Power System Protection
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Lecture 35
Capacitor Voltage Transformer

Welcome to NPTEL course on Power System Protection. In this module on current and voltage transformers we will discuss on capacitor voltage transformer.

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Our focus will be on transient response of capacitor voltage transformer. In the last lecture, we discuss on current transformer particularly during faults. So, in that transient situation what is the response of current transformer that is important because of associated relay decision. Similar situation we will see here during fault the voltage also goes through transient and how is the response of the corresponding voltages sensing device that we like to analyze.

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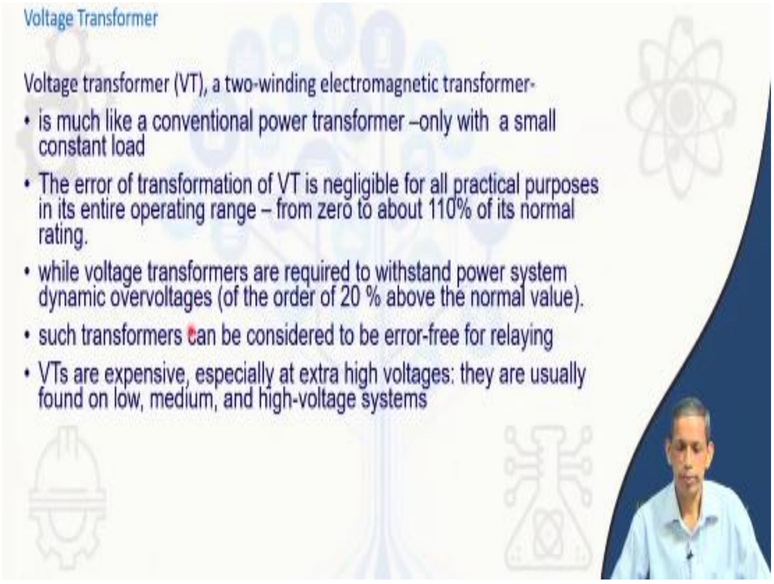

Now, for the voltage signal to the relay the straight forward solution will be a voltage transformer otherwise called also potential transformer also. Such a transformer is a two winding normal transformer only difference is that the loading is very small and thereby associated design also is different. The error of such voltage transformer VT is very negligible in all practical purposes. The voltage variation from pretty low voltage to 110 % or so the response of such VT is pretty good. Of course, sometimes during dynamic process these VT may has to sustain little bit higher voltage also for transitory period and in practical purpose of the relaying or protection application this is pretty good enough, but VTs are expensive when you think about very high voltage system associated insulation, number of turns. So, they are more found in low voltage, medium voltage levels then winding solution for high voltage applications for the protections to derive the required voltage signal.

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For that we call it capacitor voltage transformer to the same device there are different names coupling capacitor voltage transformer. Some literature says capacitor voltage transformer so whether is CVT or CCVT of course this is a not a transformer as we normally talk about a current transformer or voltage transformer it is actually capacitive voltage divider. This i CVT is widely used for high voltage transmission system as mentioned because of the economic aspect and its usage is not only limited to protection it is also for a measurement, control and one important aspect is about for the power line communication aspect also this is being used where voltage greater than 145 kV and so we will see consider versatile use of CVT.

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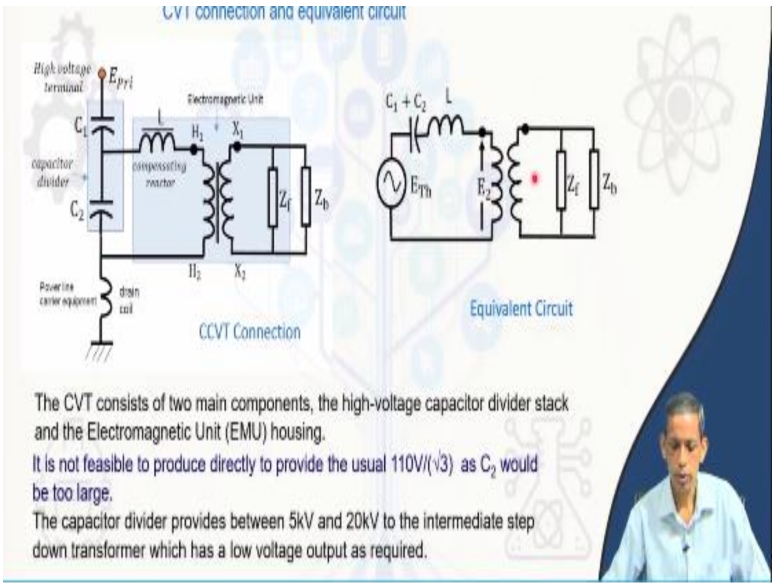

