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: 11

Lecture: 60

Title: Importance of Thermal Design and Thermal Limits for Electrical Machines

Greetings to all of you. In this lecture, we will discuss the importance of thermal design for the electrical machines and thermal limits with respect to the winding insulation. Let us consider the electromagnetic system, where the input is electrical energy and output is mechanical energy and in between magnetic domain will be there. The energy or power is flowing in both directions. The machine, which is converting electrical energy to mechanical energy, that is motor. The machine, which is converting mechanical energy to electrical energy, that is generator.

In an ideal electromagnetic system or ideal machine, the efficiency is equals to 100 percent. There is no loss, but the practical non-idealities and practical system has some non-idealities with respect to the magnetic circuit and electrical windings and mechanical structures. With respect to the magnetic circuit, we will see the iron losses with respect to the hysteresis and eddy current losses. We have discussed different type of losses already while discussing the induction motor design.

With respect to the windings, we will see the copper loss. With respect to the mechanical structures, we will see the friction and windage losses. So, because of these losses, the efficiency is not equals to 100 percent. These losses are dissipated in the form of heat. Because of this heat flow among the different parts of the machine, there will be a temperature rise.

Because of this temperature rise, the loss in the machine will increase such that the output of the machine will come down. So, in order to attain the rated output, if the temperature is increasing, we cannot achieve the maximum output power. If the temperature is increasing, because the heat dissipation results in temperature rise and the temperature rise is eventually determines the maximum output power with which the machine is allowed to do the continuous loaded or constant loading. In thermal domain, the electrical and mechanical losses are converted to heat or thermal energy. It is a unidirectional power or energy flow.

If the temperature is rising, then automatically losses are increasing. This thing we will discuss with respect to some example. Let us consider a stator winding resistance is equals to 1 ohm and the operating temperature T j is nothing but 70 degree Celsius and ambient temperature T a is equals to 20 degree Celsius. We will see the resistance variation with respect to the change in temperature or nu with respect to the operating temperature is equals to resistance with respect to the stator at the ambient temperature into 1 plus alpha into change in temperature. This is the resistance equation with respect to the temperature coefficient alpha and change in temperature delta T.

The temperature coefficient for copper is 0.004 per degree Celsius or per Kelvin also we can mention. For aluminum, it is 0.0043 per degree Celsius. Now, we will calculate the change in resistance that is R new with respect to the operating temperature 1 into 1 plus alpha is for copper winding 0.04 into change in temperature 70 minus 20 that is T junction temperature or operating temperature minus ambient temperature. So, this will give the final value 1.2 ohm. If we will operate the winding, if the winding temperature is 70 degrees, then the increment in the resistance we can see here that is 20 percent. At 70 degree Celsius, if you are operating the winding, then the increment in the resistance is 20 percent.

Same way, if the operating temperature is 145 degree Celsius that is equals to T j, then the new resistance or resistance of the hotter conductors is equals to 1 into 1 plus alpha is 0.04 for copper thermal coefficient temperature coefficient into 145 is the junction or operating temperature minus 20 degree Celsius with respect to the ambient temperature. It will give 1.5 ohm. So, with respect to the R s that is 1 ohm at 20 degree Celsius and R new, if you are operating the windings at 145 degree Celsius, it is 1.5 ohm at 145 degree Celsius. From these two numbers, we can conclude that the resistance is increased by 50 percent.

If we will operate the windings at 145 degree Celsius, same way if we will increase the temperature, automatically the resistance of the winding also increasing. If the resistance of the winding is increasing, I square or loss for the same current is not changing or is increasing. That means, the copper loss also will vary in a same ratio at 70 degree Celsius.

There will be a 20 percent increase in the copper loss. If you will maintain the current same and only resistance is increased by 20 percent and at 145 degree Celsius, the copper loss will increase by 50 percent, where the resistance is increased by 50 percent and current is constant.

sSo, from this analysis, we can conclude that the temperature rise results in resistance increment and this resistance increment results in copper loss increment. So, once the losses are increasing, means output power will come down and if the mission or winding operating temperature is exceeding the safe operating limits, then there is a chance of insulation failure. If the temperature limit exceeding the safe operating limits and it may also results in complete machine failure or shut down.

