Electrical Measurement And Electronic Instruments
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Lecture - 44
Errors in Instrument Transformer

Welcome, we are studying Instrument Transformers CT PT. Previously, we have studied ideal instrument transformers, but since this is a course on measurements. So, it is important to understand the errors in accuracies that we may encounter in a practical instrument transformer. Therefore, we need to understand the equivalent circuit of a practical transformer. Yesterday in additional video, we have tried to develop the equivalent circuit very quickly ok.

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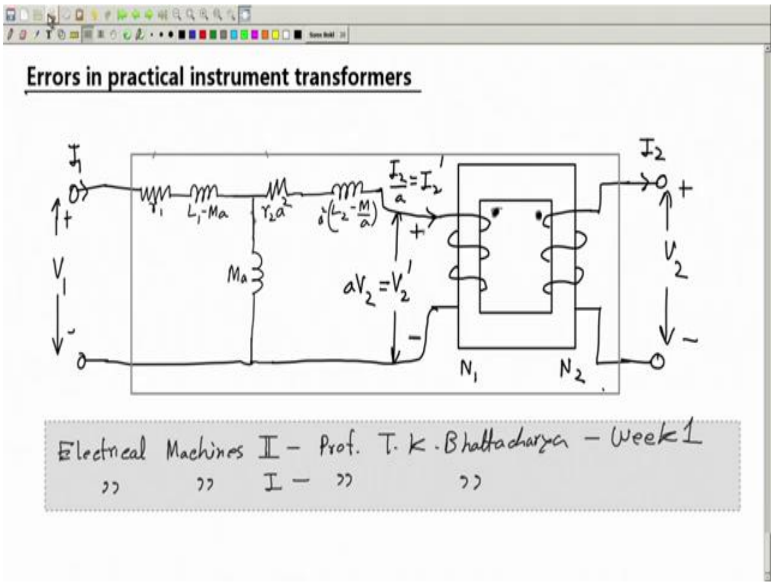

So, we did it in (Refer Time: 01:16) and I will refer you if you want a better understanding, please look at the video lectures on Electrical Machines - II offered by Professor T. K. Bhattacharya. It was offered by him in the last semester. So, you can look at the recorded videos; look at week 1 ok.

So, this will cover magnetic circuit I mean basic magnetic circuits, mutual inductance somewhat. And then, you can also look at the course on Electrical Machines - I offered by the same Professor which is offered in this semester, again in NPTEL again. So, you can look at his videos on transformer. So, have a better understanding. If you have not studied these things before, so you can look at these things and you can also get his notes from the NPTEL course webpage of these two courses ok.

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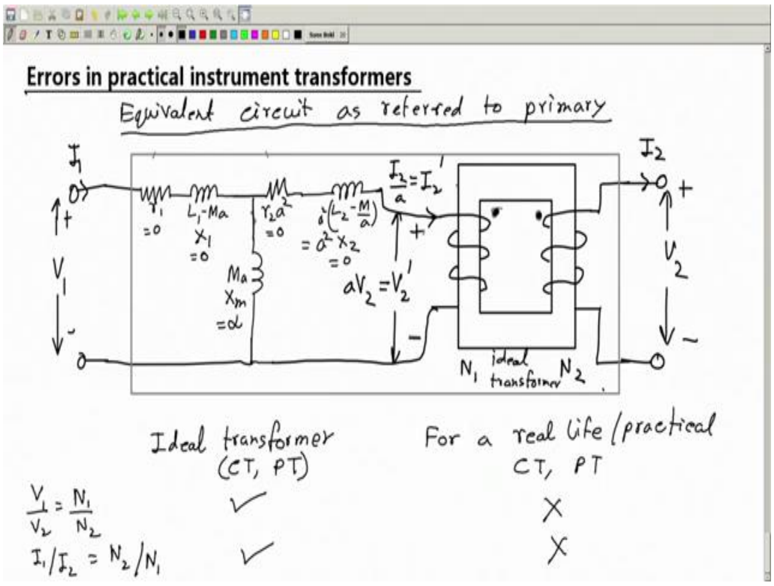

Now, we know that for an ideal transformer which can be ideal CT or PT; ideal current transformer or ideal potential transformers because they are anyway transformers ok. So, for ideal transformers, this relationships V1/V2= N1/N2 this holds. Similarly, I1/I2=N2/N1 this also holds. But for a practical transformer for a real life transformer CT or PT neither of these equations hold true. And then, how do we analyse a practical transformer?

The way to analyse a practical transformer is to model it with an equivalent circuit like this. So, this is called the equivalent circuit as referred to primary side ok. Equivalent circuit is not unique, you can have many different equivalent circuits. But this is one of them. This you can call the equivalent circuit referred to primary which is made up of an ideal transformer.

So, this is an ideal transformer, this part is an ideal transformer and before it. So, at the primary we have this impedances r 1; this is like t, this reflects the call resistance of the primary of a practical transformer. This you can call the leakage reactance X 1. This is this part you can call leakage reactance of the secondary side referred to primary a X 2. This thing you call mutual inductance X m ok. So, if we take an ideal transformer and put suitable values of this impedances r 1 X 1, r 2 X 2, X m before this primary, then this thing together, then everything together these impedances and this ideal transformer, they together can model a practical real-life transformer.

So, a real-life transformer is not an ideal transformer it is something more. These extra things are added, these non-ideal ties are added to this ideal transformer, then it becomes a practical transformer. And we also have seen that for an ideal transformer if r1= 0, this leakage reactance equal to 0, this impedance 0 this also 0; the mutual inductance should be infinite. This is possible only if the permeability of the core of a practical transformer is very high, then you can short circuit this, you can short circuit this, you can open circuit this. Then, all these things are gone only this ideal transformer remains.

