Advanced Electric Drives
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Lecture – 36

Hello and welcome to this lecture on advanced electronic drives. In the last lecture, we were discussing about the losses in an induction motor; an induction motor is known as workhorse of the industry, because about 60 to 70 percent of the drive used in industry or induction motors. So, there are scopes to minimize these losses. We have seen that the losses are occurring in the stators, occurring in the rotor, it could be in the stator core, it could be in the stator copper, and same thing is also for the rotor. Now, we have seen a typical distribution of losses in an induction motor, let us look at the loss distribution once again.

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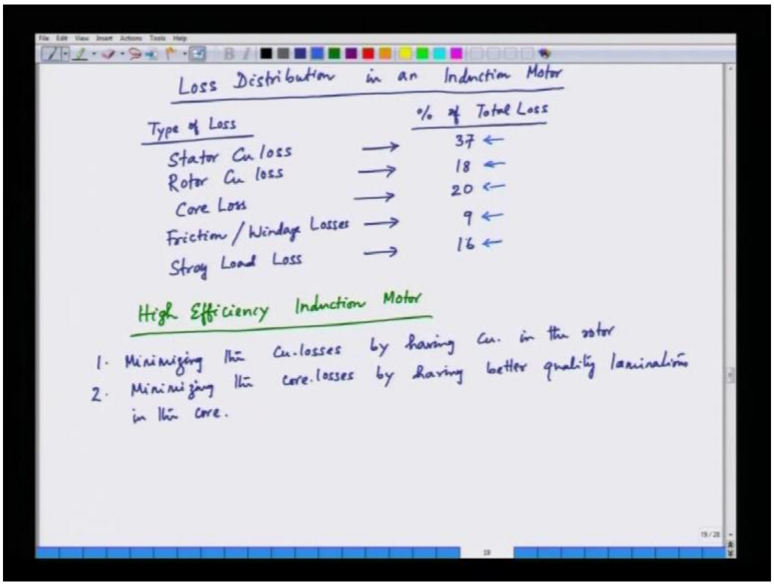

Now we have seen that the typical loss distribution is the stator copper loss is about 37 percent; this is the percentage of the total loss. It is occurring in the stator. The stator copper loss is basically occurring in the stator winding; physically, it is in the winding of the stator. In normal 3 phase machine we have phase a, phase b and phase c, and these losses the stator copper loss occur in the physical winding of the machine. Then we have the rotor copper loss occurs in the rotor bars; in case of a squeal case machine about 18 percent of the total loss. The core loss occurs both in the stator and also in the rotor is about 20 percent of the rotor loss. Then we have the frictional windings loses 9 percent, the stray load losses is about 16 percent.

So, these are basically the various losses in an induction motor. Now we can minimize the losses in an induction motor in two ways. We can have more copper in the motor; we can have the rotor made up of copper, usually the rotor bars are aluminum. So, we can replace the aluminum bars by copper bars, and hence we can have better efficiency. The rotor copper losses will be reduced. And similarly we can have better quality of stamping which will minimize the rotor core loss. The core loss consists of Eddy current loss and hysteresis loss. So, if we can have thinner stamping and a better quality material in the stamping we can reduce the core loss. And hence by improving the efficiency by minimizing the losses we can have high efficiency induction motor.

Now these efficient motors are used in those applications where we aim at energy saving. So, we can save this energy by using efficient induction motor in which the losses are minimized. So, let us have a look at the thermal model of the motor. We are mainly concentrating till now about the electrical aspects, the control; the thermal aspect is also important. Now we have to select a particular motor, and we should also understand that what should be the rating of the motor for a specific application. Now for that we should we should have an idea about the thermal model of an induction motor. In general it could be any motor; it could be an induction motor; it could be a dc motor, or it could be synchronous motor. What we do here we consider the motor to be homogenous body to simplify our calculation. So, let us look at the thermal model of a motor.

