Electrical Machines - I
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Lecture - 9
Harmonics and Switching Transients in Single Phase Transformers

So far we have assumed that when you apply a sin wave voltage to a single phase transformer; the flux in the core is sinusoidal, and the current drawn by the transformer is also sinusoidal. However, in practice this is not the case; similarly due to the nonlinearity of the magnetic core used in a transformer, which is made up of ferromagnetic material.

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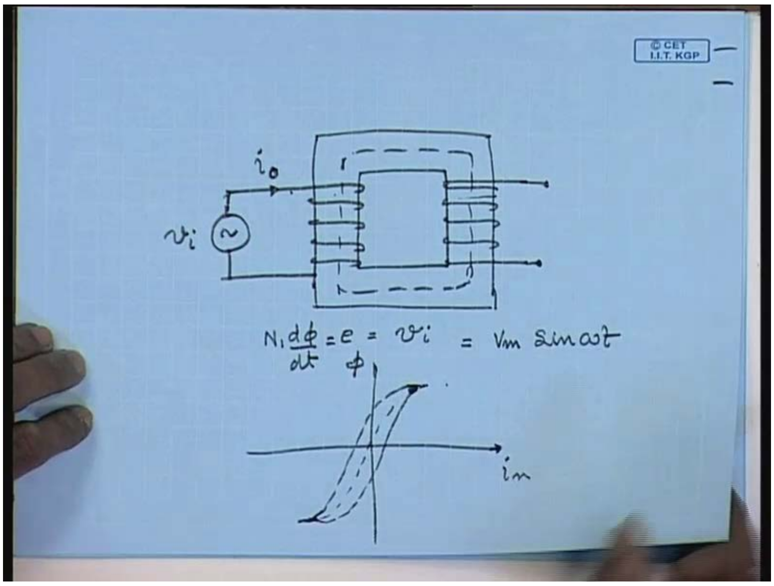

So, a practical transformer you will have a core on which the windings will be placed one on the other winding the load may be connected. The applied voltage we assumed to be sinusoidal, if we neglect the resistive drop in the winding, then the counter induced emf must completely cancel the applied voltage; that is the counter induced emf e should be equal to V i.

Hence, the flux which is given by N 1 d phi d t equal to e will be equal to this will be sine wave. So, the flux in the core will be sine wave; and the flux will also lag the applied voltage by 90 degree. Now, had the magnetic material be in linear; the current drawn the magnetizing current drawn by the transformer it also have been a sine wave.

However, this is not the case in practical transformer. In a practical transformer the no load current, the magnetizing current and the flux are related by the V H characteristic on the material; due to this non-linear V H characteristic we will soon see that the no load current drawn by the transformer will not be a sine wave. But it will be distorted with different harmonic components. Let us examine this a little more carefully.

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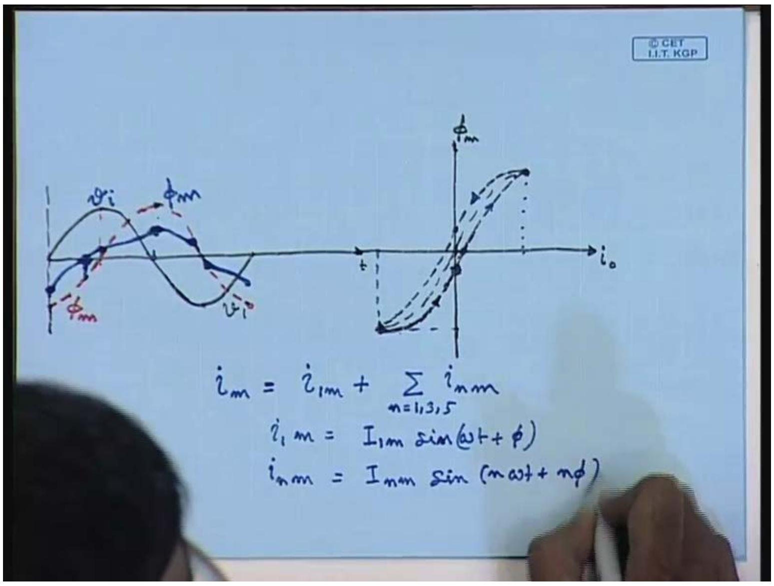

