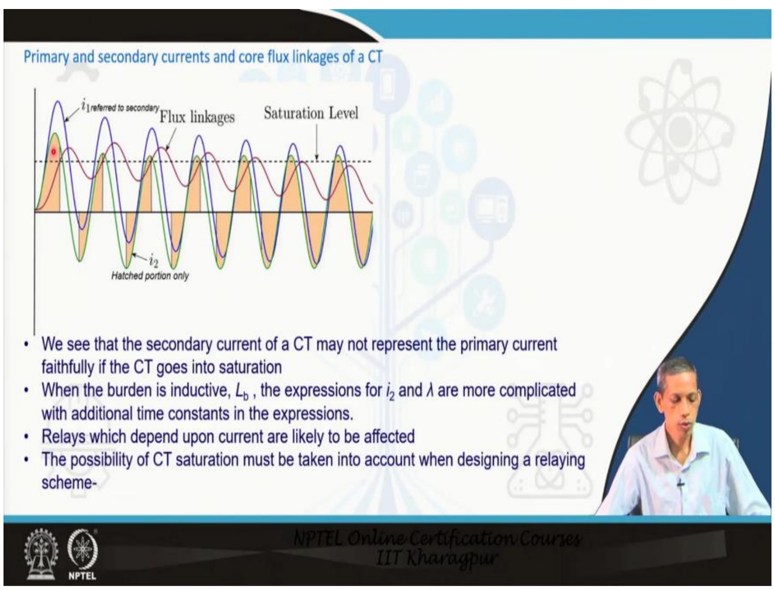

Now, for this case example if you plot the i_1 and i_2, so that looks like we can say that will like to see. So, now I see here you can say that this is you can say that the blue core either decaying DC current which we have given in that expression for i_1 and now for you can say that corresponding i_2 you can say that to trace it out.

These you can say that red one is for the flux linkage λ and now let us you can say that for this CT core we have a saturation level for this one that corresponds to that beyond that you can say that this CT goes to the saturation this is from the base core of the core. Let us say we assume this for the particular core of the CT, then what does it mean?

Now, when the corresponding flux becomes more than that then the CT becomes saturated and one CT goes to the saturation the corresponding $d\phi/dt$ becomes 0 and therefore there we induced EMF in the secondary output will be 0 and that will lead to consider the output current or the i_2 to be 0.

Now, let us you consider at this crossing when the flux linkage becomes more then you can say that the corresponding CT goes to saturation till this point and therefore in this region the corresponding CT will be consider having 0 output. So, this is the portion of 0 output. Now, what will happen here if you can say that this i_1 the corresponding i_2 of the CT should following the green curve that is the what you found from the i_2 expression Now, this only top of that what we are seeing here if the corresponding core will having this level of saturation then what is the corresponding actual output of from the CT. So, at this point the way to the saturation and therefore you can say that till this it follow to these expressions what we have already obtained and then you consider it goes to suddenly this output becomes 0 because of the saturation till the corresponding level of these and then you can say that it will follow we consider the i_2 expressions so what we have there. Now we can say that here again, you consider it crosses the corresponding lines this point again, the output will be equal to 0 and then you can we say at this point so till and then we can say that again the output will be in terms of this so what we say here we consider that the hatched portion is nothing but the corresponding output from the CT that is i_2 in actual considering the CT saturation.

It will not go into saturation then the i_1 will be the expressions for this then i_2 will the corresponding green line but with saturation level of this dotted line then the corresponding i_2 from the CT will be the hatched portion only. So that means you consider that with saturation what we see that the primary current the secondary current which we see from this plot that the second current of the CT may not reproduce the primary current faithfully and this is due to saturation. When the burden is inductive this is you consider as resistive when the burden is inductive the expression of i_2 and λ becomes more complex and it contains additional time constant in the expressions and but then again the corresponding distortions on the secondary output is also of significance. Also in the last lecture we see that you can say that for the presence of similar R_b and L_b value then L_b leads to more error in the system because of the more I_m current as compared to the corresponding same value of R_b.