Now, to see how this CVT functions what are these different components of CVT. First, we will discuss on the steady state perspective and then we will go for the transient analysis situation like fault or so. A CVT as already mentioned is a capacitive voltage divider so it has a stack of capacitors. This part is connected to the bus or to the conductor as required. So, this is the high voltage terminal this red point here.

We have stack of capacitors and then we can say that from the lower end of this capacitor we take the tapping which should be connected to the relay or measurement or any control device. As already mentioned that this is also used for power line communication aspect. So, inductance otherwise called drain coil also is connected in series. The role of these coil is that a normal fundamental frequency 50 Hz or 60 Hz the impedance offered by this is pretty small.

So, almost as if not there, but for high kHz level where the communication signal is being dispatch also it has a high impedance value to that. Now, besides that one point there are two components in this CVT. One is the block of the capacitor divider block, stack of capacitors. The other the electromagnetic unit EMU so in that part this part we consider links to the relay the burden part of the system.

Like we discuss in the CT the Z_b corresponds to the burden here and the portion from this capacitor connection to the burden is called electromagnetic unit. We have a basic diagram here so this electromagnetic unit contains the transformer the reason behind this if we try to take the corresponding from the very high voltage to the corresponding low voltage like we talk about 110 V- or 120 V line-to-line for relay applications.

Then the size of the capacitor will be very large and that becomes an hindrance in the design and associated cost. Therefore what is being done that a medium voltage transformer is used typically ranging from 5 kV to 20 kV depending upon the design and this transformer again transforms the corresponding voltage which is taken from the capacitor to the required voltage to the relay typically it is a 110 V or 120 V line-to-line voltage and because this is phase $(110/\sqrt{3})$ V coming to picture.

Now this transformer polarity we have mark here H_1 X_1, H_2 X_2 and so. In addition, what happens because a capacitor is connected we are taking the tapping. So with respect to the corresponding system voltage the relay we can say that the relay observe the phase angle difference with respect to this input voltage E primary. So, therefore to compensate the angle the compensating reactors are being connected.

Of course, the transformer has certain reactance so in addition to the corresponding L compensates the corresponding capacitor and thereby at nominal frequency 50 Hz or 60 Hz the relay the Z_b part see no phase angle difference with respect to E_{pri}. In between that the corresponding inductance and equivalent capacitance seen from this side is such that whatever input voltage is there to this electromagnetic unit block same voltage is being obtained by this Z_b.

So, it is the corresponding L equivalent of this electromagnetic unit part and this C equivalent from this side as seen they do match each other. Now, looking into this basic diagram of CVT if we go for the equivalent circuit diagram for analysis. So, from this side if we see the corresponding Thevenin equivalent because we are concerned about the relay side secondary to this transformer side.

So, then E_{Th} the Thevenin's equivalent voltage and then Thevenin's equivalent reactance seen from this terminal so C_1 and C_2 will be in parallel. So $C_1 + C_2$ that equivalent comes and inductance in series with that. So, we got this E_2 here and then this side is the secondary of the transformer and then we have Z_f and Z_b. These Z_f is a ferroresonance filter we will discuss more on this in the next slide.

