Course Name: Design of Electric Motors

Professor Name: Dr. Prathap Reddy B

Department Name: Electronic Systems Engineering

Institute Name: Indian Institute of Science Bengaluru

Week: 10

Lecture: 51

Title: Loss Calculation of Induction Machine -1

Greetings to all of you. In the last lecture, we have discussed the parameters of an equivalent circuit and its analysis of an induction machine. In this lecture, we will discuss the loss calculations as well as efficiency of an induction machine. If we will consider a induction machine, where we are giving electrical power as a input and we are taking the mechanical power as a output for a motor and it is opposite for the generator case. So, what are the loss components involved in this machine? So, there are mainly two components and one more with respect to the mechanical thing. Like if we will see the major loss components are the copper losses that are the windings with respect to the windings at the stator side and rotor side.

This is the squirrel cage rotor and the second type of load loss component is the loss component with respect to the magnetic materials that is the core and third component is nothing but with respect to the mechanical aspect like the friction between the air and rotating object. So, here in this slide, I am showing different loss components, the copper losses, core losses and mechanical losses and stray load losses. So, we will discuss one by one and how to calculate these losses with the different equations. And finally, we will find the output power and efficiency of a complete machine.

First we will discuss about the copper loss. So, the general equation for the copper loss is nothing but I square R loss.

Here R is the dissipating element which is dissipating the power loss as a form of heat and I square is nothing but current flowing through that particular resistance. If we will see with respect to the stator side, the stator copper loss that is I square R loss, I square R formula only into number of phases will come and some winding like AC resistance factor also will come that is Kcrf. If we are operating the machine at higher frequencies, we have to consider the skin effect factor also that is AC resistance factor and resistance with respect to the temperature variation is the Rs1.

Rs phase is nothing but actual resistance of the stator phase at the ambient temperature. And Tj and Ta are the operating temperature of the machine as well as ambient temperature. So, with respect to the temperature variation, the resistance of a machine or resistance of a stator winding will vary. So, that resistance we have to consider to calculate the stator copper loss. Similarly rotor copper loss also we can calculate based upon the same equation I square R loss I square into R, but here we are considering the rotor resistance referred to the stator side and rotor current referred to the stator side.

Because of that reason we can consider directly ms that is three phases only stator number of phases as well as rotor number of phases are equal into IR square and rotor resistance and at the operating temperature and AC resistance factor and Rr dash phase is nothing but actual resistance of the rotor at ambient temperature. So, based upon the temperature variation we can calculate the rotor resistance at that particular operating temperature and then we can calculate the rotor copper losses. The temperature coefficient with respect to the copper winding and aluminum winding we can see here. For a squirrel case machine stator windings are designed with copper and rotor bars are designed with aluminum bars. In most of the electrical machines we will see the copper windings only.

The temperature coefficients we can see here depends upon this temperature coefficient and operating temperatures we have to calculate the copper losses. And one more thing if we are operating the machine at higher frequencies then we have to consider the proximity effects and skin effects appropriately to calculate this copper loss. Then the core loss component, the core loss we can categorized into two types one is hysteresis loss other is eddy current loss. Some of the hysteresis and eddy current loss will give the core loss that is loss happening with respect to the magnetic material of stator as well as rotor. First we will discuss about the hysteresis losses.

The hysteresis losses are related to the memory of the magnetic material. The magnetic material lecture we have discussed under the if there is no magnetization or if there is no MMF is applied all magnetic domains are aligned in a random direction. If we will apply the MMF that is N into I then the magnetic domains will start aligning with respect to the applied magnetic fields and at certain point all domains will aligned in one particular direction that is the maximum flux density value or saturated flux density value. After this point if we will increase the number of sorry MMF or H fields there is no change in B value it will not change only H will change after this point and mu value permeability value is equals to 0. If we will reduce the applied MMF then the BH loop will follow in the with respect to this curve and it will reach to this point.

At this particular point all magnetic domains are not equals to the position where we have started the BH loop. There will be a memory of magnetic material in order to bring back the B value to the 0 this is the B residual B or I can say higher residual values we can see for larger BH loop for smaller BH loop it will be small. In order to bring this value to the 0 we have to apply the negative MMF. If we will apply negative MMF then B value will come down to 0 but H value is negative MMF value is negative and this point is called as a cohesive point or cohesive flux intensity point. Similarly, if we will apply a negative MMF the BH loop will follow in this same way and it is coming back in this fashion and it will reach to this point now.

