Course Name: Design of Electric Motors

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Title: Design of Electromagnetic Systems

In the last lecture, we have discussed about the force equations in a magnetic circuits. In this lecture, we will discuss the design of electromagnetics. So how to design the electromagnet or how to design the any electro mechanical system or electromagnetic system? Now the design is not a specified procedure. Design is an iterative procedure, where we have to work towards with respect to one particular objective. Let us say we want to design a system, consider a system. I want to design this system to meet higher efficiency for a given power rating and I want to produce this much of torque.

So, the design has to consider these three requirements and after doing the final design, so we have to meet the same requirements. In the design, there is no specific solution or there is no specific approach because of the multiple constraints and multiple variables present in the system. For designing the electromagnet, we have some variables we have considered as assumptions and some variables we have to consider as a defined values and we have to make the iterative process to meet the required objective. Now in this lecture, we will see how to design the electromagnet.

Here we can see one electromagnet designed in the design of electric motors course, where the electromagnet is this one, E type electromagnet is designed and other side we have the I type bar. So, this is the I type bar. It is get attracted towards the electromagnet once the coil is excited. So, how to design this kind of system or electromagnet for door locking system or for lifting the weights or for electrical electromagnet for relay and other applications? The design procedure is same, depends upon the objective, we have to do the iterative process. So, first I will start the design of this kind of electromagnets.

Consider the electromagnet. In our analysis, we have considered a C type core which is stationary and I type core which is moving and with respect to the depth, this is the depth of the core C type core like side view of this electromagnet. If you will define the variables like what are the dimensions, this width is nothing but ew and this width also ew and back iron height is nothing but bw and height of the window is hw from this point to this point. This is the hw and air gap length is g. Earlier, we have considered lg by 2.

lg by 2 is nothing but g. I am considering with a variable and this height is nothing but again ew with respect to the x axis, the dimensions are this one is ew and this is the width of the window that is ww and again it is ew and C type core of a permeability mu and area of cross section Ac and the area of cross section with respect to this core also Ac and depth is nothing but dw. Depth of the C type core as well as I type core is dw. Now, we will consider the coil which is placed on a C type core. This is the coil which is present in the inner layer and on top of that, we have n number of conductors like this manner.

Similarly, at the top, so this is the complete coil area where n number of wires we are making as a coil and the other end is this one and it has a number of turns n and excited with current I. So, we can see here, this is the assume that this is a core. On top of that, we are making a winding. I am considering the copper wire and we are making the winding on the core. We can see here, so this is the inner layer.

On top of that, one more layer will do like that n number of layers I have represented here. Inner layer is this one. This is the inner layer and second layer third, fourth, fifth, sixth like that n number of layers are there in the circuit to make the coil. So, this is the circuit what we are going to design. So, first step I will consider, we are seeing this copper wire.

How to select this copper wire? First step I am discussing with respect to the copper wire. How to select the copper wire SWG? The current density with respect to the copper wire J equals to RMS current per unit area that is cross sectional area of the conductor. So, AC equals to I RMS divided by current density. It is in mm square, but current density in ampere per meter square or mm square. So, if we know the area of the cross section of a copper wire, then based on this AC, we can select the SWG of a wire based on the data sheets.

If let us take 1 mm square is the copper area, conductor area or 0.1 mm square is the conductor area. So, with respect to this conductor area, we can select the SWG wire of a data SWG wire data. Now, the current density for copper is 3 into 10 power 6 ampere per meter square for copper. Similarly, for aluminum and different materials has different current densities.

Next step, we will see the MMF. Apply the amperes law and MMF is equals to HG like intensity with respect to the air gap and length of the air gap plus HC into LC that is MMF with respect to the core is equals to n into I. The third equation with respect to the

Faraday's law, we have derived the inductance value. L equals to what? N square by reluctance or n into phi by I. Any one equation we can find.

So, from this equation 2 and this is equation 2 and this is equation 3. If you want to find the reluctance, we can find it or inductance is given and reluctance also known. Then, we want to find the number of turns. We can calculate it based on equation 2 and equation 3. So, from equation 3, n equals to square root of inductance into reluctance or inductance by permeance square root.

Next step, we will see the magnet like this is the electromagnet. This is the I core and this is the E type core in this example or C type core. So, how to select the area product? We will see that one. Consider the window area available for winding is AW. So, this is a C type core means available window area is this much.