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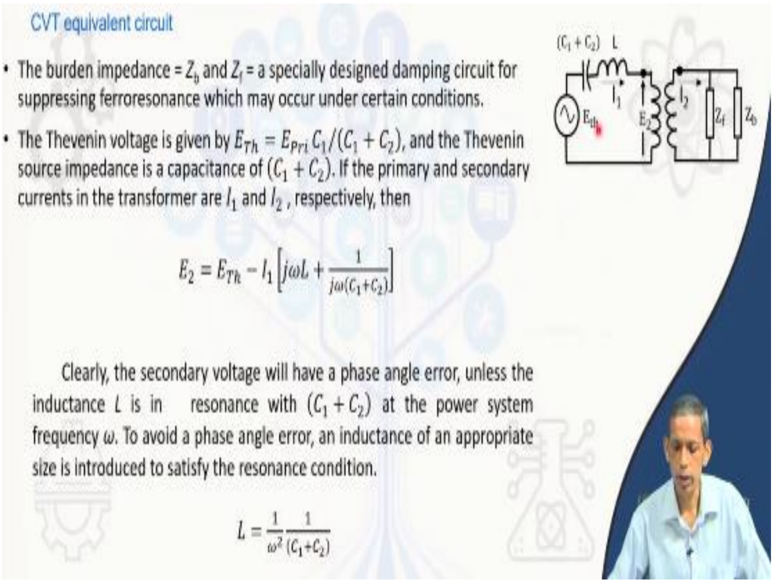

The burden impedance Z_b we have already mentioned and Z_f we can say that as mentioned is designed to damp out the corresponding oscillations to suppress the ferroresonance we can say that effect may occur during light load conditions in the system. So, the ferrro words comes from here because of this transformer associated. We say that in an iron core at different operating points the inductance of the system may match with the capacitance in the circuit particularly in case of even subharmonic component and thereby those signals may be amplified to significant level. To suppress those we can say that the Z_f is a filter which consists of different RLC combinations to eliminate those aspects. On the Thevenin's voltage E_{Th} across the transformer is given by

$$E_{Th} = E_{pri} \frac{C_1}{(C_1 + C_2)}$$

C_1 and C_2 are the capacitance connected between the line conductors and potential transformer. Thevenin's equivalent become impedance becomes (C_1+C_2). Now, If the primary and secondary currents in the transformer are I_1 and I_2 respectively, then the secondary side voltage E_2 is obtained from

$$E_2 = E_{Th} - I_1 \left[j\omega L + \frac{1}{j\omega(C_1 + C_2)} \right]$$

It is observed that the secondary side voltage will have a phase angle error unless the inductance L is in resonance with $(C_1 + C_2)$ at the power system frequency ω. To avoid a phase angle error, an inductance of an appropriate size is introduced to satisfy the resonance condition given by

$$L = \frac{1}{\omega^2} \frac{1}{(C_1 + C_2)}$$

But this L equivalent that in combination with the transformer we have taken about we can say that ideal transformer here in this diagram.

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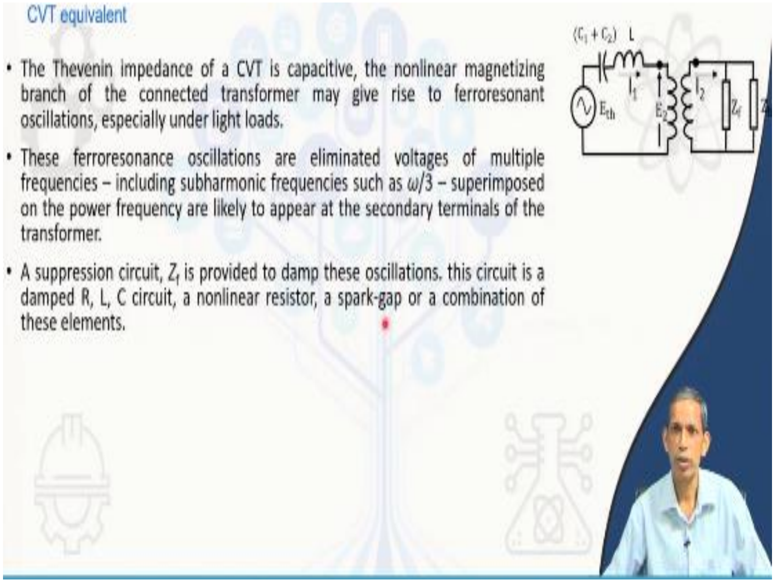

The Thevenin's equivalent CVT capacity and in non linear magnetizing branch of the connected transformer give rise to ferroresonance as already mentioned I have told and this we can say that ferro resonance can be limited by this Z_f branch that is where the filter and so that we can say that has different subharmonics and so as already mentioned this Z_f consists of RLC circuit non linear resistors and spark gap combination of these element that depends on the design. So, there are variants you can say that of such you can say that filter available from different manufacturers.