At this particular point again we will see some memory of magnetic material. The memory is nothing but all domains are not aligned with respect to the original state or some magnetic domains are aligned with respect to the previous state it is not coming down to 0 exactly. And from this point to this point if you want to reach then we have to apply the positive MMF such that B value will be equals to 0 and H value will be not equals to 0 and this is the positive cohesivity point. So, the loss associated with this yellow highlighted hysteresis loop is nothing but hysteresis loss. So, depends upon the area under this curve we can calculate the hysteresis losses.

So, in order to find the power if we will consider the potential variable on X axis and kinetic variable on Y axis then product of these two over a time period we will get the hysteresis losses. The general equation for hysteresis losses is equals to hysteresis coefficient into maximum flux density power, stain made constant and frequency into volume.

Next we will discuss about the eddy current loss component. The eddy current loss are caused because of the induced currents in a magnetic material. As per the Faraday's law if we will place a closed coil in a magnetic field there will be a induced current.

These induced currents results in induced magnetic fields that are exactly opposite to the applied magnetic fields. We can see the applied magnetic field is green color and induced magnetic fields are in black color. So, eddy current losses are equals to I square R loss based things only. Here I square term is nothing but induced current magnitude and resistance is nothing but the resistance with respect to the coil or resistance with respect to the core material. So, the core material also we can consider as a closed path and there will be a induced current I.

So based upon this induced current we will see the I square R loss. In order to reduce the eddy current losses we have to make the laminations of this core such that I square term will the induced currents can come down. So, that we can see here. So, if we will make the core into small laminations or small areas then the induced currents will come down. With respect to that we will see the reduction in eddy current losses.

Because of that particular reason we will see in most of the electrical machines some laminations. This is the laminated stator core and each lamination thickness we can see some smaller thickness values here. This is the laminations with respect to the stator core. The hysteresis equation we can derive from the I square R loss equation only. Here R is nothing but rho l by a area of the magnetic material and length of the material and resistivity of the material.

Based upon the I square R loss equation we can derive this thing and here K eddy is nothing but eddy current coefficient and V max is nothing but maximum flux density and frequency of the machine and Tsh is nothing but thickness of the each lamination and V is the volume of the machine or volume of the magnetic material. It is not volume of the machine. So, first method is in order to find the core loss it is a combination of hysteresis and eddy current losses. The designers of electrical steels they will give the total loss in terms of watt per kg. So, here one data sheet we can see with respect to the non oriented electric steels with respect to the Tata steels data sheet.

So, the loss in terms of watt per kg at different flux densities of operation and at different frequencies we can see in this chart. For example, if we are operating the core or machine at 1.2 Tesla and frequency is 50 hertz, this is the 50 hertz component associated with the 1.2 Tesla, then power loss will be 1.23 watt per kg. So, if we know the watt per kg, then multiply this specific loss into mass, then we will get the total core loss. So, here p loss factor is nothing but total iron loss or specific loss in kg watt per kg and m is the mass of iron in kg. So, based upon that we can calculate the core loss.

Similarly, if we will see the other data sheet with respect to the Nippon steel corporation or Nippon steel data sheet. So, Nippon steel data sheet with different variations with respect to the 0.23 thickness and JIS steel and IEC 60404 steel, we can see here. So, different steels at different thickness of the material, we can see what is the specific loss watt per kg. This is with respect to the grain oriented electric steel and right side we can see non grain oriented electric steel for electrical machines. Grain oriented steels we will utilize it for transformers where the magnetic domains will be aligned in one particular direction and these are the things with respect to the loss calculations using method 1. Next in method 2, we will calculate the loss by utilizing the sum formula.

The hysteresis loss is nothing but K hysteresis, hysteresis loss coefficient into frequency into flux density square into mass. That is the general equation with respect to the hysteresis loss and eddy current loss will be frequency square and B max square. We can see the same equation. Here the Carter coefficients are considered to see the exact equivalent length of the material or length of the core. So, we will calculate the hysteresis and eddy current losses together for different parts of iron.

So, the total core loss with respect to the method 2 is nothing but the core loss with respect to the stator teeth, the core loss with respect to the stator core, the core loss with respect to the rotor teeth, core loss with respect to the rotor core.

