Electrical Machines
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Lecture 28
3 Phase Induction Machine
(Constructional Features and Principle of Operation)

In the last class, we started on 3-Phase Induction Motor and I was talking briefly about the 3-phase machines in general.

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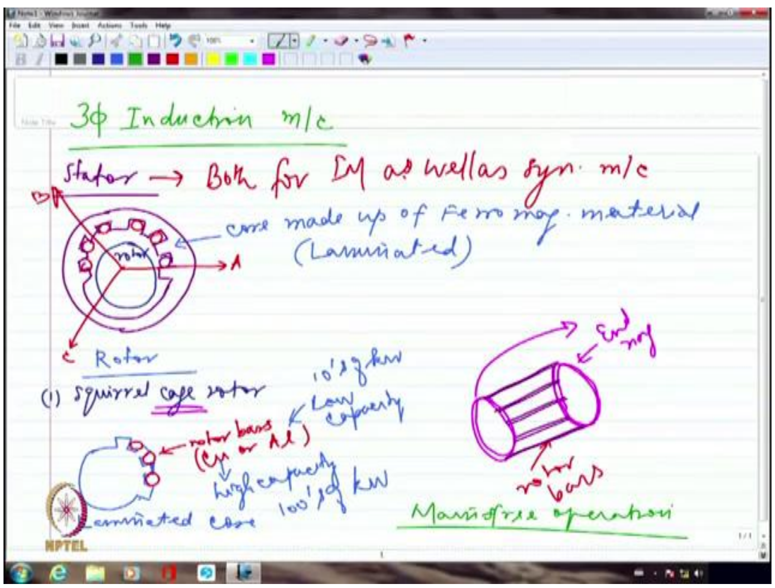

And we started off with the structure of stator and rotor. So, we said first that the stator, which is the outer member, will have basically the 3-phase winding housed inside that. So, we are going to have the stator somewhat like this with slots in the inner periphery like this. So, this is how the slots are going to be. I am just showing the slot somewhat like this and we are going to have the windings in the slot like this. So, we are going to have the windings inside the slot like this which will be actually a 3-phase winding, so, I will have R Y B specifically or A B C phases wound independently.

But the access will be in such a way that if A phase access is somewhere here, B phase access will be somewhere here, and C phase access will be somewhere here. All the 3 of them will be 120 degree shifted from each other that is how they are going to be wound. So, this is the structure of the stator winding for both induction as well as synchronous Machines. So, both are going to have very-very similar structure as far as the stator winding structure and the stator structure is concerned. The core is made up of Ferro-magnetic material and I am going to have them basically laminated. Unless it is laminated, I will have huge amount of Eddy current losses. To minimize the Eddy current losses, it will be made up of several laminations which will be stacked together with the help of resins of course they will be insulated from each other with varnish just like what we did in the case of transformer, same thing holds good. And as far as the rotor was concerned, we said there are two types of rotor and we talked mainly about the squirrel cage rotor in the last class.

The squirrel cage rotor will also be having the conductor embedded inside the rotor slot, the rotor slot will be in the outer periphery of the rotor. Because the rotor will be the internal member, I will have the rotor sitting here, this is the rotor. So, if I say the rotor is sitting inside I am going to have the rotor essentially having slots in the outer periphery somewhat like this, this is how it is going to be and the entire thing is completed like this. So, all over the outer periphery I will have teeth and in between the two teeth is the slot, basically.

And I will have this also laminated, this will also be laminated core because this will also have induced currents which are alternating in nature. So, obviously I cannot have them without lamination. So, this is also a laminated core because of which I may have conductors put in each of these slots like this. If it is a squirrel cage rotor, squirrel cage rotor in that case these conductors are going to be thick, so they are called as rotor bars. Rather than calling them as rotor conductor which is thin in nature these are rotor bars which are really-thick.

So, they can be made up of a either copper or aluminum, so this may be copper or aluminum. So, if it is a low kilo watt motor it may be aluminum because we do not care so much about the efficiency i^2r losses may be slightly higher as compare to copper. But if it a very high capacity motor the current carried will also be large, so I have to make sure that i^2r losses are not too high and I should not have very low efficiency, generally large capacity motors retain to design with a better performance.

Because every percentage efficiency matters in terms of the energy or the power that is being consumed, so that is the reason generally high capacity machines are paid at most attention in terms of design. So generally, for high capacity motors it may be copper. Whereas for low capacity motors it may be aluminum. So, if it is tens of kilo watts we may still call it as low capacity. If you are talking about of hundreds of kilo watt, we may call that as high capacity. We are not talking about fractional kilo watt at all, hardly ever 3-phase machines are used for fractional kilo watts.

Most of the times, we use single phase machines for fractional kilo watts capacity. So what we are going to have in this case is two end rings will be there, if I forget about the core I am going to have essentially the rotor bars being in the slot and at the ends they are going to be essentially short circuited with the help of something called end rings, so this is the end ring.

End ring will also be made up of aluminum or copper. So, they are essentially short circuited I cannot interfere with the structure of the rotor at all, I cannot vary the resistance, I cannot vary any of the parameters of the rotor, it is already set in stone. When I design, I would have designed it with a particular resistivity of the copper material or aluminum material that is done. I just cannot change it. So, this essentially looks like a cage and that is the reason why it has got the name cage rotor and it is like the lines on the squirrels back, so it is generally known as squirrel cage rotor.