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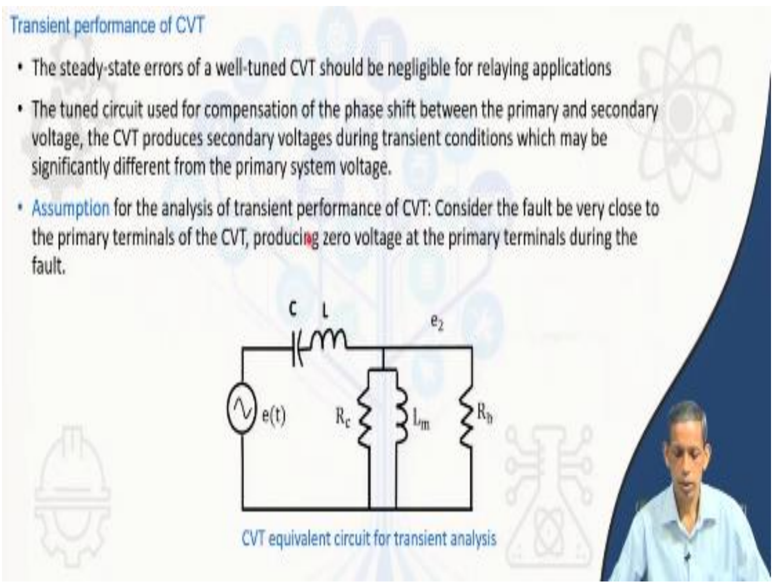

Now, we will go to the transient performance of this CVT. So, we saw that during normal steady state it is expected that the voltage which is there in the primary proportionate voltage in phase voltage will be available to the secondary that is to the relay, but during transient what is the situation that we like to analyze. Steady state error for this CVT is pretty negligible for protection application.

The tuned circuit compensate the phase angle also phase shift we can say between primary and the secondary voltage that is system voltage to the relay voltage, but that does not happen in case of transient or fault situation and so. Now, let us analyze the system we will consider an equivalent system like this as already mentioned L C with R_c and L_m corresponding transformer branch modeling.

And then we can say that E_2 voltage across the R_b. For simplicity we have not considered the resonance part and also we consider here that a worst situation or the analysis when the voltage happens to be 0 following the fault inception. So, this is a close in fault situation and then we say that suddenly the corresponding voltage becomes 0 so that worst situation we like to see how the corresponding CVT performs during such situation.

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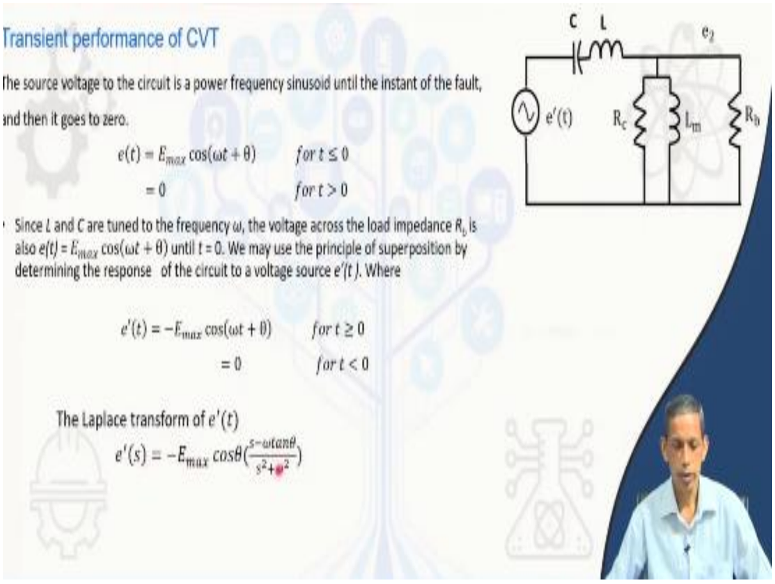