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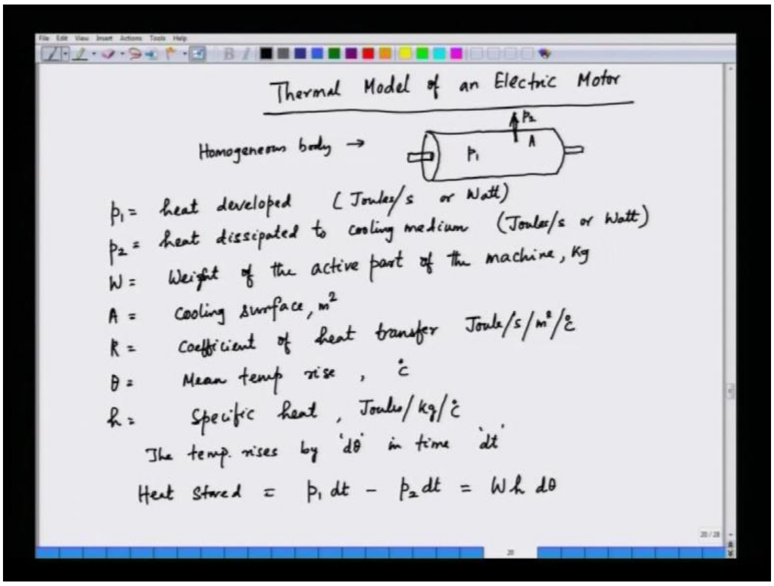

The thermal model of an electrical motor, so what we assume here we assume that the motor is a homogenous body. It is made of homogenous material, and that is some loss occurring inside the motor, and hence we have some heat generated inside the motor. Now this heat is dissipated to the surrounding primarily by convection. So, we have heat generated and heat decapitated, and whatever heat is trapped inside is responsible to raise the temperature of the motor. So, we have the motor here; this is a motor. So, what we have in his case is that we have p 1 is generated inside this machine, and p 2 is dissipated to the surrounding. And whatever heat is remaining is responsible for raising the temperature of the motor.

So, we will considering that the motor is a homogeneous body; although, it is made up of copper and iron the core is made up of iron, and the windings are primarily made of copper; for simplicity we assume that it is homogeneous. So, when it is homogeneous we can assume a constant or a uniform specific heat. So, we will assume that the motor is a homogeneous body. So, we have assumed here homogeneous body. So, we have the following data with us. Now what is p 1? The p 1 is the heat developed, and the unit is joules per second or watt. So, this is the basically the loss of the machine which is expressed in terms of joules per second or watt. Similarly p 2 is the heat dissipated to the surrounding and that is also power. So, that is also joules per watt.

So, p 2 in this case is heat dissipated to the cooling medium primarily the surrounding, and this unit is also joules per second or watt. We will assume w is the weight of the active part of the machine, and that is basically in kg. And A is the cooling surface in meter square. So, whenever we have we have the motor. The motor has got some surface area. The surface area is primarily for cooling. Now we must have seen that in an induction motor or in many motor the surface of the motor is not quite smooth; it is basically corrugated. The surface is corrugated primarily to increase the cooling area. If the area is more, the cooling will be more effective. So, in this example we have we have this is basically the surface from which the heat is coming out and this is having area that is A. So, that is in meter square.

And then we have k is coefficient of heat transfer, and this is primarily in joules per second per meter square per degree centigrade; this is the unit of this. And then we have theta is the mean temperature rise, and that unit is degree centigrade. And h is the specific heat, and the unit is joules per kg per degree centigrade. Now since we have assumed that the motor is homogeneous body, so we can also think that the motor has got a uniform specific heat. The specific heat of the entire mass is giving by h that is specific heat. Now after defining all these parameters we will define a dynamic equation. It means we have some heat generated inside this motor; some heat is dissipated to the cooling medium through the surface. And whatever heat is remaining inside is used to heat up the motor to a temperature that is theta.

So, we can write down the dynamic equation in the following fashion that p 1. So, we can say here that the temperature rises by an amount d theta in time d t. So, we will assume that it rises by d theta in time d t. So, heat stored here is basically the heat developed p 1 into d t minus p 2 in to d t. So, this p 1 is the heat generated inside; the motor is basically loss of the motor in watt, and p 2 is the heat that is dissipated to the cooling medium. And heat stored inside the motor is p 1 d t minus p 2 d t is basically in an interval of d t time, and that heat is responsible for rising the temperature of the motor. So, we have the weight is w; that is equal to w is the weight. The specific heat in this case is h, and change in temperature is d theta. So, this is the dynamic equation.

And this equation is very important equation. This gives basically the dynamics of heat transfer and the temperature rise. Now if we solve this equation we will get the temperature rise of the machine for a given load at given time. So, let us simplify this and try to solve this equation, and get a close form solution to the temperature of the machine.

