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: 12

Lecture: 66

Title: Thermal Equivalent Circuit- 1

Greetings to all. In this lecture, we will discuss the basic thermal equivalent circuit for any type of electrical machine. We will consider a case study by considering only a stator circuit and related losses like stator copper loss and stator iron losses. We will consider and we will develop the thermal equivalent circuit. You can see here, the heat flow in electrical machine, what we have discussed in the earlier lectures by considering the different nodes and different type of losses, I am showing here. Now, as a case study, we will consider only stator circuit and the associated losses are stator copper losses and stator core losses.

Rotor losses and mechanical losses, I am neglecting. Next example or next case study, we will consider these losses also. To make the simple study, I am considering only stator side losses and stator circuit only and heat flow also, I am assuming radial direction of heat flow and 5 thermal nodes, I am considering to develop the thermal equivalent circuit. The nodes are air gap and stator winding and stator core and frame and ambient.

These are the 5 thermal nodes and because of the symmetry, half of the circuit I am showing here, the top side of the stator circuit. The temperature at these 5 nodes are temperature at the ambient, I am representing as Ta and at the frame Tf. Similarly, at the stator core Tsc and at the stator winding Tsw and at the air gap, it is Tg. So, with respect to these temperatures at various nodes, there will be a thermal resistance. Let us consider the heat stator winding is the highest operating temperature point or heat generating source.

If I will consider the stator copper loss, so with respect to this thing, heat can flow towards the air gap or heat can flow towards the core. So, first we will see with respect to the stator winding to air gap. Through the air gap, it is flowing that is the thermal resistance with respect to the air gap to stator winding. Next thermal resistance with respect to stator winding to stator core, what is the resistance value? The thermal resistance from stator core to frame and from frame to ambient. Here, thermal resistance I am representing with respect to the different temperatures of the various nodes.

Depends upon the temperature difference like whatever the node having the higher temperature from that point to the lower temperature node, heat will flow. Loss components or heat generating points, I am incorporating in the thermal network that is stator core losses. I have incorporated at the node stator core and stator winding, the copper losses I am incorporated at this node. The thermal capacitances which is representing the heat energy stored with respect to the stator core node to ambient thing, ambient node that is Cth_sc. The thermal capacitance with respect to the stator winding node to ambient is nothing but Cth_sw.

This thermal resistances and capacitances we have to calculate. Then at the end, we can write the transient thermal equations based upon that thing. We can calculate the thermal temperatures at various thermal nodes. Then we can analyze accordingly and we can design the appropriate thermal circuit. In order to calculate the thermal resistances at the various nodes and various heat flow mechanisms for conduction, it will be this equation R theta conduction is equals to l divided by thermal conductivity into area with respect to the heat flow and l represents the thickness here.

Thermal resistance with respect to the convective manner is nothing but 1 by hc is nothing but thermal convective coefficient and area with respect to the convective heat flow. Same fashion for radiation also 1 by hr represents the thermal radiative coefficient and A or represents the area with respect to the radial heat transfer method.

Thermal capacitance equation we can see here Cth is equals to mass into specific heat capacity. Mass we can represent with density into volume and thermal conductivity of metals as well as insulators we can see in this tables. For cast iron the thermal conductivity is 40 to 46 watt per meter Kelvin.

Similarly, for copper it is 360 watt per meter Kelvin. Same way for insulating materials like slot liner for example, mica sheet it is 0.4 to 0.6. How to calculate the thermal convective coefficients h c in watt per meter square Kelvin is nothing but h c is equals to 7.8 into velocity power 0.78 for air or gas type of cooling. This is an empirical formula and hc is equals to 0.568 into specific heat capacity into density power 0.78 into thermal conductivity divided by length surface length in the direction of coolant flow into velocity power 0.78 gives the thermal convective coefficient for liquid type of cooling. These two are the empirical relations to find the convective coefficient. Similarly, the thermal radiation coefficient we can consider from this table with respect to the different ambient temperatures and different temperature rise watt per meter square Kelvin we can select from this table. Now, we have to analyze the thermal resistance between the different nodes. First I will start from this point that is air gap point thermal node.

The resistance or thermal resistance offered by the air gap for the heat flow we will calculate. Consider the conductive type of heat transfer in radial direction. From bottom to top heat is flowing depends upon the temperature. Here we can see the temperature with respect to the stator winding is higher as compared to the air gap, then heat flow will be in the bottom direction. So, here heat will flow in this direction.