Relay which depend upon current are likely to be affected by that hatch current input to the relay. But actual system current in the blue current. So the relay decision will be affected in terms of that. So, point is that if there is possibility of such situation is so in the relay in the CT then the corresponding protection mechanism must consider while designing the scheme.

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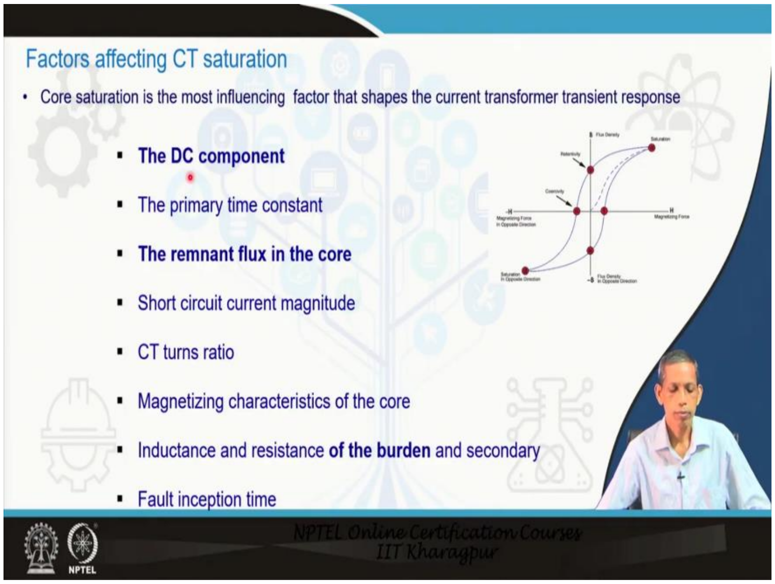

One point here is that we talked about BH core by simple curve in the first quadrant, but actually the corresponding BH core will have the four quadrants you can say that like this. We talked about hysteresis loop. Furthermore it might go to the saturation region depending upon the magnitude of current in the input that is the primary current.

So, that is one other aspect if the current around will be smaller you can say that then the corresponding loop will also smaller and may not reach to the saturation also. The corresponding core saturation which significantly affects the current output as you have seen in the last plot the currents are being affected by the DC component if the corresponding things happen to DC current component as you know saturation will be more prominent primary time constant T that you have seen on the expression. The core residual flux short circuit current magnitude i_1 magnitude of I_{max} CT turn ratio we have seen you can say that it can have you can say that multi ratio. So that is how many terms are being used at it how many terms are being used at a particular for a particular connection.

Magnetizing characteristics of the core, the corresponding parameters R_c and L_m inductance and resistance of the burden R_b and L_b the secondary leakage impedance furthermore, the fault inception time that in θ we talked about. So, these are the important factors you can say that which govern the saturation level and that you can say that has an impact on the secondary current in the CT which goes to the relay.

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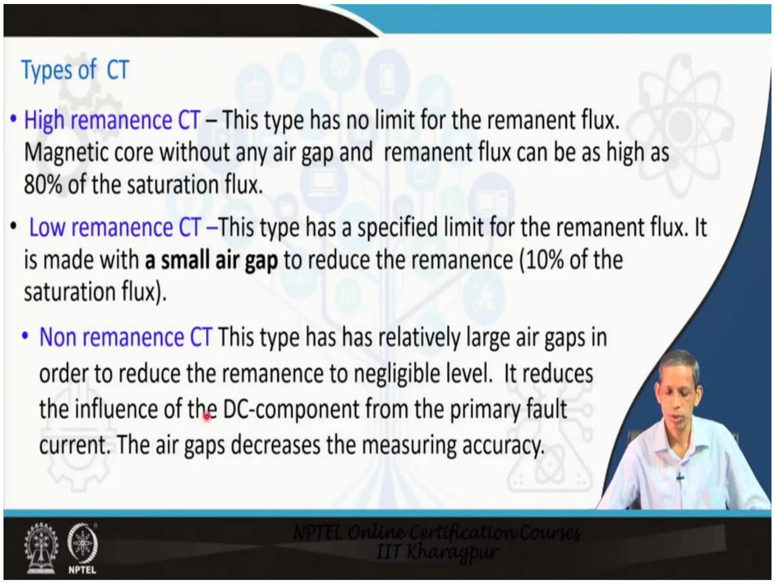

