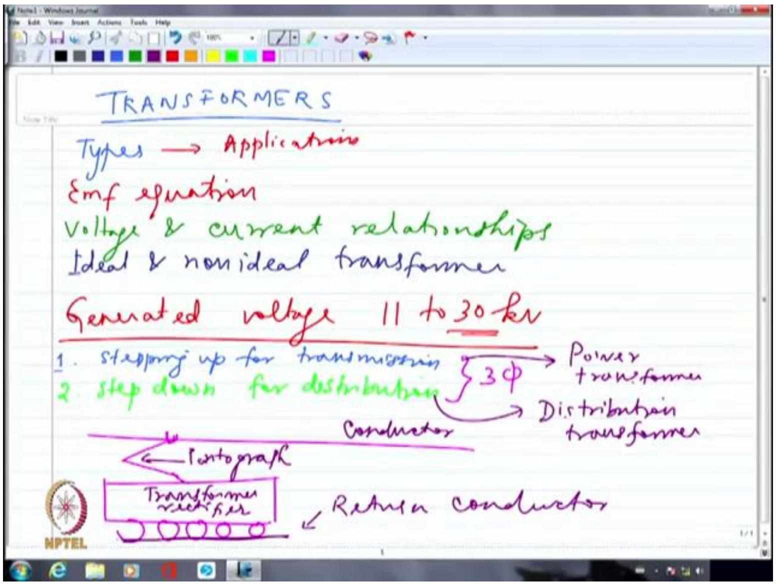
Electrical Machines

Professor G. Bhuvaneswari
Department of Electrical Engineering
Indian Institute of Technology Delhi

Lecture 4

Transformers- Introduction

(Refer Slide Time: 0:25)



So, we are going to start on the next topic which is Transformers. So the topic that we are going to cover under transformer basically are, let me talk about today first, I will be talking about types based on both applications as well as contraction and single phase and three phase these are the various types we will be talking about. So in the process we will also be talking about applications.

So we will be talking about the applications as well, then we will be talking about EMF equation for a transformer. After talking about the EMF equation it will become clearer why we have $\frac{V_1}{V_2} = \frac{N_1}{N_2}$, so we will talk about voltage and current relationships. So the next thing that we will be talking about is voltage and current relationships. After this we will talk about ideal and non-ideal transformer and then the phasor diagram.

This is a sequence, after this we will worry about what further we will discuss. So I will then cover ideal and non-ideal transformer which will take us to equivalent circuit and so on and so forth. The major application of a transformer is to step up and step down the voltages and this will be used in transmission as well as distribution. So normally the generated voltage level if we look at is generally about 11 to 30 kV, in fact I should say 15 to 30 kV.

The limitation is because of the insulations that I have to put around the winding which are placed inside the slot. So when I have slots within the machine and I put conductors inside if the conductor is having extremely large voltage I have to insulate it against the slots as well. So the insulation will become thicker and thicker if I go for higher and higher voltages, so that essentially prevents me from having extremely large voltages.

Because the insulation will become prohibitively thick, I will not be able to place it properly inside the slots and that is the reason why we generally limited to less than 30 kV at any rate but if I try to transmit the power at 30 kV the current will become enormously high, literally because of which I necessarily need to step up the voltage, so that I would be able to keep the current within limits despite transmitting extremely large amount of power.

So when we talk about transmission capacity, the overall generation capacity of our Power Grid, right now is about 210 GW. This is not including all the renewable that are being added every day. So 210 GW of power is being transmitted all over the country, all the time. So if you think of transmitting this at lower voltage level, it is going to be unimaginably large current that is a reason why we step up generally the voltages.

So first application I would say is stepping up for transmission and very clearly on the other side I have to step down for distribution. Mostly these two are done in 3-phase, not in 1-phase. Only the distribution at domestic level is done as a single phase configuration, and most of the power transmitted for any industrial use is all in 3-phase. The only exception is a suburban train system, normally if you look at Bombay or if you look at Chennai for that matter very old suburban train system what is there which takes people from one station or one locality within the city to another locality, most of it is in single phase it is not in three-phase although the power capacity is pretty much high. It is generally 25 kV, what is being transmitted there is 25 kV.