So, how to calculate these losses means hysteresis loss coefficient we have to know and eddy current loss coefficient we have to know depends upon the material. It will vary 1 to 5 and frequency of operation and maximum flux density and mass of the each part of iron. So, how to calculate the iron loss in stator teeth? We will see now. Let us consider the stator core with different dimensions of the stator slot.

dc is the depth of the back iron and ds is the slot depth and d naught is the slot opening height and r 1 and r 2 are the radius of the stator slots at the top and bottom side. t is nothing but width of the stator teeth. So, first stator teeth iron loss we have to calculate. So, how to calculate the mass of stator teeth? Because hysteresis coefficient and eddy current coefficient for magnetic material like steel or iron we can get it from the data sheets. So, here Mts with respect to the stator teeth is equals to density of the core material into volume of the stator teeth.

We will see from the data sheet and volume how to find? We have to multiply the length with respect to the x axis, y axis and z. So, with respect to the x axis we can find the length will be the length of each teeth will be t. So, how many teeth are there like that Qs number of teeth or stator slots number. So, that is t into Qs and length of the core that is le into k s that is tacking factor and then depth of the slot complete slot height. So, the d naught is the slot opening height and r1 and r2 are the radius of the slot at the top side as well as bottom side and d s is the depth of the slot.

So, together we can consider complete height of the stator slot from this point to this point, this is the height of the stator slot. So, by this equation with this equation we can calculate the mass of the stator teeth. Once we know the mass substitute the mass here and how to calculate the castor coefficients we know based on that thing we can calculate the iron loss with respect to the stator teeth.

Here we can see the density of the different steels. So, the density of the steel is mentioned 7.6 the first number I am considering 7.60 kg per d m cube, d c meter cube. So, how to convert 7.60 kg per d c meter cube to meter cube means with this equation 1 kg per d c meter cube is equals to 1000 kg per meter cube. So, based upon the steel data sheet we can get the density. Same way the iron loss in the back iron, same equation only the flux density with respect to the back iron, flux density or mass with respect to the back iron we have to calculate in this region, what is B c value and what is mass of this region completely.

So, here mass is equals to again density into volume. So, this portion area we have to calculate. So, consider as a hallow cylinder area with some depth d c. So, we can calculate it the area with respect to the outer diameter of the stator that is pi d naught square by 4 minus with respect to this point.

The in between area we are calculating it. So, pi into inner diameter of the stator plus 2 into actual depth of the stator slot, 2 into d naught plus r 1 plus d s plus r 2 square by 4 into l e into k s. This term represents the area into length will give the volume.

Then iron loss in the rotor core, iron loss in the rotor core is a combination of rotor teeth and rotor back iron. So, rotor teeth will be in this portion, what will be the core loss. So, first we have to see the flux density with respect to the rotor teeth and mass of the rotor teeth.

So, mass of the rotor teeth we can calculate again density into volume. So, x axis length that is t r into Q r length of the core and actual height of the each slot that is r 1 r plus d naught r plus d s r plus r 2 r. Addition of these 4 terms will give the actual height of the slot at the rotor side multiply all these 3 terms, then we will get the volume and density we can select based upon the data sheet. Then this will give the mass of the rotor teeth and this will give the power loss or with respect to the rotor teeth or iron loss. The power loss is nothing but here iron loss with respect to the rotor teeth.

Then the iron loss in rotor yoke or back iron in this region, now we have to calculate the iron loss. For that again we have to find the area and length, then we will get the volume. In order to find the area first we have to select with respect to the outer diameter minus slot actual height. This is the slot actual height and outer diameter will be up to this point from the blue color 1. Then outer diameter minus 2 into d naught r plus r 1 r plus d s r plus r 2 r actual height of the slot square minus pi d I r that is inner diameter of the rotor with respect to this point.

Then we will get the volume with respect to the rotor core or back iron. So, finally, we can substitute the flux density with respect to the back iron that is B c r and mass of the back iron, then we will get the iron loss with respect to the rotor yoke or back iron.

So, with this I am concluding. So, we have discussed the stator copper loss and rotor copper loss and how to calculate the core loss with different methods. Method 1, we can directly take the power loss in terms of watt per kg multiply with mass then we will get the core loss directly.

Method 2, by utilizing the equations in terms of hysteresis coefficient and eddy current coefficients and mass of the different parts of iron etcetera. Thank you.