Let us say this is the applied voltage waveform. The applied voltage waveform V i and the flux waveform which will lag the voltage by 90 degree; it will be somewhat like this the core flux. Now, let us try to find out what will be the current due to in order to establish this flux in the core; what that we will have to consider the V H characteristic of the material. So, for the current let us see that at time t equal to 0 when applied voltage was 0 and increasing; the flux voltage was at its negative peak. This was the mellow of the flux and hence the corresponding current was this. So, current was at negative maximum.

Let us say this corresponds to the negative maximum of the current. Now, as the voltage is increased now flux is increasing and while increasing in a V H curve the flux follows this path. So, we see the current when the current become 0 the flux still has a negative component; that is the current will become 0 before the flux becomes 0. So, this is the point let us say where the flux will become 0; where some current still exist, some flux still exist. When the flux becomes 0 we find that the current has become already small positive. So, this corresponds to the point; again when the flux reaches its positive peak which coincides with the zero crossing of the voltage the current also reaches its positive peak. So, this is the corresponding point of the current. And since the V H curve is symmetric around x axis; the positive peak of the current wave form and the negative peak of the current waveform will be equal; while returning though the flux takes a different path because of hysteresis.

So, we see that when the current becomes 0 the flux still has some positive value. Therefore, the corresponding point here will be let us say this. And when the flux becomes 0 the current has already become negative and here again it is negative peak. Therefore, the current waveform will look somewhat like this; which is not sinusoidal although it is symmetric around y axis. But it is not sinusoidal unlike the applied voltage waveform V m; V i or the flux waveform phi m. So, this current waveform is not sinusoidal; of course it can be divided any into Fourier components it will have. So, the current drawn i m will have a fundamental component i 1 m plus harmonic components. And because of its odd nature it will have only odd harmonics; that is where i 1 m equal to I 1 m sine omega t cos omega t plus sine omega plus phi and i n m equal to I n m sine n omega t plus n phi.

So, this is the source of mostly the source of harmonics in a single phase transformer. And mostly in the magnetization current that this harmonic will be observer; there is one interesting thing to note here that the zero crossing of the flux waveform and the current waveform do not coincide. In fact, the zero crossing of the current waveform leads the zero crossing of the flux waveform by some angle; although the peak of the current waveform coincides with the peak of the flux waveform. If one decomposes the current waveform into its Fourier components at the fundamental we will find that the current waveform has a component which is larger component; which is in phase with the flux waveform phi m. And a smaller component which is leads the phi m and in fact it is in phase with the supply voltage V i.

So, the out of the phase that is component of i m which is in phase with phi m. And in quadrature with that is at 90 degree lagging V i is responsible for setting up the flux in the core. While the in phase component of I m that is the component which is in phase with the applied voltage V i supplies the hysteresis loss; of course this magnetization current waveform will also be modified by the eddy current component. However, this component is sinusoidal because the flux is sinusoidal which introduces a sinusoidal voltage in the core. And sinusoidal current in the core material which will be compensated by drawing sinusoidal current from the source which will be in again in phase with V i. So, the in phase component sinusoidal component of V i will increase that will make the waveform less distorted.

Therefore, the no load current of a transformer will have a in phase component; which is due to in phase component which is in phase with the voltage which is due to the hysteresis and eddy current loss. And a component which is perpendicular which is lagging V i by 90 degree and in phase with the flux waveform which establishes the flux. In addition to this 2 fundamental components there will be harmonics; odd harmonics that is third harmonic, fifth harmonic, seventh harmonic etcetera of the fundamental frequency; which are due to the saturation of the core material. The different 2 saturation the transformer walks the more will be harmonics and the nature of the current waveform will become very peaky.