Then it is stepped down within the railway car which is known as the electric engine and that there is a rectifier sitting which would be converting that into DC and with the DC motors, DC series motor drive the electric vehicle.

That is what is done in Bombay, the old system, newly there have been some convergence to AC, for example if you look at the Western Railway route in Bombay that is most of it is now converted into AC whereas if you look at the Central Railway route in Bombay that is mostly in DC. So that is AC transmitted converted into DC and the DC motor is driving the vehicle that is what I mean by DC, basically the drive train is DC drive train basically.

This particular railway electrification is done with the help of single phase AC because the return route is not there at all, return conductor is not there at all, and the rail serves as a return conductor. There will be generally a line which is the overhead transmission line somewhat like this and you would see that a U shaped conductor will be touching from the train, so this is actually your train.

These are the wheels, I just arbitrarily drawing a diagram basically to represent it. So this particular thing is generally known as the pantograph. The pantograph basically is a kind of a brushed kind of arrangement which is actually made up of a thick conducting material which is insulated by some plastic, bakelite and so on and then that is having a U shaped conductor which is actually sliding over the overhead transmission line to collect electricity.

So this is only conductor that is being used throughout the railway electrification zone, so this is the conductor or overhead conductor that we use and whatever is the rail here that is supposed to be our return conductor. So basically it is going to save on huge amount of copper, that is the reason why single phase transmission is being used only for traction application, of course inside the electric car that will be a transformer and there will be a rectifier normally, both will be sitting there along with DC motor drive that is how the entire thing is driven.

So I would say that this transformer which is stepping up for transmission be normally called that is power transformer, whereas what we use for distribution we will call that as distribution transformer, so power transformers normally step up the voltage from the generator and distribution transformers normally step down the voltage from the transmission line and send it to whatever is your domestic application or industry applications and so on and so forth.

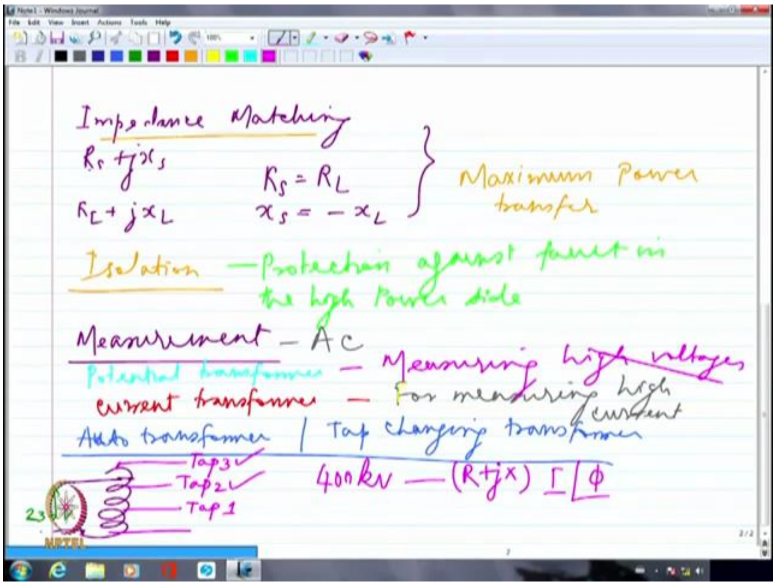
Again in terms of functionality the power transformers will be functioning only when the corresponding generator is generating, let us say the generator has been shut down for some reason maybe for maintenance, maybe there is a fault, maybe some prime mover has gone crazy, something is wrong, so you are shutting the generator. If you are shutting down the generator then the transformer will not be energized.