This is the available window area. So, this height is HW and width is WW. So, available window area is nothing but HW into WW mm square. This much area is available for designing this type of electromagnets, but if you will see this electromagnet here, whatever the electromagnet is designed in the laboratory as a part of course, here two areas are there. This is first area and this is the second area.

So, we can add these two areas to find the actual available window area for windings. So, we can see here like this two segments are there. So, the available window area for windings are these two. Now, we will see how many number of turns we can place to make the winding. So, consider n number of turns are there with an area of cross section AC.

Then how to fit this number of turns into the available area AW. So, AW I am considering into some window factor should be equals to n into AC. Here this is KW is nothing but window utilization factor. Generally, this value 0.5 to 0.75 depends upon the designer and expertise skills. AW into KW is equals to n into AC. This is equation 4. From the inductance equation, L equals to what? n phi by I. So, n into flux I am replacing with magnetic fields over an area.

A is nothing but cross sectional area of the core and maximum flux density is Bm and n is the number of turns divided by I and here I is nothing but maximum current. From here, if you will bring AC at one side and remaining terms, if you will push that side, L into I, L into Im divided by n into Bm. So, here if you want to relate the maximum current and RMS current, crust factor is nothing but KC equals to Im by I RMS. So, from the crust factor, we can derive the AC value. AC equals to L into Im divided by KC crust factor into n into maximum flux density.

So, this is equation 5. So, from equation 4 and equation 5, if you will get the area product, based on the area product, we will select the cores like this. This is the I core.

What is the area product? This is the E type core. What is the area product? So, for magnetic core selection, we have to find the area product AC into Aw equals to from equation 4, we can get Aw that is n into AC divided by Kw into AC is nothing but L into Im divided by KC into n into maximum flux density. Here AC is nothing but what from the equation 1.

If you will see the equation 1, this is the equation 1, right? AC equals to what? I RMS per current density. So, n into I RMS divided by current density into Kw and AC term L into Im divided by KC and Bm, all terms will follow and n will cancel each other. L Im square divided by KC Kw into current density into maximum flux density. So, this is the final area product. So, if you will replace L into Im square as a energy stored in the magnetic circuit, 2 into EL because half Li square, EL is nothing but that is why 2 into EL, I am considering directly KC Kw into current density and maximum flux density.

So, once we know the area product, based on this area product, we will select the different type of cores, whether it is C type core or E type core or any type of core, depends upon the data sheets. We will find the area product first and once we know the area product, then we can do the remaining analysis. So, for the for the required area product, we have selected so and so core, whether this core is able to accommodate the pre-designed number of turns or not. So, in order to check that window area factor, so the new window area into window utilization factor should be greater than N into AC.

This is the window check equation. For the selected core, let us assume that this core we are selecting. So, this core has a window area Aw1. So, this Aw1 into this Kw should be greater than the number of turns into area of cross section. The next step, we will find the reluctance. Reluctance is with respect to the core and with respect to the air gap.

So, with respect to the core, it is nothing but LC by mu naught mu R into AC with respect to the air gap LG divided by permeability of the free space into cross sectional area of the air gap. Now, as of now, we have seen the magnetic circuit with respect to the area product like how to select the magnetic core and inductances and number of turns and how to select the gauge. Now, let us see here the electromagnet. Here we are seeing this coil. So, what is the coil resistance? How to find this resistance? Resistance generally R equals to rho L by A area of cross section of the conductor.

So, here LC or L coil and A coil or coil I will replace it because LC term we have used it for length mean length of a core like that. So, here rho L coil divided by area of the coil. So, first we have to find the length of a coil and then area of a coil and then based upon the resistivity value, we can find the resistance of a coil. So, first we will see the length of a coil. How to find the length of a coil? Let us take the I type core on top of that I am making the winding for example.

So, this is layer 1. If we will see from this direction, the length of a single turn is nothing but perimeter of this I bar. This is I bar this perimeter plus the 8 times the diameter of the coil. Will you agree? So, if you will see the diagram. So, this is the core having a cross sectional area or perimeter of this thing and we are making the coil like this manner.