Now, as a mitigation strategy we can say that we can classify a CT in terms of this remanence flux at the core material and the associated magnetic circuit. So, three class you can have three types of CT in that sense to overcome the issue of saturation and so more saturations more problem to the relay decision and so. Higher remanence CT in this case there is no limit to the remanent flux let it be free and the magnetic core does not have air gap or so remanent flux can be as high as 80% of the saturation flux why that is what the situation. The second category low remanence CT this type limit for the remanent flux and the there is a small air gap in the arrangement on the magnetic cores arrangement and the air gap is introduced to reduce the considered remanent flux, and they remanent flux is limited to below 10% of the saturation flux.

Now you can say that remanence in the CT. So, these are you can say that larger air gap and the almost you can say that the corresponding the remanence flux, is reduced to negligible value. Now this it reduces the influence of the DC component because it only operates in the linear region, so there will be no saturation perspective therefore influence of the DC current also be negligible or there will be no influence on that but the air gap decreases the measuring accuracy, the linkage will be small and that will can say that lead to you can say that performance accuracy to be less. So, this these you consider three types indicate about depending upon the residual flux and so and what level of saturations will be reach you can say that in that particular arrangement depending upon different applications we can suitably select the requirement.

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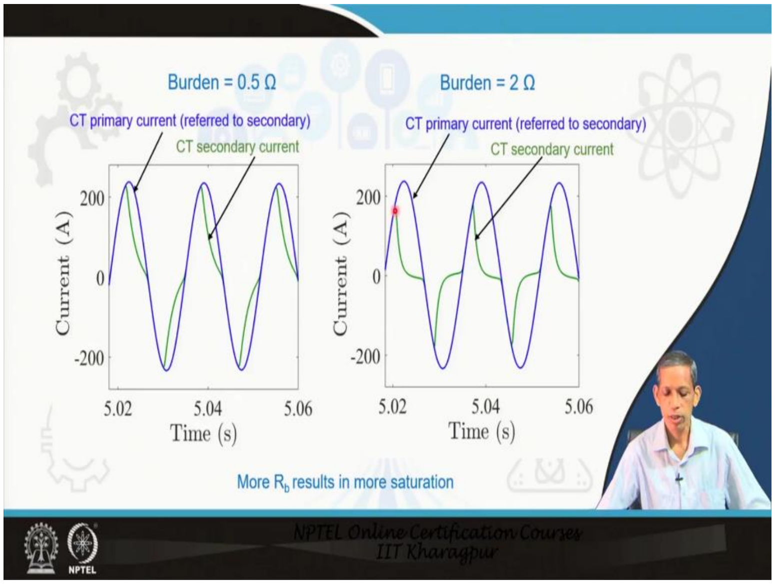

Another situation we see that in the last class also we talked about the burden importance you can say that is one more important factor and that burden you can say nothing but the lead impedance plus the corresponding resistance and other equipment connected in the secondary of the CT.

Let us consider for a situation or a CT arrangement with burden you can consider of 0.5-Ω resistive burden and burden of 2 Ω resistive burden relay both are resistive burden only. So, with that 0.5 Ω, if we see consider the corresponding blue one is primary current you can say that referred to secondary that is what we expect that the CT secondary should provide to the relay.

But what happens with this burdens the CT secondary current for this case does not follow you consider the blue core the green one you can say that is the CT secondary current and you can see you can say that due to the saturation there is a difference between the proportion at primary current and the secondary current. Now if the burden you consider the 2Ω then you see consider the corresponding saturation will be more prominent more significant and that is we can say that more problematic in the second case.

So, what we consider that we conclude from these two plots is that R_b results in more and more saturation with higher value. So, in an arrangement, these R_b is in the connect connectivity lead you can say that impedance and the corresponding impedance of the relays and other accessories connected to the secondary of the CT. So, considering that substation can you control that, can you reduce that then accordingly consider the CT saturation can be also reduced in a particular application.