So the power transformers will be functioning only when the corresponding generator is functioning and it will be almost functioning at 100 percent load to its fullest capacity. If I say it is 200 MVA generator it will always be delivering a power corresponding to 200 MVA normally. So power transformers will be functioning along with the generator to its fullest capacity normally, whereas, distribution transformer will be functioning no matter what 24*7 all the time, 365 days in a year. Let us say I have a distribution transformer probably which is supplying power to LHC even if one class is happening, I have to energize the transformer, even if no classes are happening probably in the anticipation that something might happen at any time I have to have it functioning most of the times.

Similarly, any domestic environment if I look at the locality I cannot say all the loads will be ON all the time even if one customer is wanting the power I cannot switch off anything. So distribution transformers normally will be energized 24 hours a day, 365 days in a year all the time they will be energized. So there is no guarantee that distribution transformers will function at 100 percent load, it may be much less than what is actually it is rated for.

So you are basically going to look at this difference in terms of later on the design efficiency calculations and things like that. We will be looking at it later. So these are two specific applications that I talked about for transformer.

(Refer Slide Time: 11:51)



Apart from that I may have a transformer for impedance matching. You guys must have studied about something called maximum power transfer, when if I say that the source impedance is $R_s + jX_s$ this is the source impedance, the load impedance if it is actually $R_L + jX_L$ if I may say then I have $R_s = R_L$ and $X_s = -X_L$ I am going to have maximum power transfer.

So whenever I have an intervening transformer between a source and the load I will be able to make or create a situation as though the load impedance and source impedances are being matched depending upon the turn's ratio. It is known that from the secondary side whatever is the impedance, I can look at it from the primary side as $\left[{N_1}/{N_2}\right]^2$ multiplied by whatever is the impedance on the secondary side.

So by having an appropriate turns ratio I can create a situation such that the load impedance and the source impedances are matched this is done very often in many of the electronic circuits, so that the maximum amount of power transfer takes place to the load from the source because the available power itself will be pretty small and I want to transfer as much as possible to the load, so I would like to match the impedance, this is one of the applications of transformer.

Another application I would say is isolation. Isolation is between high voltage and low voltage I might like to have some amount of separation between their grounds. I do not want them to be connected to the same ground, so earthing or grounding what you do for high voltage source will be separated from the low voltage side with the help of transformer because the transformer does not have any direct electrical connection, it is coupled only by electromagnetic induction, it is only magnetic coupling.

So there will not be any direct current flow from the high-voltage side to the low voltage side or low voltage side to the high-voltage side, so they are not conductively connected. They are not connected through a conductor, so if there is something going wrong on one side it will not or it may not affect the other side. So I would like to isolate a high-voltage side from a low voltage side or high-power side from a low-power side.

For example, if I am controlling the speed of a DC motor what I am supplying as power to the DC motor may be at kilowatt level but if I am using a transistor or something to control the power to the DC motor, the transition will be turned on and off with the base drive. So that based drive it will be at 15 V level or even less whereas the motor will be operated probably at even 1 kV level, it is possible.

So I might like to have the isolation between the motor and the transistor based drive circuit that can be done very nicely by using a transformer. So generally transformers are used for isolation when I require some protection, so this will actually give me some protection against fault in the high-power side. So in the high-power side if there is some fault that will not affect the low-power side. I may have a computer microprocessor controlling my DC motor, I do not want a computer to conk out completely, if that is a problem in the high-power side, so I may use an isolation.

Another application is for measurement I mentioned about this already once. So this can be potential transformer, I may like to measure 400 kV quantity from a transmission level. I will not have a voltmeter of 400 kV range. So I might like to stop it down using a potential transformer and then give it to a voltmeter of lower range. So essentially this is for measuring high-voltages.

Similarly, I may have current transformer which will actually bring down the current value, so that it is falling within the ammeter range. So this is essentially use for measuring high current but obviously this can be done only for AC measurement it cannot be done for DC measurement obviously it is only for AC measurement.

Last but not the least, there are also auto-transformers and tap changing transformer. Auto transformer is for example a single winding transformer, so I may just have a winding which is bound on a core, I am not showing the core right now. So, if there are 1000 turns I may actually supply the voltage only until 980 turns.