The source voltage for this we like to have some simplification and we will try to analyze we for the system. The source voltage to the circuit a power frequency sinusoidal unit before the fault inception. The source voltage to the circuit is a power frequency sinusoid until the instant of the fault, and then it goes to zero.

$$e(t) = E_{max}\cos(\omega t + \theta) \qquad for\ t \leq 0$$

$$= 0 \qquad for\ t > 0$$

So, this is the worst scenario we can say that in the system side and what is the response of the CVT we like to analyze. So, we know L and C are tuned to the power frequency. The voltage across the load impedance R_b is also e(t) = $E_{max}\cos(\omega t + \theta)$ until t = 0. Already mentioned the R_b burden the relay gets the same voltage from the input side of the voltage because L and C are tuned to ω. So, there is a proportionate voltage obtained by the relay as compared to the system voltage in during normal situation. Now, we will apply the principle of superposition by determining the response of the circuit for the analysis of transient situation to a voltage source *e'(t)*.

$$e'(t) = -E_{max}\cos(\omega t + \theta) \qquad for\ t \geq 0$$

$$= 0 \qquad for\ t < 0$$

You see $e'(t)$ we are defining like this before the fault inception it was sinusoidal now it is 0, but for t less than 0 $e'(t)$greater than equals to 0 it is just in opposite phase we can say that. So, this helps in considered about on the principle of superposition to find out the response for a signal like $e'^{(t)}$for the CVT circuit.

The Laplace Transform of $e'(t)$ that becomes equal to

$$e'(s) = -E_{max}\ cos\theta(\frac{s - \omega tan\theta}{s^2 + \omega^2})$$

So, we took the Laplace Transform of this that helps in analyzing such a situation mathematically easier way.

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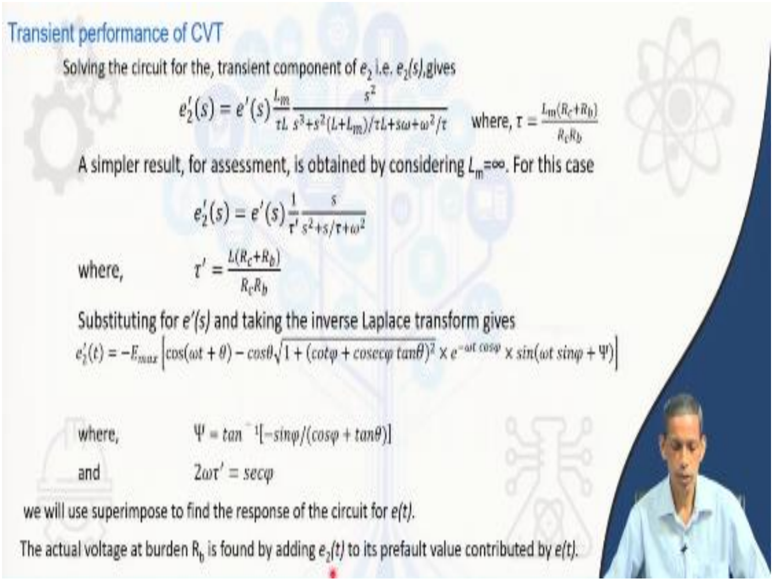