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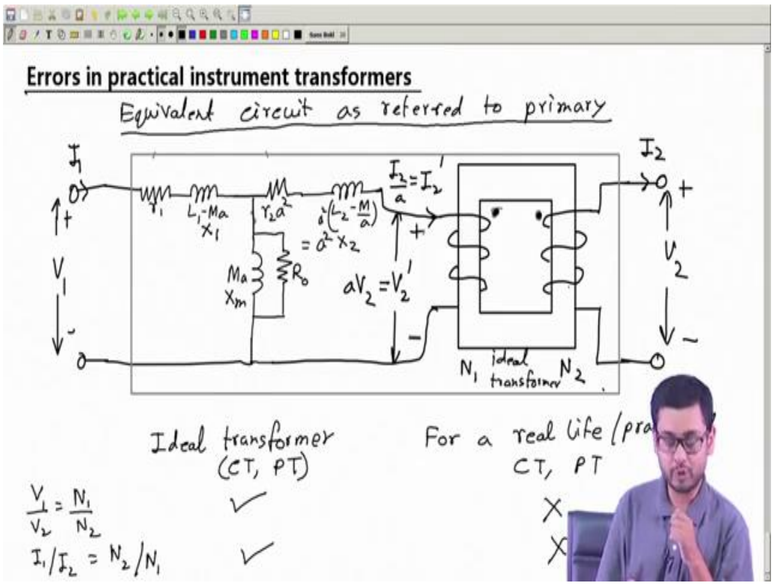

So, that is how an equivalent circuit of a practical transformer becomes same as the ideal transformer, when these things are 0 and this thing is infinite ok. And you might have seen a slightly different equivalent circuit in your books or in your college, school, where we have seen possibly only this part ok. So, possibly you have not seen this ideal transformer also added in this equivalent circuit. But that is not actually different, that is same as what I am drawing now, because you can check in that circuit, you have this right side has current I2'and V2' ok.

So, then they call only this part as the equivalent circuit, but then the output from this is I2' V2' not I 2 V 2. But if we put this ideal transformer then we get I 2 and V 2 at the right side ports at the output side. So, then this entire thing together behaves exactly like a practical transformer ok. So, you might think that this is different, we have study something different; no, this is same. But I am doing it this way because I believe this is easier to understand ok.

So, and yeah one more thing I will mention is that, so this circuit is actually for an air core transformer ok.

So, the equations that you have developed yesterday and this circuit this is for an air core transformer which has no iron core, no core loss. We also said that the conductivity of the core is 0, but practical transformers use iron core and therefore, they have core loss. Now, I will just tell how to model or incorporate that also in this practical, in this equivalent circuit. How to incorporate that? Simply put an additional resistance call it R whatever R 0. So, if you put this extra resistance, then this circuit can model even core loss.

We are not deriving it, we are not proving it ok so, you may have the question why this is so, we are not answering that. I am just telling you that please accept, please believe me at this moment that it is possible that if we put a resistance like this, then even the core loss can be modelled for practical transformer. Or you think in this way that given a practical transformer, we can always put this structure this impedance, this impedance, then this X m R 0 before the primary and then, you find out the suitable value of this r 1 X 1 r 2 X 2 X m R 0 everything. Somehow maybe by experiment ok. Do a lot of experiment and find out these values.

If you find these values appropriately, then this circuit, this entire circuit together will behave exactly like a practical transformer, which has core loss, which has a coil resistance, which has leakage reactance everything. So, this is what is called equivalent circuit of a transformer. So, I am stating this again and again ok. Now, let us come to the errors ok.

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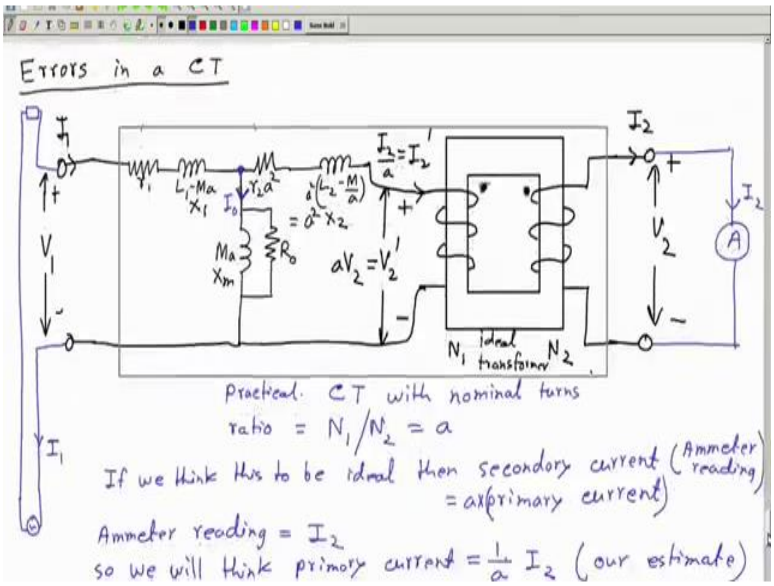

So, let us consider first a CT so, errors in a CT; Current Transformer. So, what do we, how do you use a current transformer? If I have say a line, say a transmission line like this which is carrying some current maybe this line is like this. So, it has a load and this side is the source ok. So, this is along transmission line and I want to measure the current in this circuit, in this long transmission line call it I ok. Call it I 1 ok.

Then, how do we measure it? So, we will take a CT. So, now, this is our CT this is the equivalent circuit of a transformer practical transformer. So, this can also be an equivalent circuit for a practical CT. So, this thing is our CT. So, we will do this we will open this and connect this CT in series this is a practical CT, this is connected in series and the output side will have an ammeter. So, here we will connect an ammeter ok.

Now, the ammeter reading gives an indication of this current right that is what we know, but et us see where does the error come from ok. Say this CT has a nominal turns ratio of N 1/N 2 with nominal or rated or name plate turns ratio is equal to N 1 is to N 2 which is equal to a ok; N 1/N 2 = a. So, if you think that this is an ideal transformer, if we think this to be ideal, then secondary current will be equal to a times primary current right. Because I 1 N 1 = I 2 N 2 from that you can show that secondary current or ammeter reading this will be equal to a multiplied by this primary current.

So, we will think; so, if ammeter reading is I 2 ok. So, ammeter reading will of course, be I if this current is I 2 then, so ammeter reading is I 2. So, we will think primary current ok; that means, the estimation of this line current here ok. So, this we will assume to be secondary current or ammeter reading by a; 1 over a multiplied by ammeter reading which is I 2.

So, you will think if we believe that this is an ideal transformer, if we by chance think that is an ideal transformer, then this is how we will calculate the primary current from the ammeter reading or the secondary current by dividing the ammeter reading with factor a nominal turns ratio. But is this primary current actually equal to I 2/ a? No, it is not.