So what I am connecting is only to lesser number of turns then what is the total number of turns that are available in my transformer. Maybe I am connecting to 230 V, so what I get at the output can go easily up to 250 V, so it is like stepping up not with 2 windings but because the number of turns on the other side is a slightly higher, so I am supplying the voltage only to let us say 900 turns but what I am tapping at the output is corresponding to 1000 turns.

So obviously if I am applying 900 volts to the 900 turns then I would be able to get 1000 volts out of 1000 turns which are the total number of turns in the transformer there is no isolation here clearly. The primary and secondary are essentially the same binding, only thing is less number of turns are there in the primary side and more number of turns are there in the secondary side that's all is the difference.

So this essentially will allow me to step up or step down depending upon how many turns I am tapping. So I am calling it as I have got multiple number of taps, I may tap it from here, I may tap it from here, I may tap it from here, so I can call this as may be 1, this is tap 2, this is tap 3. So I can have multiple number of taps and I can choose to tap any amount of voltage out of this auto transformer, I should be able to do this as per my requirement.

So this kind of transformer is also known as tap changing transformer because you may change from one tap to another these applications are very much prevalent in our substations and it may be there even in your generating stations switch yard because let us say my generator is generating 15 kilovolts and I am trying to step it up to 400 kilovolts for transmission.

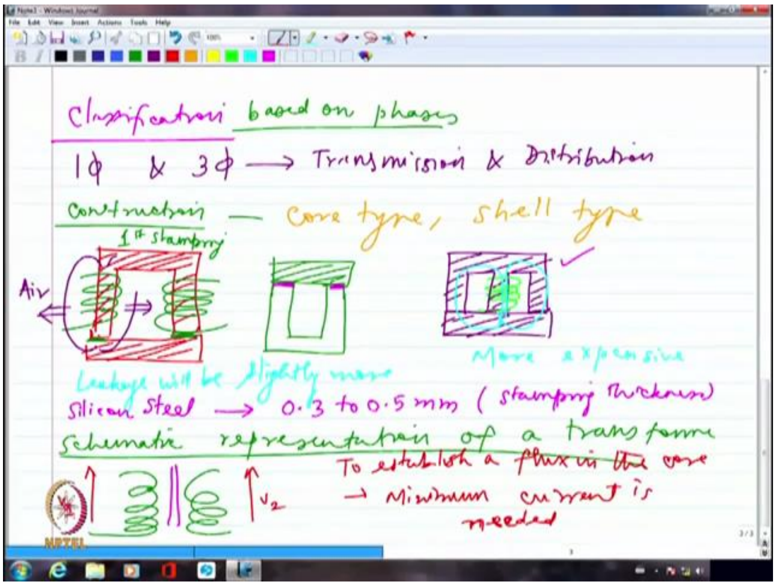
When am having 400 kilovolts at the output on a nominal load, say 100 percent load obviously there will be some internal drop within the transformer, within the generator because all of them are having some R and some jX, so depending upon the current that it is equipment are carrying going to have some drop, so I would say the voltage at the terminal of the generator will be 400 kV minus whatever is my $R+jX$ of the transformer and generator multiplied by the current. Of course I have to include the power factor angle, no doubt, this is how I am going to get terminal voltage.

If I switch off some of the loads, the loads are gone then the current is going to decrease. If the current decreases, $R + jX$ multiplied by the new current will be definitely smaller compared to what I got earlier, so if the drop is lower originally let us say I was getting 400 minus this drop was 380 KV and I was expecting 380 kV only at the end of the generator terminal or the final terminal of the transmission line.

But now it might go high as higher 390 or even like 395 kV my equipment may not be able to withstand the 395 kV, so I might like to put the tap at a lower number of turn, are you getting my point? So if I put originally maybe my tap was here, now I might like to put my tap at a lower point, if I put it at a lower point even the incoming voltage is decreased somewhat.