Student: What is the difference between copper and aluminium conductors in terms of resistance and current carrying capacity?

Professor: Aluminium has basically higher resistivity if you compare the resistivity of the two materials copper will have better current density, higher current density it will be able to withstand. Aluminium will be able to withstand a lower current density only and similarly the resistivity of copper is smaller as compare to aluminium. So, if I want a very high capacity motor I should be looking for which can carry larger current even with a smaller cross section area, which is copper. And yet will have lover i^2r losses right. So that will tell on the efficiency that is the reason. So, this is going to be end ring, both these things are called end rings and these are rotor bars, these are the rotor bars.

So, this is the typical structure of a squirrel cage rotor which is really-rugged because they are essentially welded together. If I have the rotor conductors which are residing inside the slot the copper rings will be welded, so you do not have any moving contact in there. It will be continuously rotating, even when it is rotating you are not having any moving contact everything is a solid structure. So, you would hardly see much of wear and tear in the case of a squirrel cage rotor. So, once you put it in service you can forget about it for decades, there is no problem at all.

So, maintenance free operation is one of the special selling points of the squirrel cage induction motor. So, I do not have to maintain it at all unlike DC machines where I have to play around always with the commutator brush arrangement, make sure that the spring is holding it tight, touching the commutator and so on and so forth.

The other type of rotor which we are yet to discuss, the second type of rotor is wound rotor or slip ring rotor.

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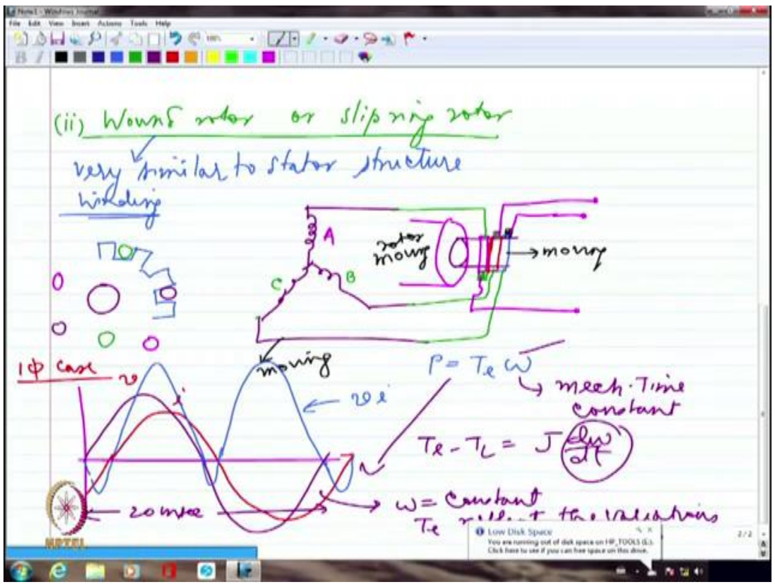

Student: Can we call rotor as armature?

Professor: There is no armature, we never call this as armature. By the way armature is the specific term used only in synchronous machine and DC machine. Here we do not call it as armature, we only call it as rotor. The rotor we will not have any control over the rotor current because it is only an induced current. How it gets induced we are going to see, the principle of operation. But the induced current is from the stator side it is like a transformer action.

So, if I have no control over the resistance that I can include or no control over an inductance that I can include in the circuit whatever is the inherent value of resistance and inductance that is what limits the current. So, there is no way I can play around with the values of the current. Whatever is induced EMF that divided by inherent impedance of the rotor will give me the current.

So, I do not have any control over the current as far as the rotor is concerned. I cannot even measure it. There is no access to the rotor currents as well as rotor induced EMF. So, it is very-very difficult to control the rotor current and the rotor induced EMF as well. We will look at the operation further which will probably clarify matters a little better for you.

Fine, as far as the wound rotor is concerned the structure is very similar to the stator structure. So, it is also going to have 3-phase winding and the winding structure is similar to the stator winding structure. So, I am going to have 3-phase windings basically sitting within your motor's rotor. So, if I have basically the rotor structure somewhat like this, I am going to have may be A phase at some point, maybe B phase at another point and C phase at the third point something like this like

I am going to have A, B and C phase windings spread around the outer periphery of the rotor. So, if I have 3-phase stator I have to have a 3-phase rotor. If I have wound the stator for 2 pole, 4 pole, 6 pole, 8 pole whatever configuration I have to have similar pole configuration for the stator as well as rotor. I cannot have different configurations for both. Whereas in cage, all the cage rotor bars will carry any current we do not know whether it is A phase current, whether it is B phase current, whether it is C phase current. They will happily depict from one phase to another or carry everything together.

There is nothing like it is going to be affiliated to a particular phase or particular pole. So, they can adjust themselves very nicely to 2 pole, 4 pole, 6 pole, 8 pole, 3-phase, 2 phase, single phase any configuration. So, when you have squirrel cage rotor it is absolutely flexible in terms of adjusting itself to any number of phases, any number of poles.

So, if I have a cage rotor which is working in 3-phase induction motor I can always fix it for a single phase induction motor as long as it is mechanically feasible and electrically feasible in terms of the current capacity. If the rotor current that is carried by the single phase machine can be withstood by the 3-phase machine as well, I can interchange the rotor, no problem at all it will completely adjust itself.