Now solving the circuit for the, transient component of e_2 i.e. $e_2(s)$ gives

$$e_2'(s) = e'(s)\frac{L_m}{\tau L}\frac{s^2}{s^3+s^2(L+L_m)/\tau L+s\omega+\omega^2/\tau}$$

where, $\tau = \frac{L_m(R_c+R_b)}{R_cR_b}$, but this seems to be pretty complex relatively to study. For simplicity we assume that the magnetizing inductance having very large value L_m=∞. For this case

$$e_2'(s) = e'(s)\frac{1}{\tau'}\frac{s}{s^2+s/\tau'+\omega^2}$$

where, $\tau' = \frac{L(R_c+R_b)}{R_cR_b}$

Substituting for $e'(s)$ and taking the inverse Laplace transform gives

$$e_2'(t) = -E_{max}\left[\cos(\omega t+\theta) - cos\theta\sqrt{1+(cot\varphi + cosec\varphi\ tan\theta)^2}\times e^{-\omega t\ cos\varphi} \times sin(\omega t\ sin\varphi + \Psi)\right]$$

where, $\Psi = tan - 1[-sin\varphi/(cos\varphi + tan\theta)]$ and $2\omega\tau' = sec\varphi$ we will use superimpose to find the response of the circuit for $e(t)$. The actual voltage at burden R_b is found by adding $e_2(t)$ to its prefault value contributed by $e(t)$.

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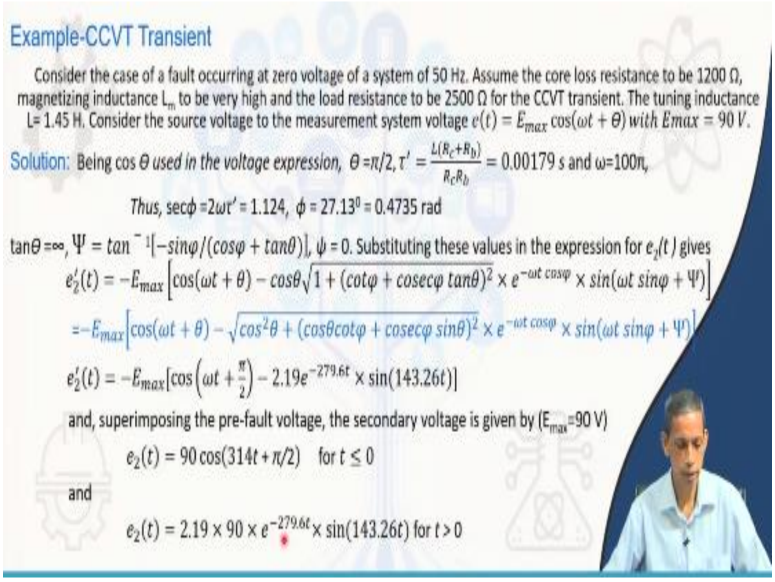

So, doing that we can get the corresponding value through that we consider an example we will have more clarity on this. Now,

Example: Consider the case of a fault occurring at zero voltage of a system of 50 Hz. Assume the core loss resistance to be 1200 Ω, magnetizing inductance L_m to be very high and the load resistance to be 2500 Ω for the CVT transient. The tuning inductance L= 1.45 H. Consider the source voltage to the measurement system voltage $e(t) = E_{max}\cos(\omega t + \Theta)$ with $Emax = 90\ V$.

Solution: Being cos Θ *used in the voltage expression,* Θ =π/2, $\tau' = \frac{L(R_c+R_b)}{R_cR_b} = 0.00179\ s$ and ω=100π, Thus, secϕ =2$\omega\tau'$ = 1.124, ϕ = 27.13^0 = 0.4735 rad. tanΘ =∞,

$$\Psi = tan - 1[-sin\varphi/(cos\varphi + tan\theta)],\ \psi = 0.$$

Substituting these values in the expression for $e_2(t)$ gives

$$e_2'(t) = -E_{max}\left[\cos(\omega t+\theta) - cos\theta\sqrt{1+(cot\varphi + cosec\varphi\ tan\theta)^2} \times e^{-\omega t\ cos\varphi} \times sin(\omega t\ sin\varphi + \Psi)\right]$$

$$=-E_{max}\left[\cos(\omega t+\theta)-\sqrt{cos^2\theta+(cos\theta cot\varphi+cosec\varphi\ sin\theta)^2}\times e^{-\omega t\ cos\varphi}\times sin(\omega t\ sin\varphi+\Psi)\right]$$

$$e_2'(t)=-E_{max}[\cos\left(\omega t+\frac{\pi}{2}\right)-2.19e^{-279.6t}\times\sin(143.26t)]$$