In case temperature at the air gap node is higher as compared to the stator winding node, then heat will flow in upward direction with respect to the half symmetry. I am considering the top side network and bottom side also same kind of structure will exist with respect to the stator wind stator circuit. Here L represents the thickness. We can see here how represented the air gap as a cuboid, rectangular cuboid and heat is flowing in this direction that is radial manner. The thickness of the air gap is nothing but lg that is air gap length and area with respect to the heat flow is nothing but x axis length is nothing but le length of the stator core and y axis length is nothing but perimeter with respect to the inner diameter of the stator that is pi Dis and lambda represents the thermal conductivity of air that is 0.03 watt per meter Kelvin. By substituting all parameters here, thickness is equals to lg and thermal conductivity of the air into pi D area is nothing but pi Dis into length of the core. So, we can see here how we have derived the area.

How to calculate the thermal resistance between the stator winding to stator core between this node and this node? Stator winding to stator core means stator winding is placed in the slot.This is a slot. Here windings or coils are placed. Here slot liner will be there. This is the slot liner which will insulate the electrical conductors and magnetic core. This green color one is the slot liner. In order to calculate the thermal resistance from this point to core, this is the stator core.

This is the stator winding. The resistance offered by the stator winding and resistance offered by the slot liner that I am representing here in series with the two resistances. Here if requires more accurate, we can consider one more resistance part that is insulation of the winding also we can consider for more accurate design, but insulating conductor insulation with respect to the radial direction, I am neglecting here. I am showing the thermal resistance with respect to the stator winding and with respect to the slot liner. We can see here this is the thermal resistance with respect to the winding and thermal resistance with respect to the slot liner.

d copper represents the thickness of the winding and lambda copper represents the thermal conductivity of winding and area of the winding. Second term represents the thermal resistance of the insulating sheet that is mica paper. Thickness of the sheet divided by area with respect to the heat flow and thermal conductivity of the sheet. This is the equation to find the thermal resistance between the stator winding to stator core. The thickness of the stator winding is nothing but this one that is dss slot height.

Slot height I am considering as the thickness of the winding with respect to the radial heat flow dss and r1 and r2, I am neglecting radius at the bottom side of the slot and radius at the top side of the slot. I am neglecting and directly slot depth I am considering as a thickness with respect to the heat flow and copper conductivity into area is nothing but area for each slot and into total number of slot. Area with respect to each slot is nothing but x axis direction into y axis direction and x axis side the length will be average of slot width at the top side and slot width at the bottom side in mean we have to consider into length of the stator core. That is what I have represented here and same manner we can calculate the thermal resistance for the insulating sheet. Thickness of the insulating sheet divided by conductivity of the insulating sheet into total number of slots into the area with respect to the insulating sheet placed in one slot.

The perimeter I am calculating here we can see. This is the slot liner placed in the slot right, this green color one. In order to calculate the perimeter 2 into average with respect to the slot widths plus height of the slot right that is dss. The same equation I am presenting here this is nothing but x axis direction what is the length and le represents the stator core length in y axis direction. If we will make the multiplication it will give the area with respect to insulating sheet placed in one particular slot.

If we will multiply with total number of slots then we will get the total resistance thermal resistance. If we will multiply Qs into area with respect to the insulating sheet placed in the single slot it will give the total area then addition of the thermal resistance with respect to the winding and insulating sheet will give the total thermal resistance for stator winding to stator core.

Next the thermal resistance from stator core to frame in conductive heat transfer method and radial direction that is this one that thermal resistance between stator core to frame. The stator core to frame is nothing but this is the one I am not considering the stator teeth only the back iron portion I am considering as a core one core portion for heat flow. So, once the heat is flowing from the stator winding to stator core then stator core point to the frame it is heat is flowing.

So, the resistance offered by the stator core is nothing but thickness of the stator core that is dcs is the thickness of stator core divided by thermal conductivity of the stator core into pi into perimeter with respect to the x axis pi into mean diameter of the core. You can see this is the outer diameter Dor this is the diameter to Dor minus 2 dcs. So, in order to calculate the mean diameter these two addition by 2 we have to do and pi into D represents the x axis length mean perimeter into length of the core will give you the thermal resistance between the stator core to frame.