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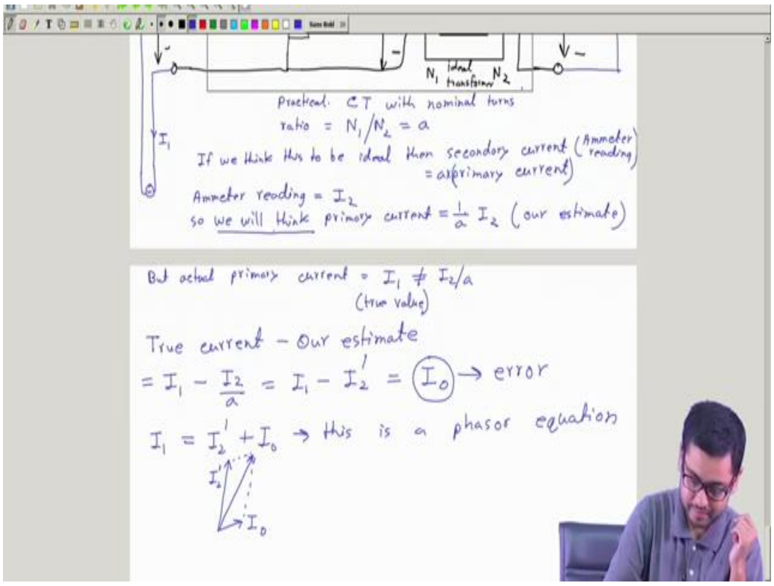

But actual primary current is equal to $I_1 \neq I_2/a$

So, this is our estimate and this is the true value ok. So, and these two are not equal. So, that is why we will have an error. Now, why this two are not equal? Let us see in this circuit, this is a balanced circuit. So, if this is I 2 then I 2/ a, this value is actually this I 2' which is flowing here. This is I 2/a and I 1 is this current which is flowing here and this current and this current is not same because some current it can get by passed through this branch. So, if I call this current as I 0; this is also called the no load current ok. So, if this ok whatever it is, if there is some current which is getting bypassed through this branch which is I 0.

True current – our estimate = $I1 - I2/a = I1 - I2' = I0$

So, this is the error. So, this is the error right. So, therefore, we have an error now let us define two terminology.

$I1 = I2' + I0$

$|I1| \neq |I2'|$

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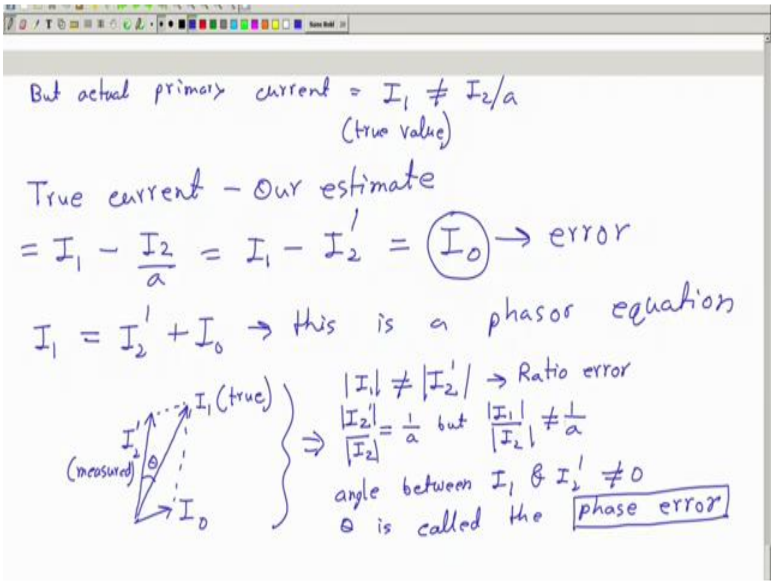

So, angle between I 1 and I 2 prime is not equal to 0 ok. So, this theta whatever it is called the Phase error. This is a new terminology we are defining. So, the current that we will see if we connect say a oscilloscope here instead of an ammeter, then we can see the waveform also. Then, this current will not be in the same phase as this primary current. There will be a gap between them and that gap the phase gap is theta that is what we call the Phase error.

This magnitude is not same this you can call the Magnitude error, we also called it Ratio error, why

$$\frac{|I2'|}{|I2|} = \frac{1}{a}$$

$$\frac{|I1|}{|I2|} = \frac{1}{a}$$

So, we are estimating this unknown primary current using the related value of a by dividing I 2 with this value a that is how we do it, but this is not the correct factor with which we should divide the secondary current to get the primary current. So, this is not the right ratio. So, this is not the ratio between primary and secondary. So, that is why this fact is called the Ratio error. So, we have learnt two terms; phase error, ratio error. We have learnt one another factor is that these two errors are mainly due to this current I0 ok.

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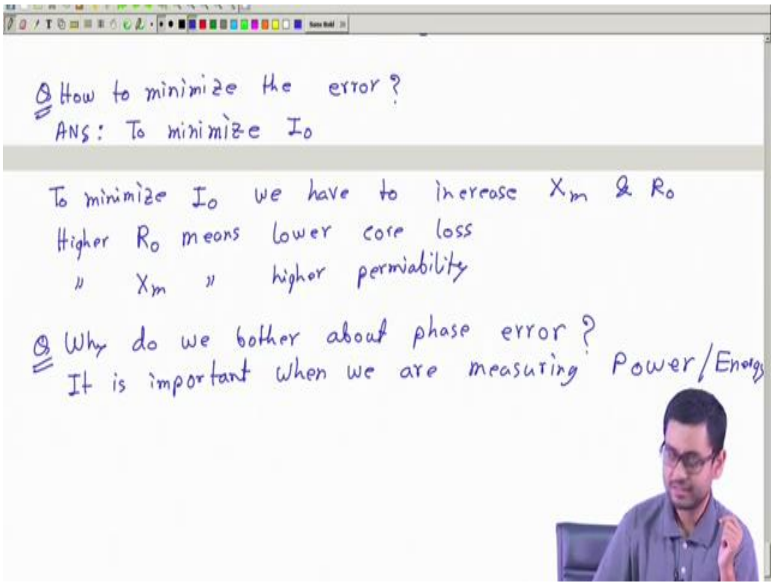

So, now we can ask because the question how to minimise or reduce the error; phase error or ratio error. What will be the answer? The answer is straight forward; answer is to minimise or reduce I 0. If I 0 is 0, then there will be no error. If say there is no bypass current, then I 1 and I 2 prime will be same; I 2 prime is our estimate our measured value and this is it true current. If this is 0, then there will be no error. So, now, how to minimise I 0? To minimise I 0 or reduce I 0, we have to increase what, these two impedances. If this impedances are high, then of course this current will be low.

So, you to have to increase X m and R 0. Higher R 0 means actually what, lower core loss. So, you have to ensure lower core loss, if we want to increase R 0 ok. So, to get higher R 0, we have to get lower core loss. So, we need core material core to have very good laminations etcetera, thin laminations etcetera and higher X m means now what is X m; where does this X m comes from? So, X m is the comes from actually this mutual inductance and on what factor this mutual inductance will depend? This will depend on the permeability of the core.