Whereas wound rotor, it is wound specifically for a particular number of phases and particular number of poles. So, I cannot interchange a 2 pole machine with 4 pole machine and vice-versa. So, flexibility is one of the major issues with wound rotor. I will not have flexibility, not that every other day we are going to change from 2 pole machine to 4 pole machine and interchange the rotors. But if there is a problem, may be the rotor has become non-functional, then I cannot simply fix up from another machine. So, if this is the way the conductors are arranged, I can show them if it is star connected, for example I can show the 3-phase conductors somewhat like this. The rotor ones in a wound rotor I can show the 3-phase windings may be connected in a star somewhat like this. Now I have not short circuited them. Please remember in squirrel cage it is inherently short circuited. Here they are not short circuited, so here slip rings come in handy.

I am going to have basically if here is my shaft imagine that this is my shaft, in here is my rotor, so rotor will be generally having a higher diameter. This is my rotor and the shaft is fixed or you know exactly it is going to be engaging clearly with whatever is my rotor structure. So, it has engaged with the rotor structure. Now I am going to have one slip ring that is like a ring which is put on the finger, similar to that you are going to have the slip ring sliding over your shaft but there will be insulation between the slip ring and the shaft itself because shaft is also made up of iron in all probability that is also a conductor.

So, I need have some kind of insulation between the ring and the shaft itself. So, I may have something like a rubber lining or whatever so that will essentially make sure that the two are insulated from each other. So, this is let us say for A phase, so may be this is A phase winding and I am going to connect this A phase directly to the A phase slip ring brazed or welded. So, when the slip rings rotate, the conductors also rotate which are within the rotor. So, I will not have the intertwining of the slip ring and the conductor.

Very similar to what we had in terms of split rings and the armature windings in the case of my DC machine. It is essentially the same, only thing is there are no copper mica kind of thing. It is a continuous ring which is made up of copper, so this is going to be one of the copper rings. The second copper ring again will be insulated from the first copper ring they will be of same thickness although I have not shown it that way, there should be insulation between these two. And I am going to have a third slip ring which is corresponding to the third phase.

So, I will connect basically from if I may call this as B and this as C, so B will be connected like this, C will be connected like this. So, I have 3 phase conductors being connected to 3 slip rings. The slip rings rotate, the rotor rotates, the conductor also rotate so there is no intertwining of the coil when the rotor is rotating, there is no problem. Now, we will have brushes which will make contact here. For example, for A phase I may have the brush here, for B phase I may have the brush here and for C phase I may have one more brush here.

So, I am going to have 3 brushes which are stationary. So, this is my shaft, on that there is slip ring and the brushes are just touching the slip ring so as they rotate the brushes going to be held stationary with the spring arrangement. This is moving right, this is also moving, this is the rotor and this is also moving because it is housed inside the rotor, the conductors are also moving, I cannot short circuit them internally.

So, what I am doing is, I am trying to bring it out and then I have put 3 slip rings, 3 brushes and from the brush now I can take the connection outside. So, these connections will come out and it will rest like armature connections in a DC motor. It will be outside of the machine, so whatever I want to do I can do. I can short circuit them directly, if I do not want to modify the resistance or inductance. If I want to modify the resistance or inductance, I can include some more resistance, include some more inductance whatever I want to do.

If I want to modify the characteristics, I can measure the voltages, I can measure the currents because I have brought out the all the terminals. So, I have complete access to the rotor currents. So, slip ring machine clearly has the advantage of having a better control over the rotor parameters as compared to the squirrel cage rotor machine. But squirrel cage rotor machine has the biggest advantage of being rugged. It cannot be broken so easily, it is maintenance free whereas slip ring rotor every now and then I have to make sure that the brush arrangement around with the slip ring is working fine, whether they are making proper contact.

It goes without saying that there will be sparking. If the contact is not proper there will be sparking. So very clearly even slip ring machine is not a good candidate for working in inflammable environment, because if there is any sparking, it is going to be hazards. So, this have its own advantages, that has their own set of advantages. Let us look at the comparison eventually when we look at the characteristic actually.

Now, first of all why do we have to go for 3-phase? Why cannot we just work with single phase? Single phase is much simpler, you can just have one winding whereas in 3 phase I have to have 3 sets of windings. This is only because when I actually look at a single phase machine, I may have voltage somewhat like this. Whereas my current if I assume it is slightly inductive, the current might probably lag behind the voltage by certain angle and if I try to look at the overall power, it is the product of V and I.

So, this is my voltage, this is my current, this is the case in single phase. If I look at the power, this current will continue like this because it is alternating in nature. So, I am going to have the power negative during this portion. I am going to have the power positive during this portion, again negative during this portion, positive during this portion and negative during this portion. So, this is the product $V \times I$. So power is not a constant, the power is continuously oscillating, and it is going into the negative direction as well. So, that is indirectly contributing to the reactive power, so it is going back and forth.

The power what flows from the supply in to the load or into the motor and then to the load that is essentially a positive power or real work done and what is going back and forth in the form of stored field energy probably in the inductance and then it is given back during sometime. So that is essentially the reactive power, so it does not go or contribute towards any useful work. So, this is one of the first points as for as the single phase and the 3-phase systems are concerned.