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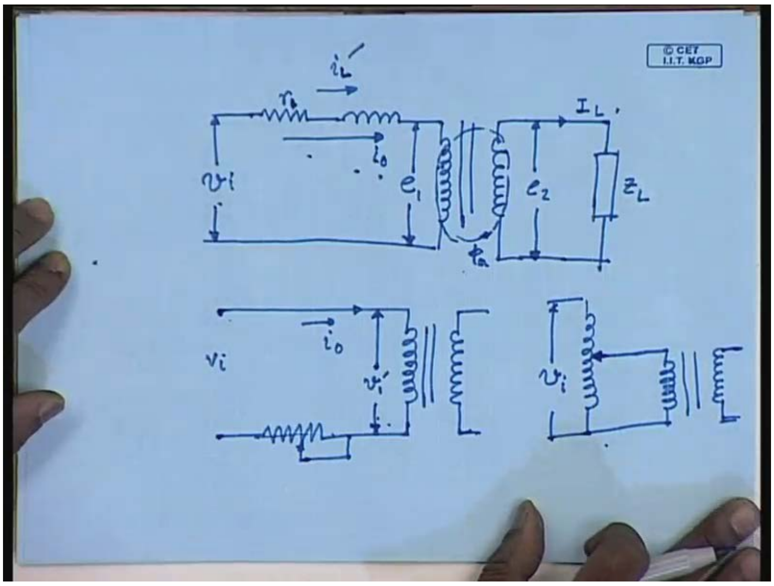

However, when you since the magnetization current is non sinusoidal one would except; if one assumes the winding resistance that the applied voltage is sine wave; the current drawn I 0 has harmonic. Then one should except the induced voltage e also to have harmonics. Hence, even the flux waveform will possibly not be exactly a sine wave which may or may not increase the harmonics in I 0 depending on the nature of the V H characteristics. However, since I 0 magnitude is very small and also the state resistance is small e and phi n can be for all practical purpose assume to be sine wave. So, in a transformer if the applied voltage in sinusoidal then the core flux is almost sinusoid. But the magnetization current drawn is distinctly non sinusoidal; it has fundamental components and odd harmonics. However, when we put a load on the transformer; I have already mentioned that there will be a reflection current i L dash flowing the transformer. Since, the core flux is a sine wave the induced voltage on the secondary side is also a sine wave. And if the load is a resistive or inductance is linear load; then the current I L will be a sine wave. And hence the, its reflection i L dash will also be a sine wave.

Now, I 0 is much smaller in a normal transformer I 0 is much smaller compare to i L dash. So, when transformer is loaded I L will dash will dominate over I 0. Therefore, the waveform will look very much sinusoidal. And although there will be harmonics of the magnetization current present. But it will not be apparent since the magnetization current consist only a very small fraction of the total output current of the transformer.

So, a transformer single phase transformer at no load draws predominate draws a non sinusoidal current from the supply consisting of fundamental and odd harmonics. However, on load the fundamental component also include the reflector load currents of the fundamental component increases but the harmonics do not increase. Therefore, unload transformer current appears to be more or less sine wave. At this point one should be careful about how one should connect a transformer for performing certain test. In this circuit we have assumed r 1 to be small. However suppose we want to perform a no load test on this transformer. And the available supply voltage is larger than the transformer voltage rating. Then one possibility could have been to connect the transformer like this. And then connecting a resistance of large value and connecting a transformer across the supply.

Since, we are doing a no load test then the current drawn by the transformer will be non sinusoidal. And the voltage; actual voltage across the transformer will also be non sinusoidal this will make the flux non sinusoidal with predominantly third harmonic component the flux waveform.