If the permeability is higher, then we will have more flux. More flux means with less amount of current, we can get more voltage ok. So that means, less current more voltage so, impedance is higher. So, we will that means, we have to get higher permeability material. Then, we can get higher impedance higher inductance ok. So, we need so means higher permeability. Also we need this high permeability to sustain for long, I mean for should not get to saturation is the late ok. So, then also core loss will increase. So, we have to use materials which has high permeability and which has low core loss. So, lamination should be thin ok so, this is how to do it. So, easy answer; so, you have learnt ratio error, phase error and how to minimise them. Now next question, why do we bother about phase error?

If we want to just measure say the RMS value of this line current, this current why do we bother about the whether these two currents I 2 and I 1 in phasor not? Because we bother only about their magnitude their RMS value, then why do you need to bother about the phase? We need to bother about the phase, it is important when we are measuring power or energy why, because suppose as I.

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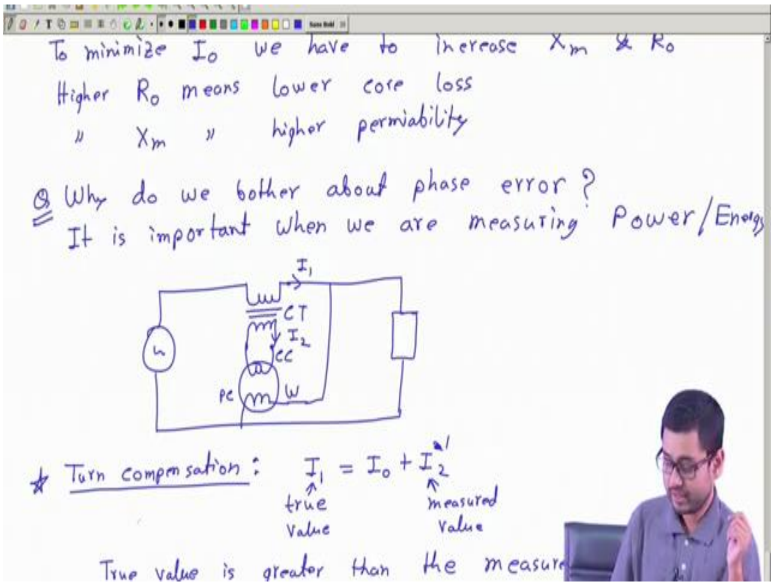

So, say there is a source, there is a load and we want to measure this power with a wattmeter. So, let this be a wattmeter with 2 coils. This is current coil, this is pressure coil and so, say this pressure coil is measuring this voltage. But this current coil is measuring this current through a CT; so, this is a CT. Now, if this current which is I1 and this current which is I2, they are not in the phase if there is a phase lag or phase lead between them, then also this voltage and this I 2 their angle between these I2 and this voltage will not be same as the angle between I1 and this voltage. So, power and energy measurement will be wrong ok. So, this is why we bother about phase error ok.

Now, so next thing we will discuss another easy point. I forgot what to say. So yeah, so the next thing, we will discuss is turn compensation ok. I will just tell you intuitively without going into much mathematics now. So, we see that I1 is equal to I0 plus I2 prime. So, where I1 is true current; true value, this is true value and this is measured value and also from this vector diagram, we will see that this true value is the vector sum of phasor sum of these two currents. So, it seems I1 is somewhat less than I mean greater than the I2 prime.

So, measured value is somewhat less than the true value ok so, although this is phasor. So, we cannot say it so easily, but roughly so what we speaking, we can say that true value is greater than the measured value. Now, therefore, what the manufacturers do ok, they use a slightly different turns ratio than the nominal turns ratio.

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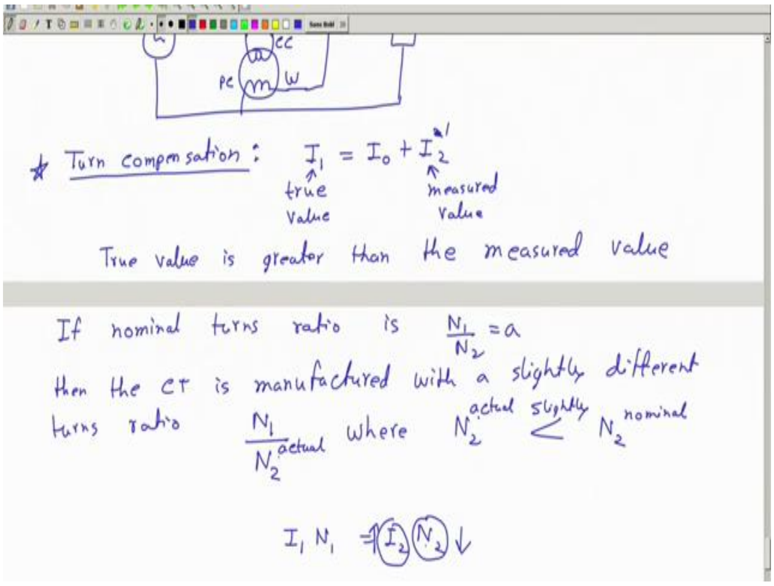

If nominal turns ratio is N 1 by N 2 equal to a, then the CT is manufactured with a slightly different turns ratio, with a slightly different turns ratio maybe like say N1/N2 new ok; where, say where I will choose N 2 new to be slightly lower than N 2 ok. If I choose this actual, so in or call this actual N 2 not new actual is slightly less than the nominal N 2 nominal ok, then what will happen this secondary current will be slightly more than the nominal value ok.

So, then the secondary current so, we know this relationship I1 N1 = I2 N2. So, if we take this value N 2 to be slightly lower, if this value is slightly lower, then this value will be slightly higher ok. So, therefore, we will get slightly higher reading and the problem we have seen that true value is less than measured value or measured value sorry true value is greater than measured value or measured value is less than true value.

So, with this arrangement we can get that error somehow compensated ok. So, this is called Turn compensation ok. So, CT is manufacture with a slightly different turns ratio, like this ok. Now, I will discuss a very important point about CT.

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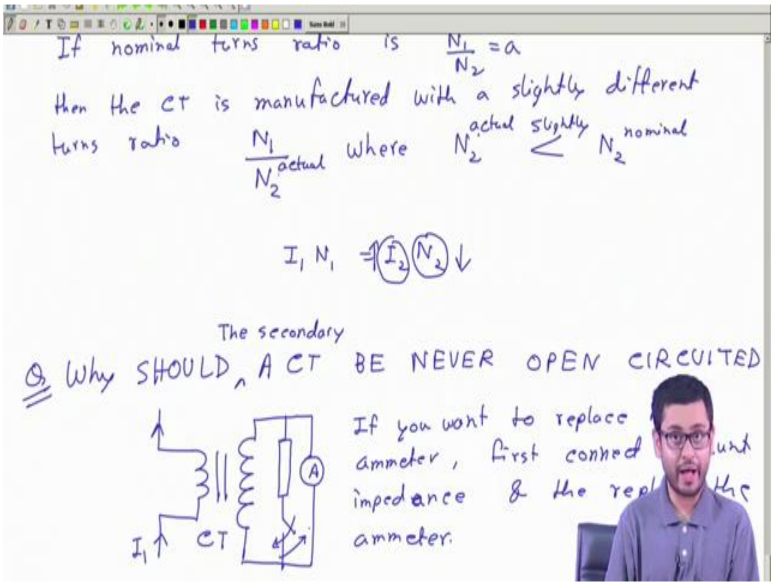

So, you might have heard that a CT should never be kept open circuited. So, why should a CT be never open circuited ok? Why should the secondary of A CT ok. So, this is very very important question ok. So, no matter whether you understand why or not, if you are an engineer, if you are a practitioner never ever by mistake open circuit the secondary of a CT.