In single phase continuously you are going to have the oscillations in the power, you are not going to have a constant power, you are also going to have a good amount of reactive power, that reactive power is essentially not contributing to any useful work done and also because I have the power oscillating like this if I say, $P = T_e \omega$. Omega (ω) is generally governed by mechanical time constant because the inertia will always make sure that all the oscillations in the torque will not be reflected up on in omega. Because the torque oscillations basically are reflecting on the $\frac{d\omega}{dt}$ which is governed by this equation, we have written this several times now. So, $J\frac{d\omega}{dt}$ indicates that J is going to act like a smoothening factor then I am looking at the variations in the speed with respect to the torque variation. So, if I say that the speed is fairly constant especially in a 20 milli-second cycle. I am looking at just 20 milli-second.

During 20 milli-second cycle I am going to see the speed fairly as constant because the mechanical time constants are generally of the order of seconds, so if that is the constant very clearly omega is a constant, so T has to essentially reflect the variations in P, in power. If the power is oscillating very clearly from this equation if omega is a constant T_e has to necessarily reflect the variations in the power, there is no other option.

So, if the torque is continuously oscillatory whether I like it or not there will be a very little small changes in omega, $\frac{d\omega}{dt}$ will not be 0 at any point in time in a single phase machine. In a single phase machine as a rule you will see that the speed will never be a continuous constant like if it is 1500 RPM it may go between 1490 and 1510, it will keep on oscillating. So, if I want a very-very precise control mechanism for the speed, where I cannot tolerate any oscillations in the speed, even small oscillations in the speed, I cannot go for single phase machine; and another thing is whenever I am going to see there is oscillation in the speed there will be more vibrations, there will be more noise.

So, if I am talking about a 1 kW machine which is a single phase machine the noise is still tolerable. If I am talking about a 500 kW machine or 850 kW machine like what we use in traction it will be impossible to withstand that kind of a noise. Then there is an oscillation, so single phase machine as a rule are not used beyond about 3 to 5 kW, the maximum we use single phase machine is only for 3 to 5 kW. Let us now go over to the principle of operation of the 3-phase induction machine.

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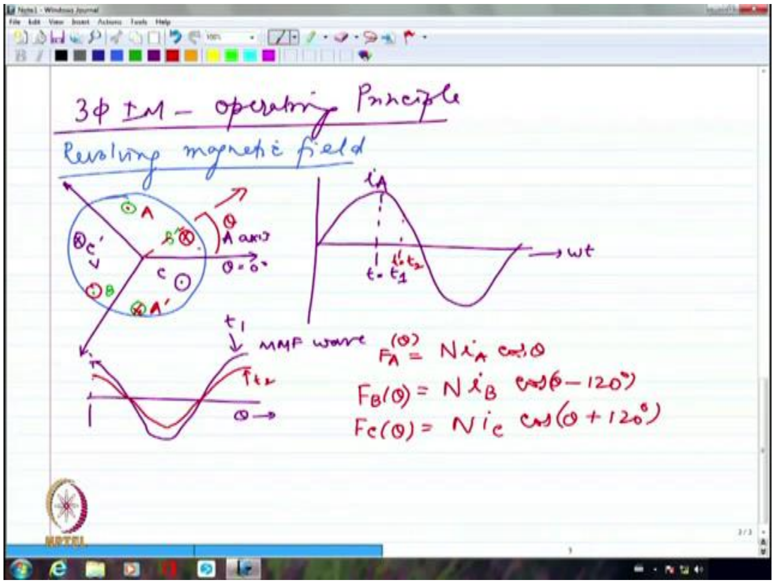

For that we will have to understand something called revolving magnetic field. This is the brilliant discovery made by Tesla and this essentially states that when you are going to give a 3-phase time shifted current to a 3-phase space distributed winding, you are going to get a revolving magnetic field. Let us first of all examine really how this is produced so we are going to look at this graphically first as to why a 3-phase time shifted current given to a 3-phase space shifted winding why it would produce a revolving a magnetic field.

So, let us try to look at the revolving magnetic field theory. Let us say I am representing the stator with 3-phase not distributed winding because it is difficult for me to draw, so I am going to just draw it with concentrated winding. So, let me call this as A and A' and I am going to call this as B and I am going to call this as B'. And the third one I am going to show C and this is C'. These are the 3 Phase windings which I am not showing completely only the ends I am showing basically in the form of a cross section.

Now, A phase axis if I assume that I am having the dot like this, the A phase magnetic field axis will be this way, so I am just showing the A phase axis somewhat like this and B axis will be 120 degrees shifted, C axis will be 120 degrees shifted further that is it. So, I have these 3 as the magnetic field axis of A, B and C phases, respectively. Now, if am having only 1 phase winding first of all let me examine how the magnetic field is going to look like, I am just going to look at only one of the phases at a time.

So, let us say I am pumping a A phase current in A phase winding which is may be $I_m \cos \omega t$ whatever does not matter at a frequency of 50 Hertz. Now, if I am actually pumping in this current, so let me call this as I_a with respect to ωt. If I assume that I am pumping in the current through this and the current is returning through this whatever, I am going to get a magnetic field in this direction, what do I do mean by that? I am going to have probably the north pole here and south pole here and so on that is it, that is what I am going to get.