So, for designing of electrical machine, the thermal aspect or thermal design also plays a significant role along with that, along with the electromagnetic design. Both are important electromagnetic design as well as thermal design. We should consider for designing any type of electrical machine. The distribution of heat sources has to be found based upon the machine geometry and losses. So, these losses are different with respect to the different parts of iron or different parts of machine and mission geometry is changing means, automatically the thermal distribution or heat distribution also will vary.

So, with respect to the mission structure or mission geometry and loss distribution, we have to select the cooling or thermal design and the heat distribution is a three dimensional problem. The heat distribution in a machine is a three dimensional problem and it should be determined with respect to the thermal conductivity of different parts of machine like iron core or windings or air gaps, bearings, etcetera. Different parts of machines have different thermal conductivity based on that thing. The heat distribution will vary and the spatial distributed contact surface of the machines, spatial distribution with respect to the contact surface of the machine. So, with respect to the different distributions of the heat, we have to define the thermal cooling mechanism or heat removal method, either it may be conduction or convection or radiation.

Next we will discuss the thermal limits with respect to the insulation. In various parts of the machine, the hottest or highest temperature operating point will happen with respect to the windings in the machine because the winding insulation is directly in contact with the current carrying conductor. This is the conductor and top of that insulation will be there. This red color line is the insulation. So, this insulation or insulating layer is directly in contact with the current carrying conductor.

That means, the insulation is directly heated up with respect to the losses happening in the current carrying conductor and heat removal from the conductor is a challenging task. Let us consider a slot where the conductors are placed inside the slot in this manner and it is a closed one. Only the slot opening is 2 to 5 times the conductor cross sectional area and there is a slot liner, which is a insulating material made up of mica or polyester film materials and the thermal conductivity value is very less for this kind of insulating paper or mica paper. So, the heat we cannot remove through the conduction here because of the insulating material. It is insulating with respect to the electrical as well as thermal also.

The thermal conductivity of the insulating paper is very less and the direct conduction or convection is not possible towards the core because of this slot liners. So, in order to design the proper thermal system for this thing, we can adopt some hallow copper pipes to cool down the temperature in high power density machines and other techniques like forced cooling by utilizing the air or liquid cooling, we can utilize for bringing the temperature down with respect to the windings. The lifetime of the insulation is inversely proportional to the temperature at which we are operating the conductors or insulation temperature. If we will see the limits with respect to the different temperatures as per the NEMA standards and IEEE standards, we can see here different class of insulating materials, class A, class B and class F and class H and the maximum operating temperature. We can see here these are the safe operating limits.

If the winding insulation temperature is exceeding this safe operating limits of the temperature, then winding insulation will damage and eventually it will damage the complete machine also. And with respect to the class A and class B, class F and class H, we can see the average expected life hours with respect to the y axis and total winding temperature on x axis, we can see. For example, for A phase, sorry, for class A, this is the lifetime versus temperature line. And if I will consider the operating point, let us say this point at 140 degree Celsius, at 140 degree Celsius, the average lifetime is almost 2000 hours, 2 k hours. If we will reduce the 10 degrees temperature, let us say at this particular point that is 130 degrees Celsius, the average lifetime we can see here that is with respect to this line.

So, this is almost 3 k, 2, 3, 4, 4 k hours, 4000 hours. This is the point t 1 and this is point t 2. t 1 is nothing but 140 degree Celsius and t 2 is nothing but 130 degree Celsius. If we will bring, if we will reduce the temperature further by 10 degree Celsius, at 120 degree Celsius, we can see the temperature is almost 8 k hours, the expected lifetime for temperature 3, 7 to 8 k. So, by reducing every 10 degrees Celsius of operating temperature, we can see the increment in the lifetime is almost 2 times.

2 times the lifetime we can increase by reducing the operating temperature by 10 degree Celsius. So, this gives that how significant the thermal design with respect to the windings and the temperature related to the windings are we can calculate based upon the electrical resistances. So, in order to find the temperature of the winding, we can use the electrical resistance measurements. By measuring the electrical resistance, we can find the temperature rise with respect to the windings, but accurate skin effects and proximity effects also we have to consider. Then, the measured electrical resistance will give the exact temperature rise with respect to the windings and the type of coolings we have to adapt based upon the NEMA standards and IEEE standards.

With this, I am concluding this lecture. In this lecture, we have discussed the importance of thermal design and thermal limits with respect to the winding insulation. Thank you.