If you have to say replace this ammeter, then before you open this you put first a shunt resistance or some shunt impedance, then you open this ammeter; put the new ammeter and then, you remove the shunt thing ok. So, no matter whether you know why or not if you are an practitioner, if you are an engineer never open the secondary of a CT ok.

So, if this is the line; this is the transmission line carrying current I 1 if this is the secondary of a CT which has this ammeter, if you want to replace; if you want to replace the ammeter, first connect a shunt impedance and then, replace the ammeter ok. This is very important; otherwise it will be very dangerous; it will be very risky ok. So, no matter with whatever you do, you should never make the secondary of a CT open circuited. So, you first connect this switch then replace the ammeter and then, disconnect the switch this is how to operate it. Now, the question is why? The answer is as follows.

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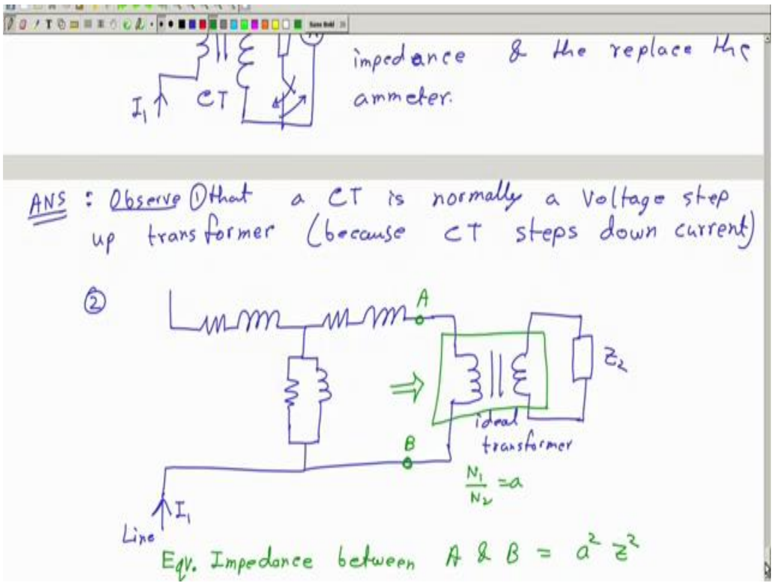

First observe that a CT is normally a voltage step up transformer; why because it steps down the current; so that means, secondary number of turns should be more than the primary. So, voltage should be stepped up. Any transformer which steps down a current it should step up the voltage because of the conservation of volt ampere ok. So, because CT steps down current one fact ok so, the observe this is one fact. Next second thing. So, in the given circuit, so this is the equivalent circuit of any transformer also including the CT.

Now, here you can put an ideal transformer, I am drawing it symbolically. Now so, this is the equivalent circuit. So, this is the main line carrying the current I 1 and here, we can have the metre or so, ok. So, this impedance you call it z 2, this can be the metre or whatever itself. Now, this is an ideal transformer. Therefore, if the turns ratio is a, then the reflected impedance between these two points, you can compute we did it assuming a ideal transformers.

So, the impedance that we will see between these two data points A and B, I have seen from this side ok. So, impedance or call it

equivalent impedance between A B = $(a\ z)^2$

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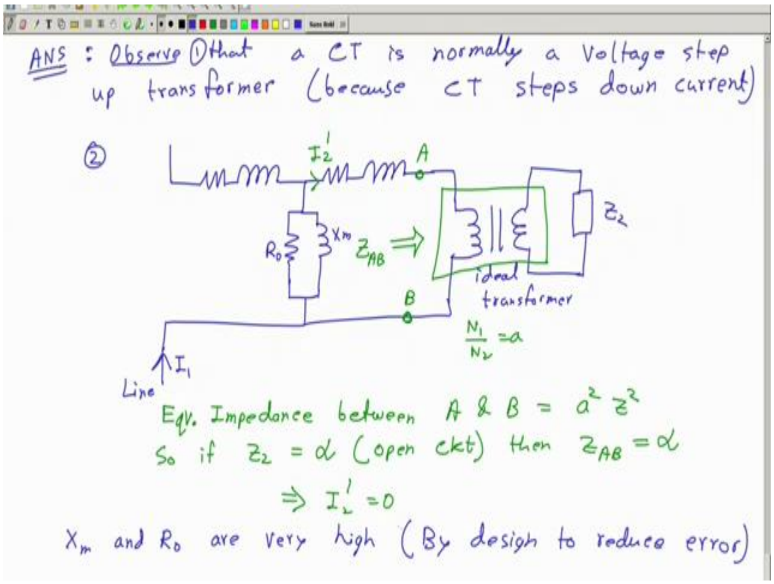

Now, so, if z 2 is equal to infinite; that means, open circuit then this is called this z AB, this is also infinite open circuit ok. So, this is infinite; so, this will imply what this current which is I 2' according to our notation. So, I2'= 0. So, this side is not there at all; this part is gone, I mean from here to here this is not effectively there. And now, you observe the point 2 is that this impedance Xm and R0; Xm and R0 are very high. Why? This is by design.

We have designed, we have manufactured the CT to have Xm and R0 very high. Why? To reduce phase error and ratio error ok, by design to reduce error; this is what we have done. And now this has created another small problem; the problem is that so this impedance is also very high ok.