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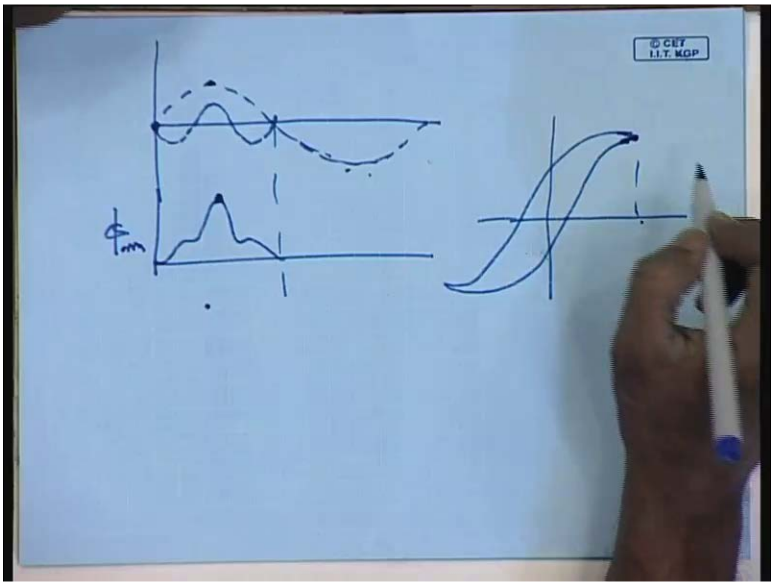

Instead of looking sinusoidal may look something like this; this is the sine wave component of the flux, this is third harmonic component of the flux. So, the resultant flux waveform near show predominantly peak in nature; additional resistance is connected here; in which case because of saturation this will be significantly higher than the fundamental magnitude of the flux.

So, the current drawn by the circuit may be significantly large. Therefore, it is not desirable to make a circuit connection like this; hence for doing no load test under such situation it will be preferable instead of using a resistance to drop the voltage. One should use a auto transformer ((Refer Time: 23:10)) in order to reduce the voltage to the desired level. Because the induced voltage in the auto transformer will be almost sinusoidal. So, far in this figure we have assumed that the transformer is operating in steady state; that is the given a sine wave applied voltage the flux waveform is also a sine wave. However, when the voltages first switched on in the transformer it under goes a transient before the flux becomes settles down to its final sine wave value. During this period the transformer can experience very larger current; let us see how?

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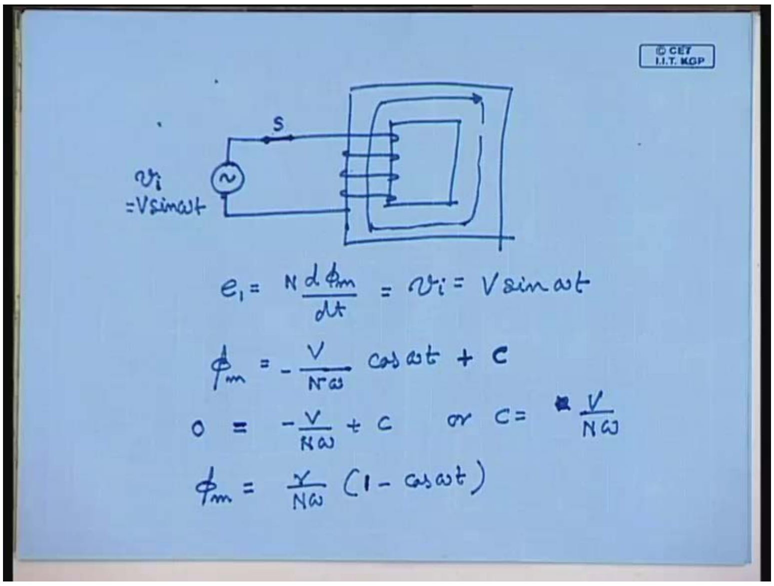

Again, let this is the transformer on no load. If we assume neglect the transformer winding resistance; then we can write e equal to N d phi m by d t equal to v i equal to V sine omega t or phi m equal to V by N minus V by omega N cosine of omega t plus and constant of integration. At time t equal to 0 one would except that core the de energized. So, phi m at time t equal to 0 may be assumed to be 0. So, at time equal to 0 or c equal to V divided by N omega or therefore, phi m assuming at t equal to 0; the voltage was 0 phi m will be V by N omega 1 minus cosine of omega t. Let us plot this.