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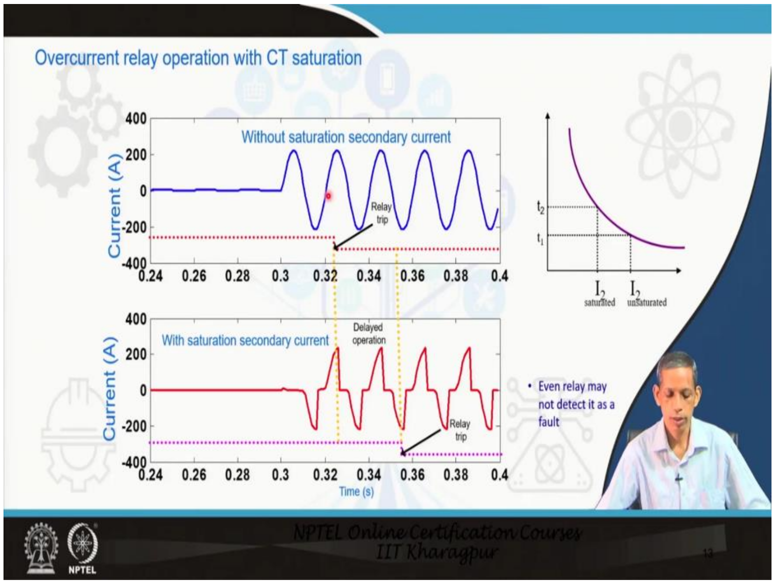

Now, let us you can say that how the corresponding saturation affects during the relay performance that will like to have a look. So, this is a case of current without saturation CT secondary current with saturation the current happens to be red curve. Now, this is a applied to an over current relay we know over current takes only the current signal through the secondary current of the CT will be input to the relay. So, what is expected there this secondary current from there the relay will able to consider adjust the corresponding primary current of this system simply in a numerical relay if you multiply this ratio you can get the primary current. But now what happens that this aspect you can say that current with no saturations means we say that this has faithfully almost represents the corresponding primary current but with situation we can say that the corresponding current is distorted significantly.

So, what you see that the RMS value of fundamental current which will be the input to the overcurrent relay decision process. So, as compared to without saturation, when you go to the saturation this second case the RMS current is being drastically reduced. So, if you consider an IDMT characteristic relay as an application, so this you can say that current corresponds this i_2 unsaturated which is even larger magnitude then the corresponding decision time is t_1.

Now, with this we consider that the RMS value will be drastically reduced as compared to this so that gives i_2 saturated then the time requirement will be significantly high. So, this means that the decision time will be delayed unnecessarily even though the current magnitude is of a very high value. So, it means that to over current relay it may lead to coordination problem depending upon the situation and it will be delayed decision saturation will lead to delay decision.

Furthermore if the saturation will be through deeper then there were a case arising there relay may not find the corresponding RMS value to be significant greater than the pickup current and the relay may not able to detect the consider default also or it will be through delay you can say that trip the circuit where the backup protection may be acting consider before that if that arrangement has no issue of saturation and so on. So, this result example depicts that saturation has significant impact on the relay decision so the decision the protection scheme process should adjust this if such a thing will happen in the system.

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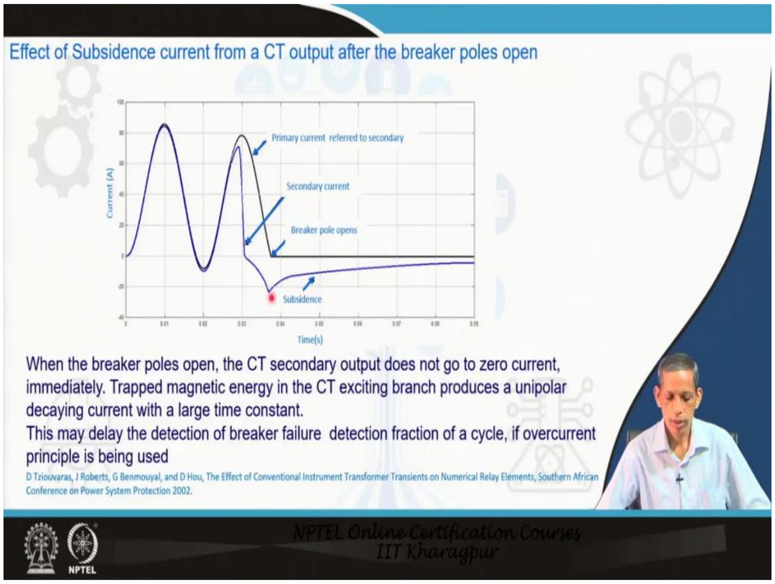