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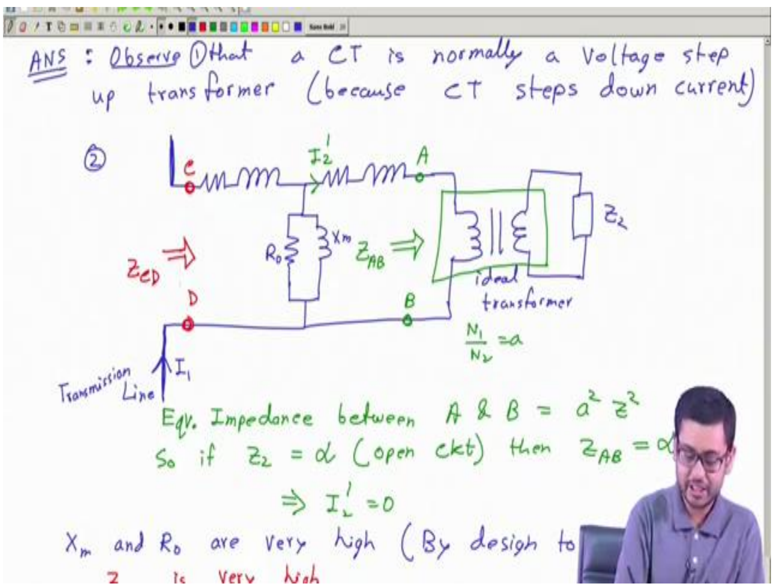

So, therefore, the total impedance say between these two points call it CD. So, let us see it from this way z CD. So, z CD is what? This impedance which is very high parallel this impedance z AB which is infinite. So, these 2 parallel combinations will be very high because this is infinite and this is also very. So, z CD; so, therefore, z CD is very high ok.

So, for example, if this is theoretical infinite, then this is theoretically infinite. Now, what will this cause? So, this is the transmission line. So, this is the transmission line ok. So, this is the transmission line and if we made z 2 infinite that is if you open circuit this, then z CD is very high. So that means, we have insert it a very high impedance in this transmission line.

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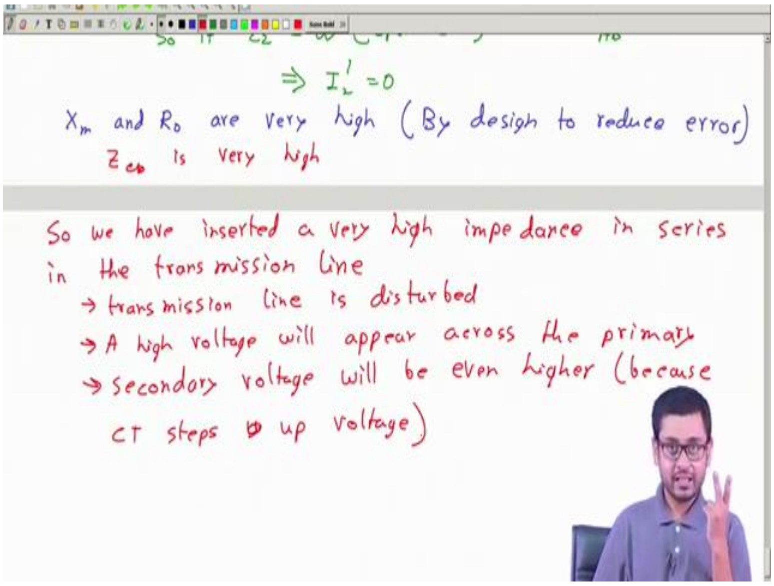

So, this implies that so we have inserted a very high impedance in the transmission line, in series in the transmission line. Firstly, we should never do it because then, I mean if we are inserting a high impedance in series, the transmission line is disturbed it is current I mean even I mean because we know ammeter should not have large impedance; why? Because it should not disturb the transmission line. But here the CT is with the secondary open is inserting effectively high impedance in the transmission line.

So, transmission line will be disturbed that is 1 thing. So, transmission line is disturbed means high voltage drop can happen something, but that is not so crucial. But next thing what will happen; so, high voltage. So, a high voltage will be appeared across the primary; why? Because this is a transmission line which is carrying a high current ok. So, a high current transmission line now a high impedance is inserted, high current times high impedance is high voltage. So, this voltage will be very high. So, primary voltage is very high and now this CT is actually a step-up transformer.

So, secondary voltage will be even higher. Secondary voltage will be even higher because CT steps up voltage ok. So, two factors CT is a step-up transformer and secondly, by design we have made this impedance to be very high. Therefore, these 2 factors are leading to a very secondary voltage which can cause what? Firstly, immediate insulation breakdown the CT will damage the, I mean a lot of damaging things can happen. Now, if somebody is trying to also say connect something at the secondary now ok, then he will face a high voltage that is risky.

So, the CT may damage one factor; if somebody is going to insert something connect something to the secondary, he might get. I mean extreme sock extreme fatal sock so; this is very risky. So, secondary of a CT should never be open circuited. So, what have we learned so for about CT? Number 1, phase error; ratio error; why they appear because of the no load current I 0.

To reduce error, we have to make no load current small and to make no load current small, we have to have high permeability material and low core loss; that means, we have to make X m and R 0 very high. Then, we have also learned that this CT is a step-up transformer and by design it has a high Xm R 0; therefore, if we by mistake make the secondary of the CT are open circuited then it is very risky. So, we should never do it. These are something's we have learned.

Now, let us come to PT that is Potential Transformer.

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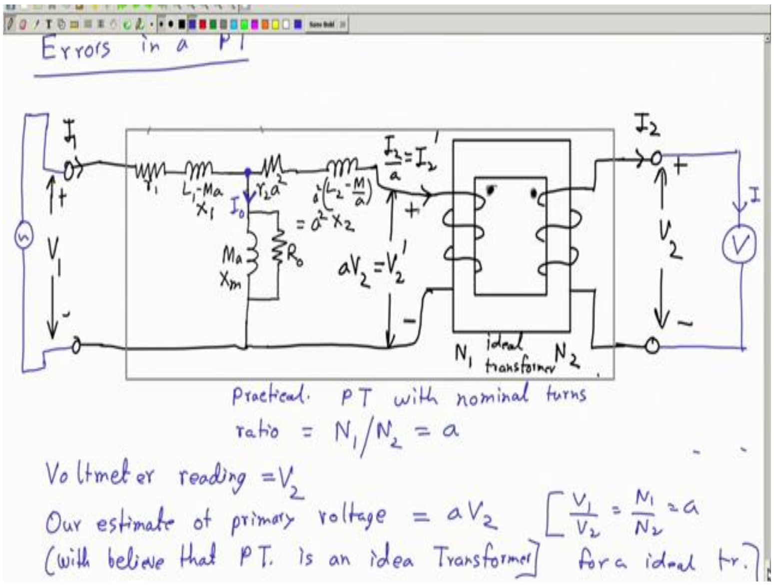

So, let us talk about errors in a PT ok. So, the discussion will be very similar like a mirror image to the discussion of the CT ok. So, we will ok; so, let this be now a CT sorry PT with turns ratio N1/N2 equal to a. So, the secondary of course, will now have a volt meter V and the primary is supposed to measure a voltage. So, let us draw a voltage source. This voltage is V 1 ok. So, now, let us do with this way. So, what will be the voltmeter reading? Voltmeter reading will be same as the voltage that appears across the voltmeter which is V 2 and this is our no ok so, this is voltmeter reading.