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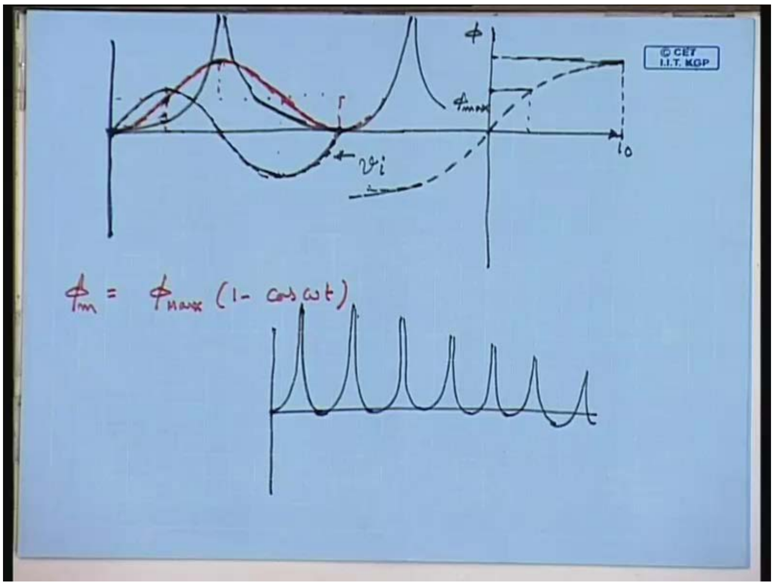

So, this is the applied voltage sine omega t applied voltage v i; we have switched on at t equal to 0 when the voltage was 0. Then the flux waveform phi m is given by of the form phi m equal to phi max into 1 minus cos omega t. At t equal to 0 it was 0; at omega t equal to pi by 2 it will become phi max. And omega t equal to pi it will become 2 phi max. So, the flux waveform will cosine wave which is shifted by phi max.

Now, let us see what will be the consequences in term of currents? As we have already mentioned a practical transformer core will exhibit a predominate saturation characteristics along with hysteresis. Let us say transformer is usually designed to operate at a transencity of phi max; maximum flux in flux phi max. However, we see that because of switching initially the flux raises to almost double the value; due to non-linearity of saturation the current will not be double it will be very large; incases it can be 50 to 100 times the normal no load peak current. The current waveform as we see at we neglect the hysteresis at t equal to 0 it is 0; phi m reaches it at omega equal to pi by 2 reaches rated value. And then at omega equal to pi it reaches a very high value and this waveform repeats.

So, if we look at a large scale; time scale we will find right after switching the current raises to very high value. And is almost entirely positive it does not become negative initially. Then slowly because of different loss in the core; the flux slowly gradually reduces and settles down to its final value; accordingly current also gradually reduces. So, this first peak cannot be as I said 50 to 100 times the normal steady state peak magnetization current; which means it can be 5 to 10 times the full load current of the transformer for first 1 or 2 cycles. This is called the in dust phenomenon in a single phase transformer; this occurs due to the depending on the wrong switching of the instant of the voltage. It is interesting to note the instated of switching the waveform; the voltage at zero crossing had we switched it at the peak value; that is if the at t equal to 0 if the switched it at peak value.