Another you can say that case I see here that if the breaker opens, you consider in the process of the transient fault current which is obvious after the command received from the relay. So, let us consider the corresponding CT is following this current it will following this current and then you consider the primary current referred to secondary and this is the where the secondary current and then you consider the interruption starch and breaker you can say that pole opens completely here.

So, breaker with the primary side of the CT so the primary current suddenly vanishes comes to 0. So, this you can say that sudden change in current in the primary at that time. Because the pole opening is very likely where the 0 current and so. So, what is consider here that the sudden jump in current as observe the corresponding CT will lead to the energy trapped in the considered CT magnetic circuit well you can say that, result you can say that unipolar you can say that damped consider current damped current you consider in the circuit and that is called as subsidence transient.

So, with the large time constant associated with the CT perspective. So, what you can say that even though the primary current is 0 still there is a secondary current in the CT and which is input to the relay. Typically consider that breaker failure detection which is based on overcurrent principle then the decision process will be delayed unnecessarily region. This still you can say that it will see current and therefore we can say that it may be delayed fraction of cycle and so.

So to conclude from this we can say that plot this example, is that the subsidence transient because in the breaker opening and so may be considered sometimes when we issue particularly in case of over current relay based overcurrent principle based breaker failure detection scheme may be delayed by consider some fraction of cycle also. So, this is the second example, we see that how the corresponding secondary current in the CT, which goes to consider that it different it provides value in proportionate to consider to the primary current will need to consider malfunction of the relay or delayed decision process in this system.

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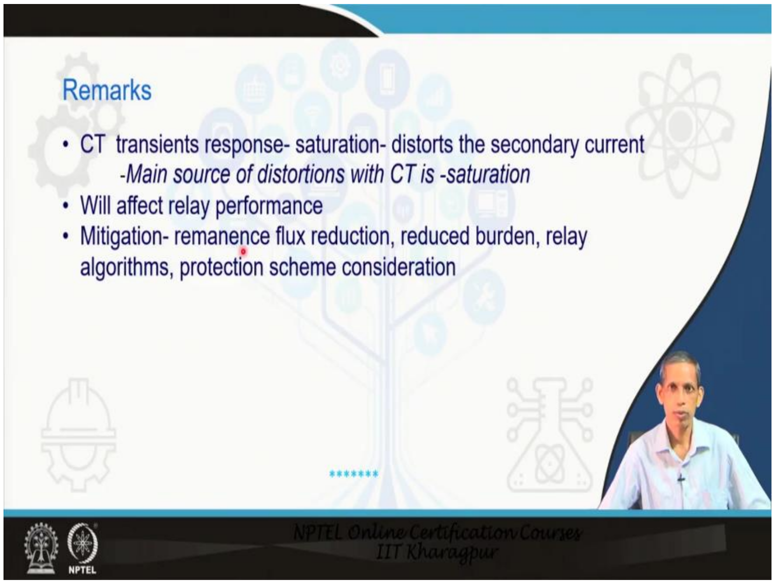

So, in overall we see that CT transient response may have saturation effect which distorts the secondary current significantly and the main source of distortion of the current as compared to the primary is the saturation and the saturation is due to numerous regions. If that happens so I mean to say that the saturation in the CT core this will this may affect the relay performance significantly, ways to mitigate must be adjust you can say in the relay scheme design process. Some of the ways you can consider if that can you reduce consider the remnant flux one we see reduce the burden that also is a one way and maybe also there is a scope in the relay algorithm also, if it can detect the saturations, or you can do any other mechanism to overcome the decision process also. Thank you.