So in which case I should say the strength of the magnetic field depends up on what is the strength of the current because MMF is going to decide how much is the strength of the magnetic field, assuming that the reluctance does not change much, so in which case I am going to have essentially may be a sinusoidal field in such a way that if I say that this is $\theta = 0°$, I am going to get probably the peak located somewhere here and then it is going essentially to look like this.

This is essentially θ, so this is going to be the MMF wave, this is going to be the MMF wave with respect to θ, please understand I am drawing the MMF wave with respect to the space, what am drawing of the current is with respect to time. So, I am talking about the time may be this is corresponding to let us say time $t = t_1$ may be this is t_1. So, this is the MMF wave at time $t = t_1$. If I say I am looking at time $t = t_2$, so I am talking about time $t=t_2$.

At time $t=t_2$ please note the overall current itself has come down right, at time $t=t_2$ the current has come down because the current has come down, the peak of MMF wave will also come down in terms of its magnitude, so I am going to get probably this as the MMF wave at time $t=t_2$. What am trying to get at is, if I look at only one phase at a time I get a standing MMF wave or standing flux wave, that standing wave is pulsating in nature it is not shifting, it is not travelling it is standing.

So, I am going to have basically a standing wave produced whenever I have a single phase excitation. It will not create a traveling or revolving field. So what I am looking at when I am have the 3-phase excitation is at any point I am going to look at the resultant of all these 3 phases. If I say this is θ, at an angle θ from A phase axis I am going to look at what is the resultant of all the 3-phase MMFs, that is what I am trying to look at now.

So, I hope you guys have understood what is the pulsating MMF wave or standing MMF wave from which we are going to derive basically what is the resultant MMF or resultant field that we are going to get from all the 3-phases right. So, if I say what is the MMF of A Phase (F_A) at any point in time? I should say it should be $N \times i_a$ and with respect to θ, I am trying to see. So, I should write clearly $\cos\theta$ because I am trying to find out the component along θ.

$$F_A = N i_A \cos\theta$$

Similarly, if I try to look at what is F_B of θ, it will be $F_B(\theta) = N i_B \cos(\theta - 120)$

N is the number of turns in any one of the phases, I am assuming all the 3-phase windings are balanced that means the number of turns is the same in all the 3-phase.

In the other case $F_C(\theta) = N i_C \cos(\theta + 120)$.

Now what I have to calculate as the overall MMF will be the summation of all these 3 MMFs, before doing this analytically let me try to look at the whole thing graphically so that you also get a better understanding physically of this. So, if I have let us say this is my sinusoidal wave as far as A phase is concerned.

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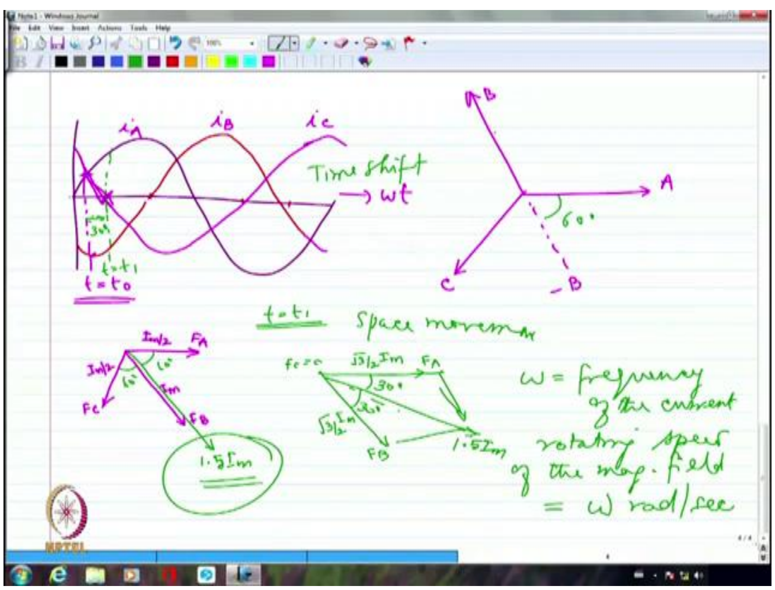

I am going to draw the other two, so I am just drawing the 60 degree intervals then I am drawing B phase and I am drawing C phase. I am sorry am not drawing them equally well they should all be balanced currents obviously. So, this is i_A, this is i_B and this is i_C with respect to ωt, 3-phase currents I have pumped in to the 3-phase distributed winding. Let me look at each of the time instants, for example let me try to look at the time instant corresponding to $t=t_0$ probably.

What is going to be the summation of all the 3 MMF waves? After all N is a scalar so I do not even have to include N that is fine. I can look at basically what is the summation of i_A, i_B, i_C along with the space because it is the space distributed winding. Let me again redraw the directions of what we wrote as A phase is here B phase is somewhere here and C phase is somewhere here this is what, this is how we drew the directions.

So, let us try to see what are all the directions at this instance? So at time $t = t_0$ I should say A phase is having only this is 30 degree approximately, so if it is 30 degrees I am going to have essentially half or whatever is the peak I have not drawn it very well, but it is half of the peak because $\sin 30 = 0.5$ so I am going to have basically i_A is going to be whatever is the peak so this will be $I_m/2$, so this will correspond to F_A basically.