Superimposing the pre-fault voltage, the secondary voltage is given by (E_{max}=90 V)

$$e_2(t)=90\cos(314t+\pi/2)\quad \text{for } t\leq 0$$

and

$$e_2(t)=2.19\times 90\times e^{-279.6t}\times\sin(143.26t)\ \text{for } t>0$$

We found that we can say that when the corresponding becomes suddenly 0 we get the corresponding e2 becomes following the fault inception happens to be a transient and let us say we consider damped sinusoid in this case. So, therefore we can say that depending upon the time constant it will go for that continuing showing sudden voltage. Whereas in the system side the voltage is collapsed we can say that to zero in this theoretical simulation.

Theoretical study so that means that you can say that the during this process during that following the fault the CVT will not give a faithful result during that time. So that will lead to we can say that signal e_2 we considered to be a non zero and may lead to incorrect decision by the relay.

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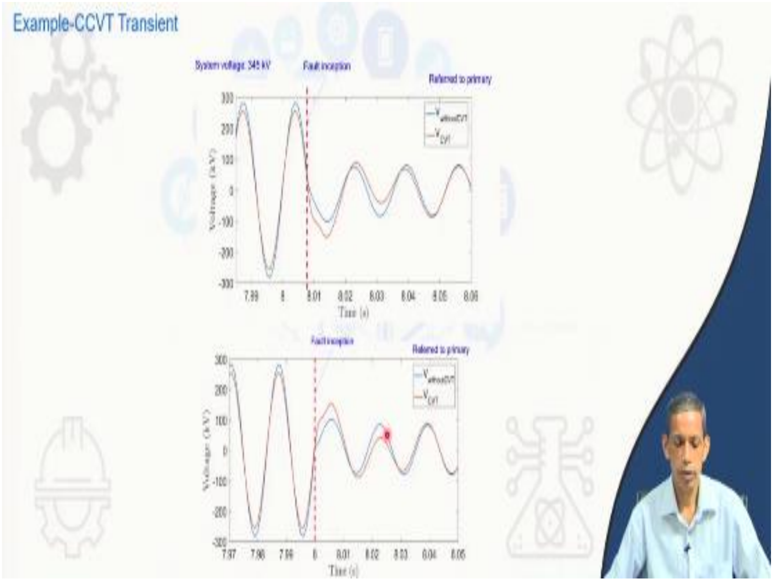

Now, so we can say that we are simulated for a 345 kV system with corresponding CVT system. So, two cases are there two fault inception angle fault inception changes. So, the blue code is without CVT that without CVT straightforward we can say that just like a VT is being used. So that we can say that the voltage is being down substantially for the fault layered and the fault is simulated for this instant. Now, when you have use CVT then the corresponding transient voltage. So, you can say that a higher value then the corresponding without CVT. Another instance here also we see here that the corresponding CVT further you can say that it deviates from we can say that the corresponding voltage which is being expected from the system. So, the blue one is for the reference one without CVT. So, what we like to see here that during the fault depending upon the depth of deviation from the prefault voltage the CVT response is affected. If this voltage change is significant accordingly the corresponding transient response of the CVT also becomes more erroneous.