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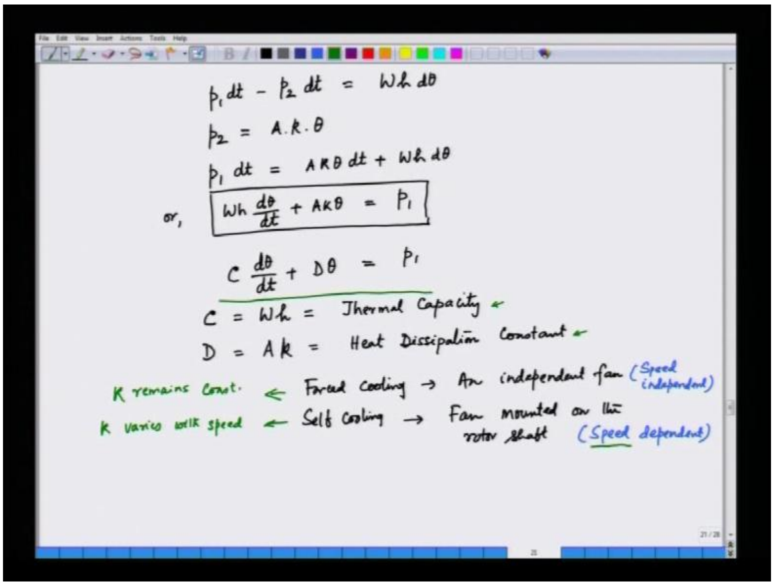

So, we will solve this in the following fashion that we have this equation p 1 d t minus p 2 d t that is equal to w h into d theta. And here what is p 2? The heat that is dissipated to the cooling medium; there is a cooling which is constantly taking place. So, p 2 heat is dissipated to the cooling medium through the surface area. So, the cooling surface area is a, and the coefficient of heat transfer is k. So, we can say that p 2 is given by A into k, surface area into k into the temperature that is theta. So, that is basically the heat dissipated. So, we will be replacing that. So, what we have here p 1 d t is equal to A k theta into d t plus w h d theta, or we can write down in this case is w h into d theta by d t; we will be dividing all this by d t. So, what we have here w h d theta by d t plus a k theta; that is equal to p 1. So, this is an interesting equation.

So, this equation gives the dynamic of temperature rise. So, theta is the mean temperature rise. So, we are seeing that theta is not constant; theta is basically function of time. So, with application when we apply load, the motor is loaded that is heat generated, we have the copper loss and we have the core loss, and this heat generated inside this machine is going to raise the temperature of the machine. Now we must take care that the temperature of the machine which is increasing with load to attain a steady state temperature. And the steady state temperature of the machine should not be more than the melting point of the material or should not be such that the insulation will degrade.

So, we will be fixing a maximum temperature rise. We know that the motors are classified into various classes depending upon the temperature rise, class b motor, class c motors and so on. And the insulation is also classified according to the temperature rise. The temperature rise is a very important criteria or parameters of the motor, and the temperature of the motors should not exceed beyond the insulation capability of the motor. So, if we simplify this further we will get another equation which is similar which is a first order differential equation, and we define some input and constant. The equation after simplification will be as follows.

Now if we simplify this we can write down this equation in the following way c d theta by d t plus D into theta that is equal to p 1. Now what is c here? C is the weight into specific heat, and that is called the thermal capacity of the machine. And what is D? D is A the cooling surface area into k the coefficient of heat transfer, and that is called the heat dissipation constant. Now we must be very careful that the small k is called the coefficient of heat transfer. Now we see that sometimes the motor is having some cooling mechanism. The motor may be having an extra fan. Now if we have an extra fan the fan will be basically blowing the air and we call that to be force cooling. And that cooling is independent of the speed of the motor.

Now sometimes the motor itself the rotor of the motor which is rotating, the rotor is itself housed with a fan. Now that fan is also responsible for the cooling that is called the self cooling. So, we can have force cooling, and that is why an independent fan or we can have self cooling. Buy a fan mounted on the rotor soft. Now the first one which is an independent fan is basically speed independent. The second one which is basically the self cooling is speed dependent. So, if we go for self cooling the cooling will be basically depending upon the speed. So, if we are talking about variable speed drive and if the motor itself is having a fan on the rotor it is basically self cooling. The cooling will be given by or will be a function of the speed of the motor. And hence the coefficient of heat transfer k which is heavily dependent on how the cooling is taking place will be basically speed dependent.