If the voltage is decreased correspondingly I am going to have in the terminal also, a little less voltage than what I was getting. So the tap changing transformer allows you to make minor adjustments in the voltage, so that any higher drop or lower drop is compensated for. So that is a major advantage of taps changing transformer. So, so much so for the applications of transformer this also gives rise to variations in the functionality of the transformer as power transformer, distribution transformer, measurement transformer, isolation transformer and auto transformer, so these are the various classifications of transformer as per the application.

(Refer Slide Time: 23:43)



So let us try to look at another variation or classification in the transformer which is actually single phase and three-phase. Single phase transformer is commonly used only in domestic applications hardly ever you would see the three, the single phase transformer in transmission or distribution application. Whereas three-phase is always used in all transmission and distribution application.

We also have one more type of classification based on construction. So based on construction we may have something called core type construction or shell type construction. What we mean by core type construction is, let us say I am going to have probably a lamination somewhat like this. Generally, laminations are made in such a way that they will be made by 2 pieces.

1 will be of C shape, if you may call this as C shape. The other one is just a straight line or a rod kind of construction. Now what I'm going to do is, to put one winding here maybe another winding here. So I call this as core type construction, please note that only on one side of the winding I am going to have iron whereas this side of the winding I am having air.

So naturally if I look at any flux lines that are probably going to flow here. I may have something called leakage, these will be leakage lines, on this side if I look at the leakage lines I have a very-very small air path not much of window available but on the other side huge amount of air is available, so in core construction at least on one side the windings are surrounded by air.

Whereas, on the other side very closely you are having the certain limb coming up whereas in shell construction I may have actually an E type of core for example I am just showing this is in the shape of E, this is how it is and I am going to have basically this as my core and I am going to close this with the help of again a straight line like this. So I may have basically the winding rather put up only here in the central portion.

So I may have primary and secondary both put up only in the middle portion of the winding which means on either side I am going to have iron surrounding it. So the reluctance in this case will be really-really low because of which the entire magnetic field lines will try to confine themselves only within the core either like this like this, hardly anything will escape into air, whereas, in the other case because I have some amount of large amount of air surrounding the winding I may have more number of lines leaking into the air. Some of them will definitely leak into the air in either case but the number of lines leaking into air in this case maybe slightly higher. So I will have basically these two types of construction, here the leakage will be slightly more and I should say very clearly this is more expensive because more amount of iron will be needed to construct this core.

So I will be needing more amount of iron to construct this core. So these are two types of construction depending upon where I cannot tolerate more reluctance I have to adopt this construction, shell type construction. One more thing we would like to do is the core is constructed like this I told you rather than basically having this C shape and a straight line kind of thing just stacked one behind the other, we may like to have the second, if I say that this is the first stack, this is the first stamping, I would have the second stamping just opposite of this.

So I may have the C shape at the bottom and I would have basically this straight line at the top. So I will put one behind the other, so that the air gap does not become continuous. I will have a small air gap whether I like it or not I am going to have a small air gap here. In this case similarly I will have a small air gap here. I do not want this air gap to continue one behind the other continuously because that will increase the reluctance. So I would like to put the first stamping with the straight portion at the bottom, I would like to put the second stamping with the straight portion at the top and vice versa, continuously I will do that, first, second, third, fourth and so on.

The same thing I should be able to do here also. In one case on the top I can put the E at the bottom I can put the straight line and the second stamping will have the straight line at the top and E at the bottom. So I can do this alternately, so that the air gap does not continue through the stampings. So the reluctance will be somewhat limited because I am alternately arranging this.

So these are some of the constructional details of the transformer, normally the core material will be silicon steel and the stamping thickness will be anywhere between 0.3 to 0.5 mm, each of the stampings will be having, you know, this as the thickness. The question was, why don't we make the core as one single stamping which is in square shape or in E closed shape? Invariably the windings are you know, really-really heavy.

If the windings are heavy it will be very difficult to actually make the winding manually or even machine wound windings around preprocessed core. Rather what you do is, you make the stamping in the shape of C then you just put the winding like, you put a ring. In a finger, so you put the ring and then close the other side, that is how generally the transformers are made because the windings are extremely heavy.