The thermal conductivity for steel type of core it is 35 to 50 watt per meter Kelvin whereas the thermal conductivity for mica sheet we can see here 0.6 and thermal conductivity for copper winding is 360 watt per meter Kelvin.

So, that is why the heat transfer coefficient or heat transfer in radial direction manner is almost negligible or small because of this mica insulating sheet or slot liner in axial direction through the copper wires the heat flow will be significant that we will discuss in the next example. And the thermal resistance between the frame to ambient, so this is the frame to the ambient heat is flowing with respect to the convection as well as radiation. So, from stator or mission frame to ambient with respect to the convection it is convective thermal resistance with respect to the radiation it is radiative or radiation based thermal resistance. So, for calculating the convective thermal resistance it is 1 by hc into area with respect to the convective heat transfer area with respect to the convective heat transfer is nothing but perimeter into length x axis length into y axis length x axis length is nothing but D naught s into pi and y axis length is nothing but le. So, this is the nothing but perimeter with respect to the outer diameter of the stator.

So, I am multiplying or increasing by 10 percent of this perimeter to get the frame outer diameter. So, this is a empirical relation 10 percent more I am considering here and length will be le. Same manner for radiative or radiation based thermal resistance we can calculate 1 by hr into area related to the radiation. So, whatever the area we will represent with respect to the convection or radiation both will be same and pi into 1.1 into D naught s is nothing but outer diameter of the stator into length of a core.

So, we have calculated the thermal resistances with respect to the convection and radiation. So, the equivalent thermal resistance between frame to ambient is equals to parallel combination of these two resistances. This is R theta frame to ambient. Next we have to calculate the thermal capacitances. Thermal capacitance basic equation is this one Cth is equals to mass into specific heat capacity.

If will represents the mass with respect to density and volume Cth is equals to density into volume into specific heat capacity. Here thermal capacitance in terms of joules per kelvin and density units are kg per meter cube and volume of the material is meter cube and specific heat capacity units are joules per kg kelvin.

So, in order to calculate the thermal capacitance with respect to the stator winding and stator core we can see here.

First we will see the stator winding node what is the thermal capacitance from stator winding node to ambient. So, thermal capacitance is equals to density of the copper material into specific heat capacity of the copper material into volume of the complete copper winding.

So, volume of the copper winding with respect to the radial direction here windings are placed in each and every slot. So, area with respect to each slot is nothing but area of copper we can consider Acu that we know once we have designed the machine area of the copper in each slot into total number of slots that is Qs into le into ks. le is nothing but length of the core and ks is giving the stacking factor steel stacking factor and thermal capacitance with respect to the stator core is nothing but density of the core material that is steel or cast iron material and specific heat capacity of the steel material and volume of the core only by considering the back iron.

So, here in order to calculate the volume first x axis length or one direction length and area with respect to the other direction pi into r square. I am representing the hallow cylinder area here area into length will give the volume.

So, this is complete hallow cylinder volume. After calculating the thermal capacitances, thermal resistances and power losses at various nodes or heat generation at different nodes we have to calculate. Once all these three variables are known, then we can realize the n number of equations with respect to the n nodes. By solving these equations, we can get the temperature at various nodes of the machine.

So, if n nodes are there in the machine for this example, 5 nodes are there. So, total 5 equations will come and 5 unknowns are there.

Then if you will solve these 5 equations, then temperature at these 5 nodes like Ta, Tf, Tsc, Tsw, Tg can be calculated. If n number of nodes are there, n equations will come and n unknowns with respect to the temperature change at various parts of the machine we can calculate. For getting the higher accuracy, higher number of thermal nodes has to be considered and with respect to thermal resistances and capacitances we have to consider.

One more thing, while analyzing the thermal resistances with respect to the convection and radiative manner, we have to consider the coolant velocity also. While discussing the thermal resistance with respect to the convection and radiation, I have mentioned the convective coefficient in the form of velocity and radiative coefficient from the table we have to consider.

So, hc here, convective thermal coefficient we have to calculate based upon the coolant velocity. With this, I am concluding this lecture. In this lecture, we have discussed the thermal equivalent circuit of the stator winding by considering the five nodes where the heat flow is in radial direction. Thank you.