And if I look at what is the value corresponding to i_C, ic is also at similar juncture the zero crossing is here for i_C and this is also about 30 degrees away from the zero crossing. So that will also be $I_m/2$ and that will be in the positive direction. So, I should say my i_C is here, so i_C is probably here again this will also be $I_m/2$ and this is F_C. Now this is i_B, i_B is at it is peak but it is in the negative direction. So, I am going to have actually i_B similar to this. But in the opposite direction, this is going to be -B right. So, I have to draw -B along this which will be I_m itself, so this will be F_B.

Now if I add all the 3 together, I will have the resultant by parallelogram law of addition somewhat like this which is going to be like this, so this is about 30 degrees or 60 degrees? This will be 60 I suppose, this will also be 60 totally this is 120. between A and C this is 120. So, it is going to be $\frac{I_m}{2}\cos 60 + \frac{I_m}{2}\cos 60 + I_m = 1.5 I_m$. So, I am going to have this to be 1.5 times I_m. This is the resultant at time $t = t_0$, if I try to look at another time interval may be this zero crossing let me take, this $t = t_1$.

So, let me try to draw this at $t = t_1$. So at time $t = t_1$ I am having $i_C = 0$, so I do not have to draw anything for F_C, $F_C=0$. Now I am going to have i_B which is actually about from the peak it has moved by about 30 degrees. So, 90+30=120 so it will be equivalent to sin120 but in the negative direction. And if I try to look at what is the value of A at this point, that will also be equivalent to $\sin 60 = \frac{\sqrt{3}}{2}$. So, I am going to say rather i_A will correspond to something like this which is actually I am sorry (this) not this much of length, so it will be $\frac{\sqrt{3}}{2} I_m$.

This what is F_A, and if I try to draw what is F_B, again it is along the negative direction please note that this is the negative current, so I am going to have again F_B somewhat like this which will also be $\frac{\sqrt{3}}{2} I_m$ and this is what is F_B. Now I have to add these two together. So, when I add these two together, I will have it somewhere in the middle right this is how it will be, so I am going to have probably this as the resultant. So, the resultant will be $\frac{\sqrt{3}}{2} I_m \cos 30$, this is 30 degrees clearly, this is also 30 because this is 60, so it will come in the middle.

So, I am going to have 30 degrees as the phase shift, so $\frac{\sqrt{3}}{2} I_m \cos 30 + \frac{\sqrt{3}}{2} I_m \cos 30 = 1.5 I_m$. You can keep on doing this for every 30 degree interval you will see that between t_0 and t_1 the phase shift is 30 degrees. Between this vector and this vector, this was 60 degrees this was now moved by 30 degrees that means every time the time shift take place by 30 degrees in the current wave, there is 30 degrees shift or movement in the MMF wave or the flux wave as per as the space is concerned.

So, this is space movement, whereas this is time shift. So, I should say basically that if I supply 3 phase time distributed current to a 3-phase space distributed winding. I see that I am going to get an MMF wave which will keep on rotating at the same speed as that of the oscillatory speed of the sinusoidal wave which is the current wave. So, I can say if omega is the frequency of the current then the rotating speed is going to be of the magnetic field that is going to be omega radiance per second in space.

Both of them are going to be exactly one and the same right, let us try to see whether we get a similar result even when we are doing it analytically. This is essentially a graphical proof, we are trying to look at the graphical proof as to if we take the component of the MMF wave along a direction θ, are we trying to get ultimately a revolving magnetic field at all. Please note the revolving magnetic field is having a constant magnitude that is $1.5I_m$ multiplied by the number of turns ofcourse I have neglected that here, that is a scalar multiplication.

So, what we did in the previous page, we had already written that these are going to be the MMF expressions corresponding to each of the phases.

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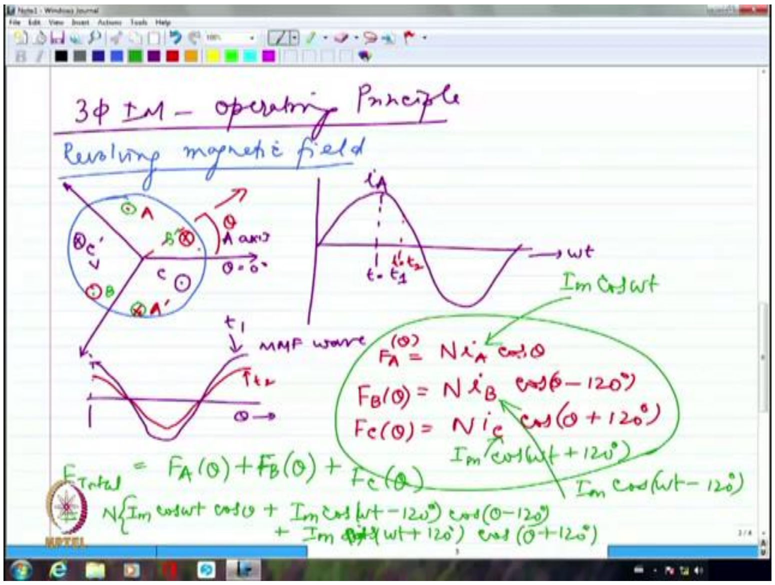