So you are essentially going to have a big problem in fact three phase transformers are very-very difficult to transport, so whenever a power station is made their rebuild the roads, rebuild the bridges, rebuild all the railway tracks to transport the transformer from, for example BHEL Bhopal, BHEL Haridwar, Haridwar makes lots of transformers, so when Ramagundam plant was constructed in Andhra Pradesh all those in between bridges, railway tracks and the roads were reinforced very strongly to make sure that it does not sink in completely.

Otherwise you would have seen that the road or the tracks would have collapsed completely. So it is very important that the mechanical strength is also taken care of otherwise you would not be able to transport normally the three phase transformer, that is one reason why, three phase transformers are normally made up of three single phase bags. We never make the three phase transformer directly three phase transformer.

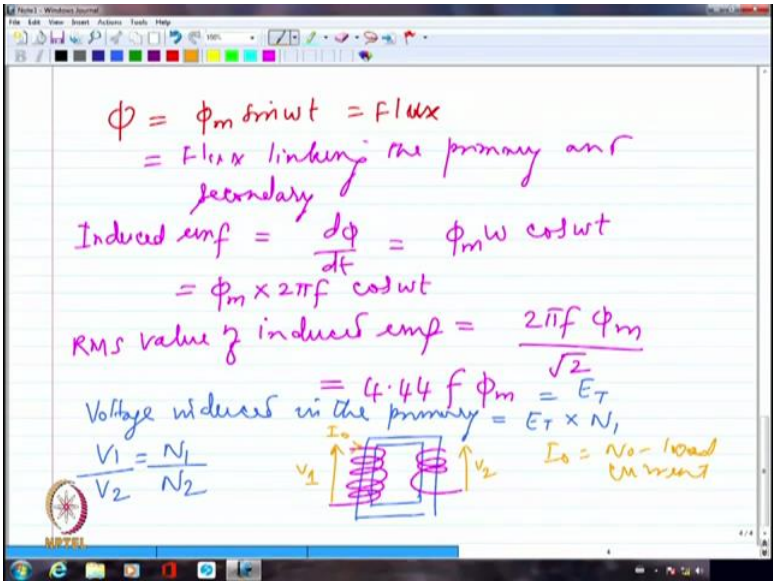
We try to make a three single phase transformers connect them in star or delta externally, so that when you transport it becomes simpler and also if you want to store some of the backups you can always store a backup as a single phase rather than storing the entire three phase, so it saves on money. So that is the reason why normally three phase transformers banks are never directly three phase construction it is three single phase transformers connected in star or delta configuration.

So let us now go to the analysis of a transformer. Let me just represent schematically a single phase transformer. So I would simply show that as two windings like this. And they will be essentially shown with the help of two parallel lines the core will be shown with the help of two parallel lines sitting in between. This is the representation of a transformer, so I am going to apply maybe a voltage of V_1 here and I am going to get a voltage of V_2 as output.

And because it is made up of silicon steel or ferromagnetic material to establish a flux which will cause electromagnetic induction in the secondary side I would not require a large amount of MMF. The reluctance is really-really small because the reluctance is small to establish a nominal flux I will require a very-very small amount of MMF. Ideally I should say literally 0 MMF should do it.

It is not true, reluctance is not 0, reluctance is some minimum quantity, so that reluctance multiplied by whatever is the flux that I want to establish that is what is contributing towards the MMF that MMF is a small quantity in a ferromagnetic core transformer. So I am going to say that to establish a flux in the core. Minimum current is needed, very minimum current is needed. This is because of the fact that I am having very-very low reluctance for the core material.

(Refer Slide Time: 36:16)



Now let us say I have a transformer and I have established a flux ϕ which is actually given by $\phi_m \sin \omega t$, this is the flux that is established in the core. Assuming that I am going to have a good amount of permeability for the core whatever is the flux that is linking the primary winding the entire flux should also link the secondary rewinding. So this flux is not only linking the primary winding, so this is a flux linking the primary as well as secondary, both are linked by the same amount of flux.