This is single turn. If you want to find this length of a single turn coil, if you will divide like this, this length is nothing but width of this I core and height of this I core at the y axis side. So, width will be x axis side and height will be y axis side. That is what I am representing here with respect to our analysis. This is B w and this is D w and diameter of a wire and here also diameter of a wire and this side diameter and this side diameter. So, the total perimeter of a coil or a single turn is equals to what? First length of a single turn we will calculate.

One is equals to 2 into D plus B w plus D plus D plus D w plus D. So, this is the perimeter of a single turn, the red color one. This is single turn in the inner layer. So, for simplification, I am representing this term with x and this term with y. So, the perimeter or length of a single turn is nothing but 2 into x plus y.

Now, what we have calculated length of a single turn? We can see here I core length of a single turn. We have calculated such turns. We have n number of turns in the inner layer. We can see here n number of turns are there in one layer. So, first we will calculate this length of a coil with respect to this n turns and then on top of that n number of coils we are making on top of that second layer, third layer up to n layer.

We can see here in this one. So, here on top of one another n number of layers are arranged in this manner from top to bottom. So, first we will calculate the length with respect to the inner layer. That is equals to 2 into x plus y into k 1, where k 1 is nothing but conductors or turns present in the inner layer. That is equals to window width into packing factor divided by diameter of a wire, where p f is a packing factor.

Generally, it will be 0.8 to 0.9. Once we know the k 1 value that is number of turns in an inner layer, how many number of turns are there in an inner layer? We can see here n number of layers are there. That is k 1 number of layers like turns are there in an inner layer. So, the equation with respect to find the length of a inner layer of a coil equals to 2 into x plus y into k 1. Now, we want to find the total length of a coil, where n number of layers are stacked one another. In this, we can observe initially one layer is there at the inner side and on top of that n layers are there.

So, we will find the coil length for this n number of layers. So, same thing I have presented in this image. With respect to the inner layer, we have calculated now with respect to the layer 2, layer 3, therefore up to the n layers, we will calculate the resistance value. With respect to the n layers, the resistance value is nothing but like length of a wire, total wire is equals to 2 into x plus y into k 1. This is with respect to layer 1 plus 2 into x plus y plus 4 d into k 1.

This is with respect to layer 2 plus 2 into x plus y plus 8 d into k 1. This is layer 3 and so on for nth layer 2 into x plus y plus 4 into n minus 1 into d into k 1. So, this is the total length of a wire. Why I am considering here 4 d for second layer means, if I will draw a second layer here in the same image, this is the second layer. From here to here, one more d is adding, from here to here, one more d, from here to here, another d and from here to here, one more d.

Like that total 8 d is added to the circuit. So, that is why I am adding layer 1 plus 4 d into 2. Here we can see that 2 into 4 d is nothing but 8 d. So, here total we are adding 8 d to the first layer. So, this is second layer equation. With respect to the first layer equation, this one we are adding extra 8 d.

The extra length is coming here and here, here, here. So, 4 plus 4, 8 d, so that 8 d we are adding in layer 2. So, the generalized equation to find the length of a coil is nothing but this one. The final equation, we can see length of a wire is equals to 2 into k 1 into n into x plus y plus 4 into n minus 1 into d. So, this is the length of a coil equation. So, earlier equation 6, this is equation 7, equation 8 and then, this is equation 9.

So, here n is nothing but number of layers. That is equals to h w height of the window into window utilization factor into packing factor divided by diameter of the conductor. Here we know the height of the conductor, we know the window utilization factor, we know the packing factor and diameter also we know. Once we know the cross sectional area of the conductor, then we can find the diameter of the conductor also. length of a coil or length of a wire, we can calculate from this expression. Here diameter of a wire is equals to pi r square, generally for a circular conductor.

This is area, area is equals to pi r square for a circular conductor. So, r equals to square root of ac divided by pi, then diameter equals to 2 into radius that will result in 2 into square root of ac divided by pi. This is in mm, ac in mm square, length of a wire the units are mm or meters. Once we know the length, then we will find the resistance of a coil.

So, r coil is equals to rho L by ac. From this expression, we can find the resistance of a coil where rho is the resistivity of a copper that is equals to for copper material, it is 1.72 into 10 power minus 8 ohm meter and for aluminum, it is 2.6 into 10 power minus 8 ohm meter. This is for copper above 1 and below 1 is for aluminum. Once we know the resistivity and length of a coil and area of conductor, then the calculation of resistance is easy.