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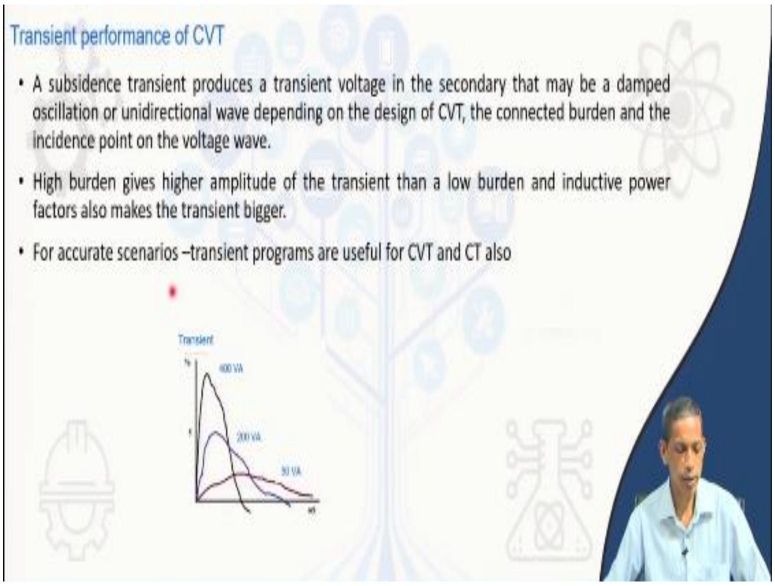

So, the transient performance of CVT that what you see there is called the subsidence transient like we discuss in the CT case also. So, this subsidence transient produces transient voltage in the secondary and as we discuss also even though the voltage has collapsed we can say that zero value, but it will show certain voltage. So that may affect the relay performance in general and this you can say that subsidence transient may be oscillatory or may be unidirectional wave depending upon the design of the CVT.

And the connecting burden in this system and so and also from the earlier slide we see the fault inception angle also. High burden we can say that of the system gives us you can say that the corresponding the high burden here 400VA, 200VA, 50 VA. You see the transient that is also higher for the higher burden so that is a challenge. So, if you like to mitigate, we can say that from the perspective low burden will be preferred.

Now, note that in the analysis what we have done that we simplified the case of L_m to be very high infinity kind of thing and we did not consider the ferroresonance filter and so, but actually those things will be there. So, in transient program we can say that these things are available. So, if you can like to study in detail about the CVT performance, transient program is very useful. So also for the CT that in mathematical analysis we consider simplified things, but for we can say that details things if someone can use the EMT package to analyze different scenario for study also.

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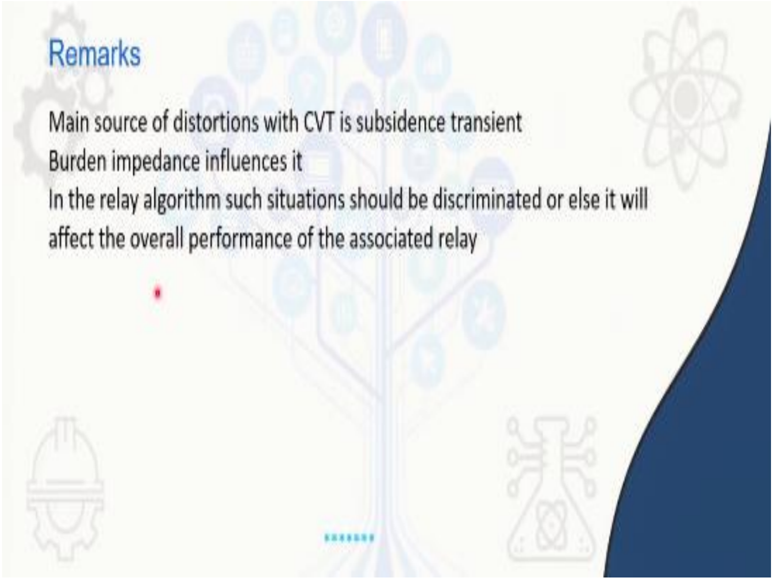

So, we say that the distortion in CVT is the subsidence transient and that may lead to challenges to the relay performance if the relay is taking that voltage signal from the CVT. The burden impedance influences the subsidence transient and numerically we can say that such situations should be discriminated because it has capability or else we can say that the performance will be affected. So, many relays used that CVT response during such worse scenario and they try to discriminate so that it will not be affected. Note that this subsidence transient is having very low value of fundamental. So, that gives us a scope we can say that to discriminate between one try we can say that voltage which is present in the signal.

So, in the next lecture we will see on we can say that the corresponding affect of CTs and VT on different relays and also continue we can say that other form of we can say that sensors which are available for current and voltage transformation. Thank you.