Now, what will be our estimate of the primary voltage? So, our estimate of primary voltage this will be how much? This will be a V 2 ok. So, this comes from the fact that V1/I mean V1/V2 = N1/N2 equal to a for an ideal transformer and we believe that we will think that this transformer behaves like an ideal transformer. If we think so, then we will estimate V 2 sorry 1 as a V 2 the so we will. So, with the belief that PT is an ideal transformer ok; so, this is measured value.

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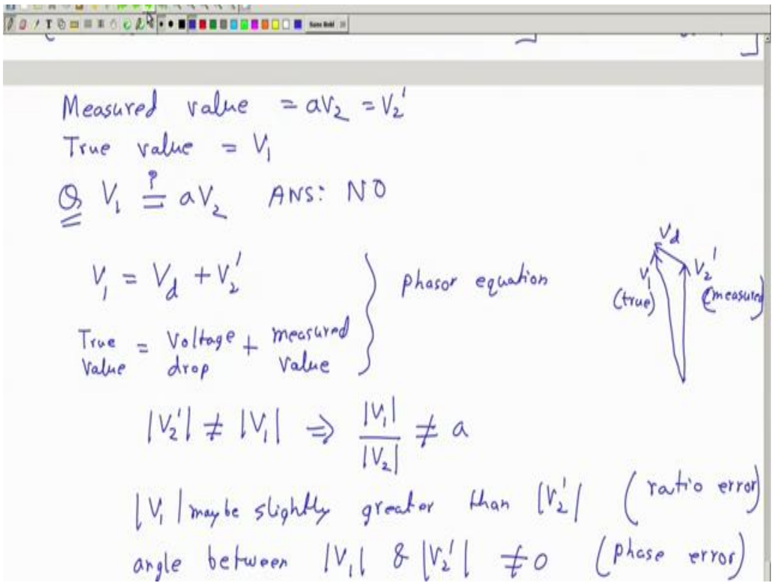

Measured value = a V2 = V2’

True value = V1

V1 = Vd + V2’

True voltage = voltage drop + measured value

|V2’| ≠ |V1

$\frac{|V1|}{|V2|} \neq a$

|V1| may be slightly greater than |V2’| (ratio error)

Angle b/w |V1| & |V2’| ≠ 0 (phase error)

No, because what is a V 2? a V 2 is actually the voltage that appears here V 2 prime here in this circuit ok. So, this is a V 2, this is the measured value and the true value is the voltage that appears here. Now, there can be a voltage drop from this point to this point because some current flows here in this circuit and that will get multiplied by r1 X1 this, this. So, there will be some voltage drop ok.

So, therefore, it is possible that V 2 prime say let me draw that V 2 prime is here and depending on this current ok; depending on this current, we will have some voltage drop here, here, here, here, here. Now, this is not this only here, here, here. So, depending on this current and this current, we will have some voltage drop. So, if Vd let me draw if I do not know maybe Vd is here.

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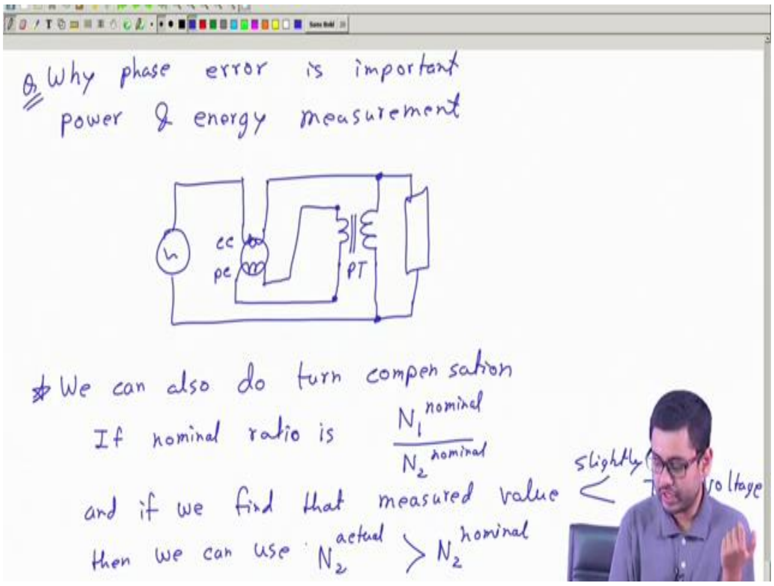

So, if we have once again let me draw this, we have a source and a load we want to measure the power. So, we have a wattmeter with 2 coils; current coil and pressure coil. Current coil we connect this in series and the pressure coil say instead of connecting directly, say we connected wires PT maybe. So, this is the PT and we connect this here.

So, now if this voltage between these two points and these two voltages between these two points are not in same phase, then the angle between this current and this voltage will not be same as this current and this voltage. So, power or energy measurement will be wrong because power factor will get changed ok. So, this is why it is important. Then, we can also do turn compensation; how? So, if nominal ratio is $N1^{nominal}/N2^{nominal}$ and if we see and if we find that measured value is slightly less than the actual value, true value, true voltage; then, we can use N 2 actual to be slightly greater than $N2^{nominal}$ ok. So, then the secondary voltage will increase ok.

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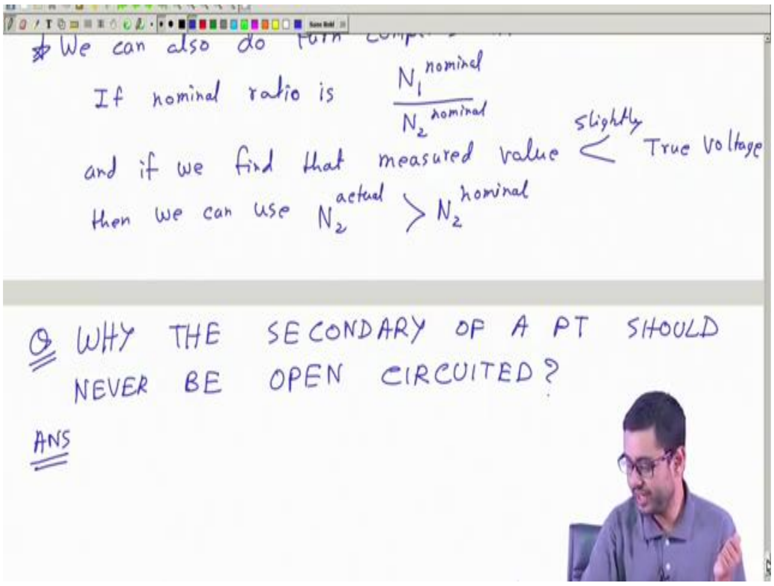

Now, the next important question, very important question can you guess; this is the last thing; why the secondary of a PT potential transformer should never be can you guess, open circuited? Answer; the answer will be very similar to the answer in the case of CT.