That is A phase, B phase and the C phase and if I want the overall MMF to be calculated I basically I have to write $F_{Total} = F_A(\theta) + F_B(\theta) + F_C(\theta)$, this is what I have to add and what is i_A? i_A is A phase current which is also sinusoidally or cosinusoidally oscillating. So, I should be able to write $i_A = I_m \cos \omega t$, I can write $i_B = I_m \cos(\omega t - 120)$ and this will be $i_C = I_m \cos(\omega t + 120)$. So, let us try to write,

$$
\begin{aligned}
F(\theta)_{Total} &= F_A(\theta) + F_B(\theta) + F_C(\theta) \\
&= N\left\{I_m \cos \omega t \cos\theta + I_m \cos(\omega t - 120)\cos(\theta - 120) + I_m \cos(\omega t + 120)\cos(\theta + 120)\right\} \\
&= N\, I_m\{\cos(\omega t + \theta) + \cos(\omega t - \theta) \\
&\qquad \cos(\omega t + \theta - 240) + \cos(\omega t - \theta) \\
&\qquad \cos(\omega t + \theta + 240) + \cos(\omega t - \theta)\}
\end{aligned}
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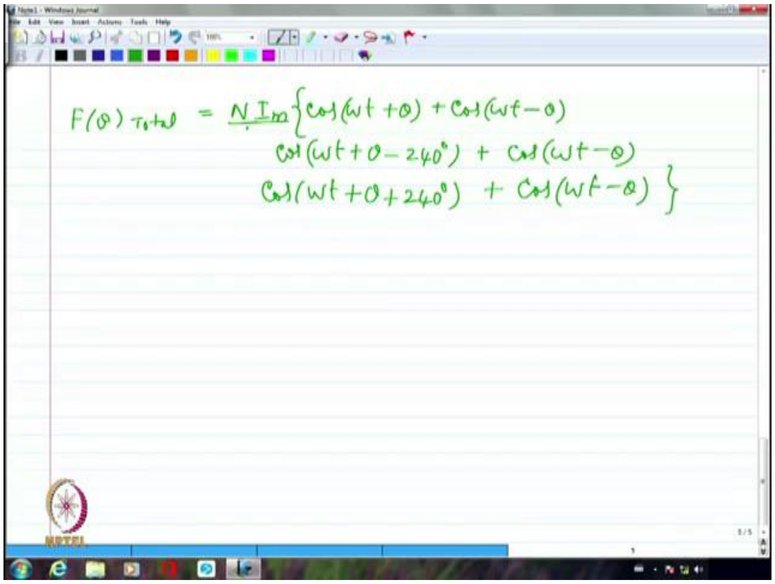

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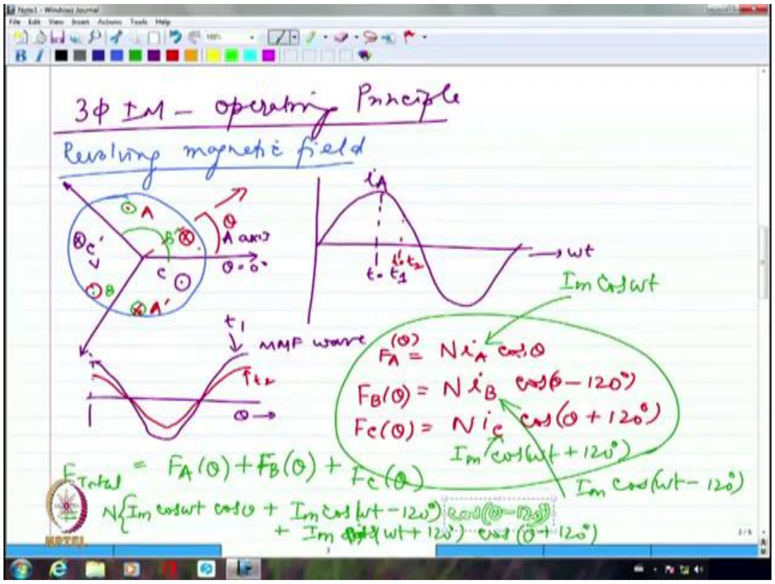

If you may recall please note B phase current is lagging behind the A phase current by 120 degrees this is lagging behind.

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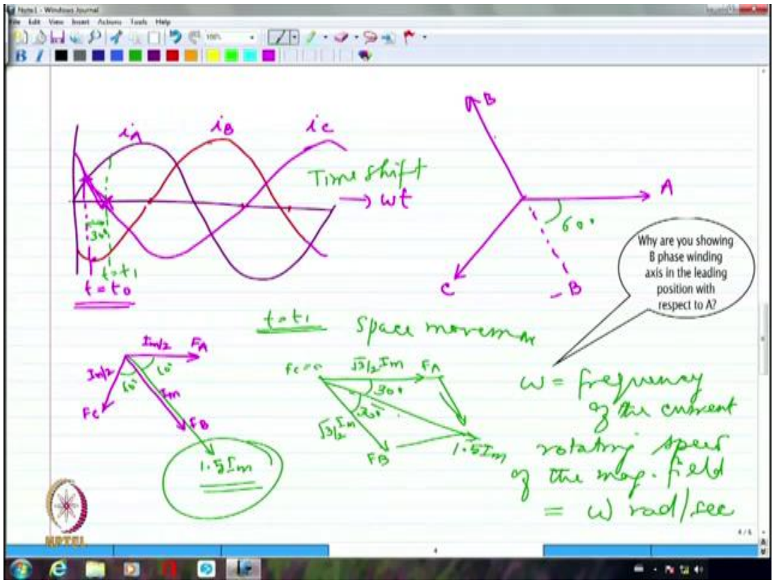

Student: Why are you showing B phase winding axis in the leading position with respect to A?