So, for force cooling we can say here k is constant; k remains constant and for self cooling where we have a speed dependent cooling here, k varies with speed. So, for simplicity we will assume that the cooling is constant. I mean we can have force cooling; the cooling is independent of the speed. So, we will assume that k is constant. So, we have the first order differential equation that is c d theta by d t plus d theta is equal to p 1, where c is the thermal capacity, and d is the heat dissipation constant. Now when you have first order differential equation we can solve this equation. So, this solution is not very difficult.

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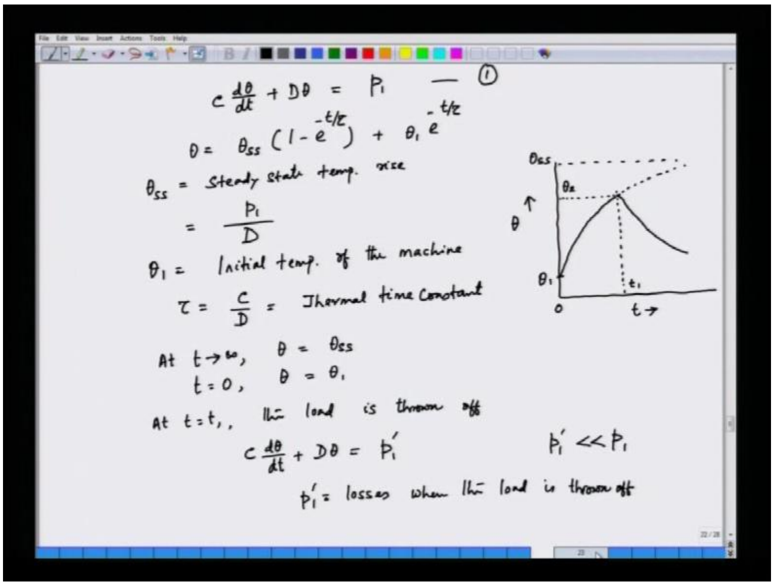

So, we have c d theta by d t plus d theta is equal to p 1 is basically is the loss which is inside the machine; p 1 is the loss occurring inside the machine, and that is for a given load it is constant. So, if we simplify this or if you try to solve this equation we see that theta is equal to theta steady state into 1 minus exponential minus t by tau plus theta 1 exponential minus t by tau. So, when we solve this equation we will get an equation which is an exponential equation; theta is equal to theta s s. So, theta s s is the steady state temperature rise. So, what is theta s s? Theta s s can be obtained from this equations, if we say this is equation number 1 let us say.

So, we can say that theta s s is equal to p 1 by capital D. So, in the steady state there is no d theta by d t; d theta by d t only comes in the transient condition. In the steady state there is no change in temperature. So, what we have here we have p 1 by d and that is the steady state temperature rise. And what is theta 1? Theta 1 is the initial temperate of the machine, and what is tau? Tau is equal to C by D, and that is called thermal time constant. So, if we plot this theta against time, t is in the x axis, and theta is in the y axis; we start with any temperature that is theta 1. It rises exponentially.

If it is allowed to rise here it may reach some steady state temperature that is theta s s. And we can see that at t equal to infinity theta is equal to theta s s; at t equal to 0, theta is equal to theta 1. So, this motor is basically changing from a temperature theta 1 to theta s s. Theta s s is the steady state temperature that could be very high value. So, if we want to operate this machine under a safe limit, we can switch of this load after sometime. And we can define class of motor like continuous rated motor, intermittently rated motor and so on. So, if we have a continuously rated motor theta s s will be a safe value of temperature. If we have an intermittently rated motor, motor does not reach theta s s. The load is switched off before it reaches theta s s, and hence the cooling process starts.

Now here if we start the cooling process let us say at this instant the load is thrown off. So, if the load is thrown off at let us say at a temperature that is theta 2, the loss is reduced, and hence the motor begins to cool. So, we say that when the load is thrown off at let us say t 1, at t equal to t 1 the load is thrown off, okay. When the load is thrown off it begins to cool, why? Because we have the same equations c d theta by d t plus d theta here, but the losses have changed; losses have changed from p 1 to p 1 prime. So, in this case p 1 prime is the losses because the load is thrown off. So, p 1 prime is much less than p 1.