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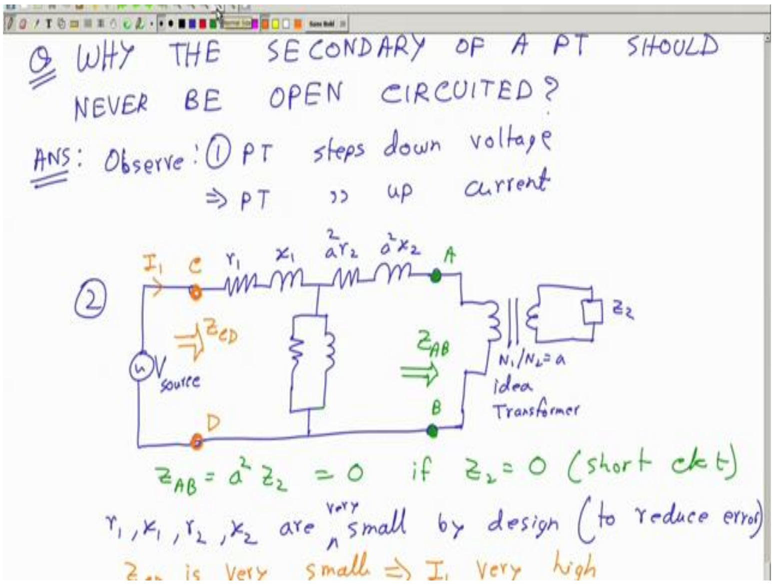

So, observe that a PT steps down voltage; so that means, PT steps up current; it has to be ok. Now, second thing second observation this is point 1 and point 2 so, this is the say this is the equivalent circuit. Then, here we have the ideal one with N1/N 2= a and if I call this impedance z 2 and here we have the voltage source V1 that we are measuring.

So, if we take z 2 = 0, then the impedance as seen between these two points call it AB. So, z AB as seen from here between this two points equivalent impedance, so z AB will be equal to a square z 2 equal to 0 if z 2 = 0 short circuit, right. And then, this impedance's call this r1 x1 r 2 a^2, a^2 x 2. Now these impedances, has to be small by design ok. So, I think I have forgot to mention this ok.

So, for a PT, we have to make this impedance's small; why? Because if this impedance is a small or 0, then there will be no voltage drop here ok. So, to eliminate voltage drop, eliminate phase radar and ratio radar we have to design the PT to have these impedances very small. So, let me just tell you I forgot to tell this before, for a PT should be designed in a way so that these impedances are small. So, we have to use very high conductive I mean low resistive coil, we have to minimize leakage reactance leakage inductance by proper design. So, PT should be designed to have r1 x1, r2 x2 very small that is the design consideration for a PT.

So, therefore, this r1, x1, r2, x2 are small very small by design to minimize error to reduce error right. Now if so, you see this impedance is 0 ok. So, this impedance is 0 so, this is very small. Therefore, and this is also very small. So, therefore, the equivalent impedance as seen between these two points call it C and D ok. So, think of the impedance z CD what is z CD? z CD is this impedance and parallelly this impedance.

Now, this is 0; this is very small. So, effectively there is a very small impedance path ok. So, z CD will be very small. So, if z CD is very small, then we are connecting a very small resistance impedance across a high voltage source ok. So, therefore, this current I1 primary current will be very high ok. So, this will imply I1 very high and then, I2 secondary current will of course be given higher ok.

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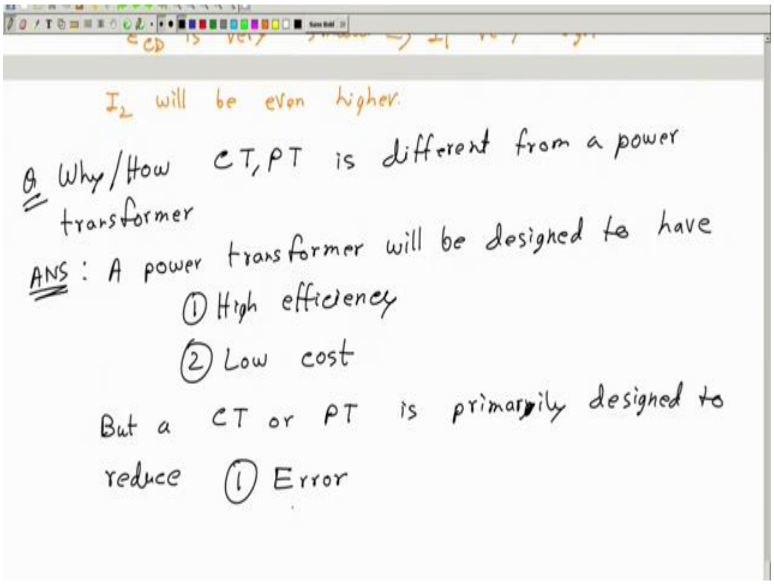

So, I 2 will be even higher. Now, all these high currents they can immediately damage the PT. High current can flow, it can cause a huge heat and the insulation may bar and it can cause a danger, it can cause some very risky things ok. So, the secondary of a PT should never be short circuited. Why? Firstly, this is a step current step up sorry yeah current step up transformer; voltage step down means current step up and then, a PT is by design has very low series impedances.

So, therefore, it high it will draw high current and it can caused dangerous things. So, that is the important things. Now, let me conclude this video by saying one or two words about why or how the instrument transformers CT PT is different from a normal from a power transformer. The answer is simple. A power transformer will be designed to for what say to have high efficiency that should be the first factor; to have high efficiency because they deal with very high power transmission. Generally so, if their efficiency is small or we will waste power and second factor could be high not high low cost ok.

So, we will not use unnecessarily high quality core because you want to reduce cost. We will not use unnecessarily very thick big conductor because you want to reduce cost. But an instrument transformer, but a CT or PT is primarily designed to reduce what error ratio error and phase error ok.

So, if for that if we need to give, if we need to put thick conductor, yes, we have to give thick conductor even if the cost is going higher. If we need high quality material core material, yes, we have to provide it because that is the primary consideration for a CT or PT or a instrument transformer. That is how a power transformer is different from a CT PT primarily from the design aspect.

Thank you.