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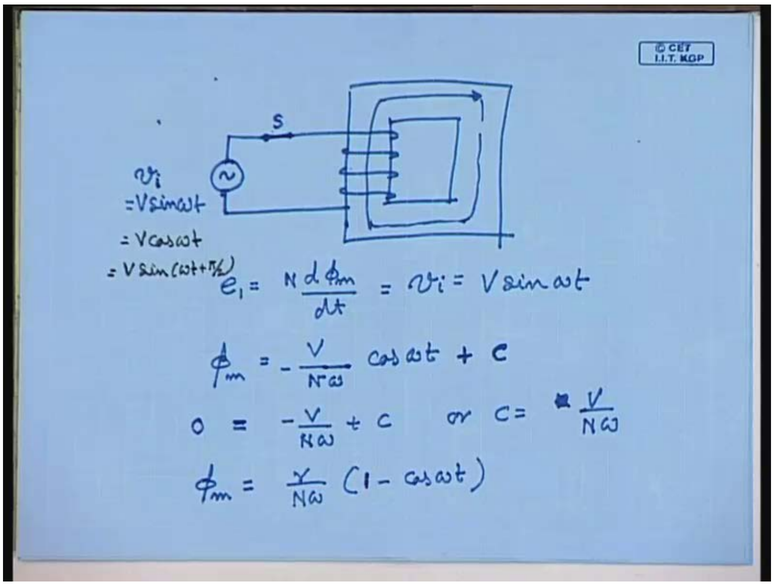

Then, V i would have been given by instead of V sine omega it would have been equal to V cosine omega t that is equal to V sine omega t plus pi by 2. In which case that it is if we would have switched on at the positive peak.

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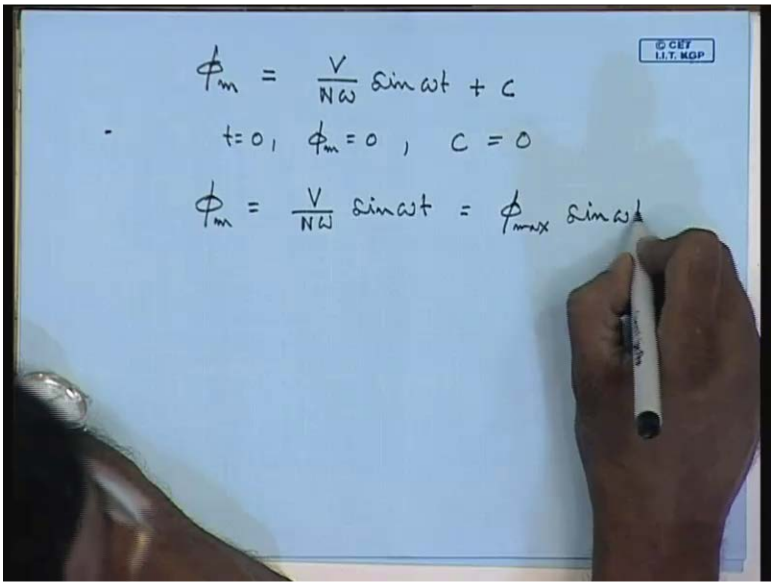

Then, V i would have been given by instead of V sine omega and if at t equal to 0 phi m was 0. Then c also would have been then phi m waveform would have been equal to V by N omega sine omega t equal to phi max sine omega t. And there would not have been any in dust phenomenon.

So, depending on when the transformer is switched on it is possible that there will be an magnetic in dust in a single phase transformer; due to which the no load current of the transformer can raise to dangerously high level for initial few cycles. The rotation system should designed to handle this. Because it is difficult to precisely determine exactly at which instant transformer will switched on the situation will become what? Since, a transformer at t equal to 0 the flux in the core may not be 0. Because of previous excitation of the transformer the there may be some flux remaining in the core this is called retentivity.

So, if you have some remindance flux in the transformer. Then the peak flux density may increase even more than twice the steady state peak flux; in which case the peak of the current in dust will also increase accordingly; one load though this effect becomes somewhat less. Because the flux decays first and the peak value of the current reduces faster. Therefore, in a single phase transformers a switching transient during term on may cause magnetic in rust; due to which the no load current can increase to very high level this current slowly decays because the losses in the transformer. And finally settle downs to the normal magnetization current.