When the motor is loaded the loss is quite large, and when the rotor is switched off when the load is a switched off the losses inside this machine reduces drastically. So, p 1 prime is the loss when the motor is a witched off in the sense that the load from the motor is removed. When the motor is unloaded the loss is p 1 prime. So, this p 1 prime is the losses when the load is removed or thrown off. When the load is thrown off it is p 1 prime, and hence we obtain a characteristic in which the temperature is decreasing here.

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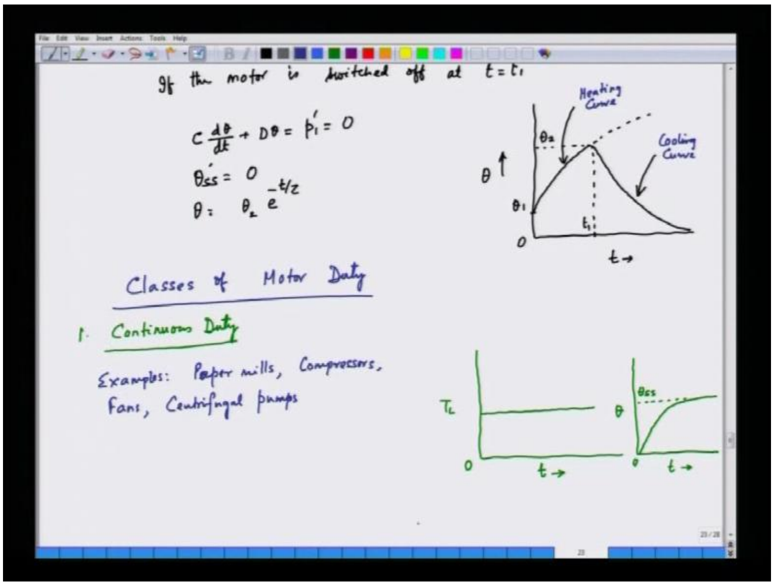

So, what happens if the load is switched off or the motor is switched off, if the motor is at t equal to t 1? So, we have the graph once again. Here we have the temperature at the time axis, and we have the temperature of the motor. So, it starts with theta 1. This temperature rises here, and then at t 1 we completely switched off the power supply. The power supply to the motor is switched off at t 1, and hence the loss becomes equal to zero. So, if the loss becomes equal to 0, p 1 becomes equal to zero. So, what we can say here is c d theta by d t plus d theta is equal to p 1 prime; that is equal to 0, and hence we can say that theta s s becomes equal to 0 here. And so theta is equal to we have some theta 2 initial value here. This is basically initially temperature when the load is or the motor is switched off. So, we can say that theta is equal to theta 2 exponential minus t by torque.

So, this decreases exponentially and finally this may go down to zero. So, this is basically the heating curve, and this is the cooling curve. So, we name this by two different names. This is called the heating curve and this one in which the temperature reduces. When we throw off the load or we switch off the power supply, the motors start to cool. And when the motor starts to cool we call that to be the cooling curve. So, this is basically the cooling curve. So, this basically gives an idea how we can operate the motor. Now based on this we can classify this motor into various ratings. It could be continuously rated motor, it could be a short duty motor, it could be intermittently rated motor and so on.

Say for example a fan. A fan is running continuously. When a fan is running continuously we call that to be a continuously rated motor. The load does not fluctuate; the loss is constant, and the temperature has reached a steady value. And that temperature is basically less than the permissible limit of the motor. So, let us discuss about the various duty of motors. So, we can say in this case classes of motor duty. Now what are the various classes of motor duty? We will start with let us say continuous duty motor. Now in continuous duty what we have here is the following. We will first draw the load torque curve. This is the load torque and this time, and we will also draw here the temperature raise theta against time.

In this case the load torque remains constant; there is no fluctuation of the load torque, say for example a fan. The fan is running continuously. When a fan running is continuously at a constant speed; we are not adding the speed, we can assume that the load torque remains constant. Similarly we have a motor, a grinding mill which is running continuously. In that case we also assume the torque to be constant, continuously rated motor. So, the load remains constant here. So, this is basically a constant load that we have here, and what about the temperature rise? The temperature rise in this case is also like this. The temperature reaches a steady state value. This is theta s s, and this theta s s is less than the safe limit.