Professor: Here space wise we are showing as though the winding what we have wound for B phase is leading. There is a specific reason. Normally when we are looking at a synchronous machine, I told you that the winding structures are extremely similar for induction and synchronous machine.

If I are looking at a synchronous machine, I have the A phase, B phase and the C phase windings what I had drawn is in such a way that first comes A phase, then comes C phase, then comes B phase that is the way I have drawn it. But in a synchronous machine what happens is the stator has the 3-phase winding which is known as the armature of the synchronous machine. The rotor has basically the magnet.

The rotor is going to have a north pole and south pole, so what happens is the north pole and south pole of the rotor is being rotated with the help of a turbine. So, when it is rotated in anti-clock wise direction please think about it. First it will meet at A, next it will meet with B, next it will meet with C. So, the EMF induced will be such that A phase gets the $\theta = 0$ corresponding EMF, the second one gets then after 120 degrees away from the first EMF that is induced in A phase and C phase gets another uh MMF or EMF which is corresponding to another 120 degrees away from the B phase, that is why it looks as though this is inverted.

Are you getting my point? We always look at the winding with respect to the fact that it is like a generator. For generator operation if the magnet is being rotated and our conventional direction is anti-clock wise direction of rotation. So, when we look at it, we want to always arrange the windings in such a way that A phase comes first, then comes the B phase, then comes C phase, so you would normally see that it looks as though we have kind of goofed up in the notation, but we have not. Basically, we are looking at the whole thing in generator point of view that is what it is.

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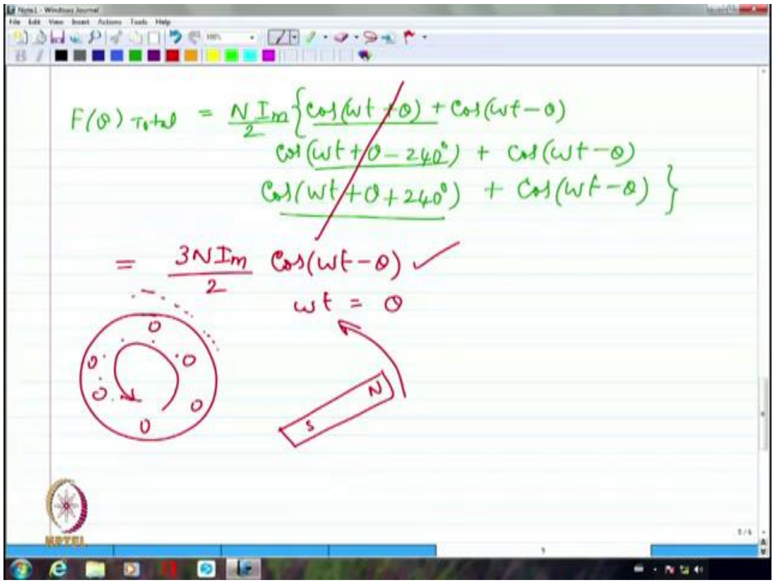

So, if we are looking at it now this is total MMF, clearly this plus this plus this is like a 3-phase current instantaneous value if I add $i_A + i_B + i_C = 0$. So, this component is going to vanish, this will not give me any resultant value because it is like $i_A + i_B + i_C = 0$, where $i_A = \cos\theta$ or $= \cos \omega t$, $i_B = \cos(\omega t - 120)$ or I can write it as $\cos(\omega t + 240)$.

Similarly, I can write it as $i_C = \cos(\omega t + 120)$ which will be equivalent to $\cos(\omega t - 240)$. So clearly this is like a normal 3 -phase system where the instantaneous values add up to 0 right, so this will not contribute to any thing where as this is going to contribute to $\frac{3N I_m}{2}\cos(\omega t - \theta)$. So, this particular expression actually tells me that what I get as the MMF wave or the flux wave in the air gap that is if I look at stator which is having the winding along its inner periphery like this.

I am going to have basically the magnetic field produced here, in the air gap, in the inner surface of the stator. So that is going to be a co-sinusoidal wave probably or a sinusoidal wave where the peak is continuously getting shifted, so I will have continuously the peak probably lying here, lying here, lying here, lying here and so on. Where I am going to have $\omega t = \theta$ at any point in time, that is $\omega t - \theta = 0$ that corresponds to the point at which the peak is located.

So, I am going to have basically it is as though I am going to have a north pole and south pole and I rotate it physically at the same speed as that of omega. I am not having really physically any magnet here what I have done is only to have a 3-phase time distributed current I have given that is a space distributed winding that has created the effect of actually having a magnet physically and rotating it at a speed which is known as synchronous speed.

We call this speed omega as the synchronous speed. So, the synchronous speed is fully determent by the frequency of the current that I am injecting to my 3-phase machine and it has to be a balanced current. So that is why I say that this is a fantastic discovery by Tesla and as far as I remember there is hardly any design difference between what Tesla designed in 1879 or 1880 and today's induction machines, very-very limited difference in the design. So, 3-phase became extremely popular only after this particular discovery was made and Tesla made the first induction machine which actually became the work horse of for all the industries.