So I can say by Faraday's law the induced EMF in the primary or secondary will be $\frac{d\phi}{dt}$, so I can write this as $\phi_m \omega \cos \omega t$, this is what is going to be the induced EMF. So if this is the induced EMF, I can write this as $\phi_m 2\pi f \cos \omega t$ where f is the frequency at which the entire current or the flux is oscillating, at what frequency it is oscillating.

Now, I can say that RMS value of induced EMF will be equal to $\frac{\phi_m 2\pi f}{\sqrt{2}}$ .The peak value of voltage is $\phi_m 2\pi f$. I am dividing that by $\sqrt{2}$ to get the RMS value. So this will give you essentially, if you calculate it, it will give you $4.44 f \phi_m$ this is what is going to be the voltage induced in a transformer per single turn.

If I talk about one turn the induced EMF $\frac{d\phi}{dt}$, if I talk about n turns which are connected in series the total voltage induced will be n times $\frac{d\phi}{dt}$, so I can say voltage induced in the primary will be equal to, E_T that is voltage induced per turn I can just say this is E_T multiplied by N_1 were N_1 is the number of turns in the primary, so I should be able to say E_T multiplied by N_2 will be the amount of voltage induced in the secondary.

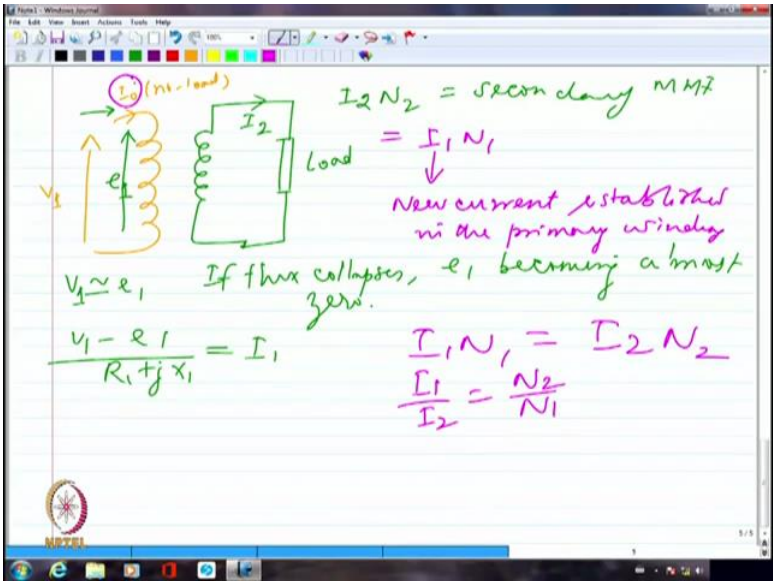
So from which I should be able to say $\frac{V_1}{V_2} = \frac{N_1}{N_2}$ which the basic voltage equation of a transformer is. So let us try to now look at what happens when a transformer is connected to a load. Let me first represent a transformer on no load condition here first, this is my core and I am showing as though primary is wound here and secondary is wound here.

I am applying a voltage of V_1 here, I am expecting that a voltage of V_2 I should get here. Currently the secondary side is left open and what is drawn by the primary here is only the current that is required to establish the flux, nothing more than that, if I want to establish a flux which is a nominal flux, I might require a very-very small amount of current because of the fact that the core is having high permeability.

So the current drawn by the transformer when the secondary is open circuited that current is known as the no load current, when there is no load connected in the transformer I may call this current I_0 as the no load current. This is the no load current of a transformer. And that will be really-really small because of the high permeability case of your core, ferromagnetic core.

Very clearly, if it is an air core transformer even the no load current will be very large, I hope you understand. Even when I do not have any load to establish the flux itself I will require quite a good amount of current or quite a good amount of MMF, so because of high reluctance of the air gap. So the core is made up of an, it is an air core transformer then I am going to require a very-very large current even under no load condition.