After that, how to find the volume of a coil and weight of a coil? Volume of a coil is equals to area into length. Area of a wire is nothing but ac, length of a wire is nothing but L wire. So, if we will multiply these two things from the earlier equations, so this is equation 9 and diameter equation 10 and this is equation 11. This is equation 1 and this is equation 9. So, if we will multiply those two things, then we can find the volume of a coil in mm cube.

Now, we will find the weight of a coil. How to find the weight of a coil or weight of a copper is nothing but W coil or wire is equals to density into volume. So, density for different materials will be different. For example, for copper density will be 8900 kg per meter cube and volume we know from the equation 12. From equation 12 and the density value, then we can find the weight of a coil that is equation 13. Now, how to find the weight of a core, magnetic core? It is same equation.

Weight of a core is nothing but density of a core into volume of the core. Once we know the density and volume, then the estimation of weight of a core is easy. For iron core, density will be 7.65 gram per centimeter cube.

Similarly, for different materials, different densities we can see. Based on the density values, we can find the weight of a core. Now, what is the voltage applied to the coil or voltage required to excite the coil? V equals to I into R, where R is series resistance in the electrical circuit. Finally, as of now, the magnetic circuit design and coil design are discussed. Now, we will discuss about the force equations. Force is equals to partial derivative of field energy with respect to the displacement over a flux linkages constant or field energy is done and co-energy is nothing but dou field co-energy partial derivative with respect to the displacement, where I is constant.

Based on this expression, we can find the force acting at the air gap. If you want to replace the displacement with the air gap, we can replace this thing with air gap. For a linear system, force equals to half I square dl by dg. Here g is nothing but air gap length. The final force equation from the earlier lectures is b square by 2 mu naught into 2 ag.

Here lg equals to 2 into g. Based on this thing, this equation is derived. This equation number is 17. Now, what is the force required to lift the mass or to attract the I bar? If the spring constant is there to overcome the spring force, how much force we have to generate with respect to the electrical circuit is nothing but F equals to m into a, if there is no spring. Just we want to lift the mass of m with acceleration a. Fm d square x by dt square is nothing but F required force to lift this mass at acceleration of d square x by dt square.

Then we require this much force Fm. If spring constant or spring is involved with respect to the moving object, then required force should be greater than mass into acceleration plus spring constant into displacement or distance either g or x. I am considering here g ma plus k into g. We have discussed the electrical circuit design with respect to the coil, how many number of turns are required and what is the SWG and resistance, length, volume, weight, everything and with respect to the magnetic circuit also, how to select the magnetic core and length, area products and inductance and reluctance, all those things we have discussed. At the end, we have to find the efficiency of the system.

Efficiency is nothing but input minus losses divided by input. This is the generalized equation for the efficiency. Here the losses involved in the system are copper loss with respect to the series resistance or at the electrical circuit and magnetic circuit loss that is core losses and with respect to the mechanical circuit, mechanical losses, friction and windage. So, copper losses can be calculated easily that is I square R losses and core losses are classified into two categories. One is hysteresis losses and eddy current losses. So, the basic formula for the hysteresis losses, hysteresis coefficient into maximum flux density power 1.5 into frequency and eddy current losses basic equation, eddy current loss coefficient into B max square into F square. Based on these two equations, we can find the losses with respect to the magnetic circuit and losses with respect to the electrical circuit, losses with respect to the mechanical circuit. So, friction and windage losses approximately 1 to 2 percent or less than that we can see, otherwise we can neglect it. So, mainly copper loss and core losses in the electromagnets will be there and based on these equations, we can find the losses and then the efficiency can be calculated.

The efficiency equation number is 19. So, with these equations, we can find the different parameters of the electromagnet system. So, once we know the parameters and different equations, then we can design any type of electromagnet system either it can be door locking system or lifting the mass or it can be any relays or other places or any other applications. The procedure will be same depends upon the objective like if you are designing the system to attain the maximum efficiency, then at the end after following all these steps or all these equations, we should meet the same efficiency as per the required objective. The design is completely iterative process and it involves different variables and different constraints and different assumptions.

So, whether at the end of our design, we are meeting the actual requirement or not. If we are fulfilling the requirement, then our design is valid. With this, I am concluding this lecture. In this lecture, we have discussed the design of electromagnet. Thank you.