(Refer Slide Time: 42:05)



Now let us say I am going to connect the load. So this is my primary. And I have applied V_1 and what I was having is I naught this was under no load. Now I am going to connect the secondary to a load, so this is the load and let us say this is actually a drawing a current of I_2. When it is drawing a current of I_2. Essentially this current is also not going to keep quite it will definitely establish a flux.

And when it is establishing a flux, it is again alternating in nature because V_2 was alternating I_2 has to be alternating and I will have definitely an alternating flux established. If this flux becomes addictive to the original flux, the flux would eventually reach infinity, very-very large value. So obviously it will be opposing the original flux by Lenz's law the new flux that have been established by I_2 will oppose the original flux and this I_2 may be very-very large because it depends upon what the load is demanding.

If I am having a 400 volts transform and if I have only 4 ohm connected than 100 amperes will be flowing, so obviously am going to have a large value of current flowing as the load current. So this large current flowing through the winding will establish a flux which will be actually opposing the original flux. If it opposes the original flux, the original flux will be collapsing completely, it will be killed.

If the original flux is killed, the transformer action ceases to exist, there is no question of any transformer action because only because of the transformer action I had V_2, only because of V_2, I had I_2 and I_2 has now come up to generate one more flux which has killed the original flux, so entire thing has come to a standstill. So what has happened is, if the transformer action collapses, if I have got V_1 and originally I had got an induced EMF of e_1, V_1 was approximately equal to e_1 assuming that the resistance is hardly anything within the transformer winding.

So now if flux collapses I am going to have e_1 becoming almost 0. So if e_1 becomes almost 0 the current that will be gushing into the primary winding which will be $V_1 - e_1$ divided by whatever is the impedance of the primary winding gradual become really-really large obviously, if e_1 is diminishing I will have the voltage difference between V_1 and e_1 actually drawing a huge current which will be equal to $I_1 = \frac{V_1 - e_1}{R_1 + jX_1}$.

And this I_1 what I get as the primary current under load condition will bounce back to such a value that it will be exactly equal and opposite to that of the secondary ampere turns or secondary MMF I got because of the load being connected. The secondary ampere turn I_2N_2 is the secondary MMF.

“Professor-student conversation begins”

Student: What exactly is I_1?

Professor: I_1 is the current that has suddenly increased in the primary, I_0 was the original current which established the flux when the transformer was not loaded. I_1 is a new current that has suddenly come up in the primary because the flux was trying to collapse and e_1 has gone too very low values, so suddenly a new current has jumped up in your primary winding.

Now this I_1 will reach to such a level exactly that it would be equal and opposite to that of N_2 and I_2. So we come back to the original flux level itself as far as the core is concerned, so this is essentially tells me that this $I_2N_2 = I_1N_1$ where this is the new current established in the primary winding. Obviously I will still have this I_0 present, I am not saying that has gone away but this I not is miniscule as compared to the new value of I_1.

So I can just say by, as an engineering approximation I can neglect I_0, just forget about I_0 and I would say that $I_2N_2 = I_1N_1$, so I can say $\frac{I_1}{I_2} = \frac{N_2}{N_1}$, this ampere turn balance or MMF balance of all the windings of the transformer is true in any case of a transformer.

Whether we are looking at instrument transformer, distribution transformer, power transformer, impedance matching transformer, isolation transformer or auto transformer in every case this ampere turn balance is valid.

“Professor-student conversation ends”

See, we have got basically I_2N_2 is the secondary ampere turns which were trying to kill the primary or originally established flux. Now the primary is bouncing back, it is not allowing the flux to be killed, so it is essentially again trying to circulate a current which is corresponding to I_1, it is bouncing back and it will circulate such a current that it will nullify whatever is the new position it has faced from the secondary side, only then it will return back to the original condition itself.

So I have to have I_1N_1 as the MMF which will oppose I_2N_2 both have to be equal but opposite only then I will come back to the original state.