So, this is continuous duty motors, and the examples are, we can sight some examples. The example of this motors are paper mills, compressors, compressor on continuously in air conditioners, fan, centrifugal form and so on. So, these are continuous duty motors. Now we can also have intermittent duty motor in which or a short time duty motor in which the load is only applies for a short time. So, in that motor the motor is switched off before the temperature reaches a steady state value. So, let us see short time duty motor.

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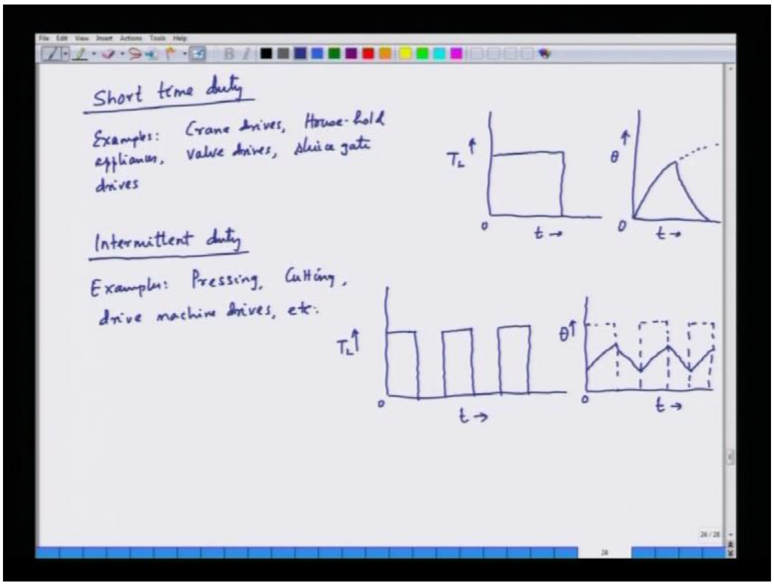

So, we can have the short time duty here. And in this case if we plot the load torque curve against time, this is time axis, and this is axis for the load torque. So, what we have here is that the load torque is applied only for a small time, and what about the temperature rise? The temperature in this case does not attain the steady value. So, this is temperature in the y axis. So, x stars raises from 0, and then it does not reach the steady state value; before that it is switched off. So, it is basically cooled. So, what are the examples? The examples are crane drives. In crane we just apply the power to lift the load, and when the load is lifted and kept the crane motor is switched off. So, this is an example of a short duty motor, and in this case the temperature rise at the temperature at the motor is less then steady state temperature that could be attained had it been operated continuously.

So, example in this case is crane raise. We can have house load appliances like food mixtures etcetera, and then we have valve drives, this sluice gate drives and so on. Now there are some type of load in which the load fluctuate; the load is applied and then removed, applied and then removed, and this class of motors are called intermittently rated motor or intermittent duty motor. So, we will see the torque and the temperature rise profile of intermittent duty motor. And what we have in this case is the following that the load here is applied and then removed. So, this is basically the load profile we have, t is the x axis.

So, this is load torque in the y axis here, and if we see the temperature rise here the temperature rises in a very interesting way. So, these are basically the applied volts. So, theta is the temperature of the motor t in this case. So, the temperature rises, then when the load is switched off it falls, then again raises and falls. So, the temperature does not reach the steady value rather it fluctuates for a minimum value to a maximum value. Now again in this type of motors we do not reach the steady state temperature. The motor is operated well below the steady state temperature of the motor in which the motor could not be sustained.

So, in this case the temperature reaches a safe value and then we switch off this load. And then we again apply the load, and hence the temperature keeps on changing between a minimum value and a maximum value. What are the examples of intermittent duty motors? Pressing machine in which you know for printing we print some papers and then the load basically varies in a cyclic way, cutting machines and so on. So, we can have some examples of intermittently rated motor. So, the examples are as follows. We have pressing, cutting, drilling machine drive, etcetera.

So, we have another class of motor in which the motor requires some starting. When a motor is large drive it has to start from rest, and when it starts from rest it also consumes a lot of power, because the motor has a large inertia, and it has to overcome that inertia and start. So, it starts and then it is loaded, and then it is switched off. So, we will have a motor in which the starting is also included; we will see that example.

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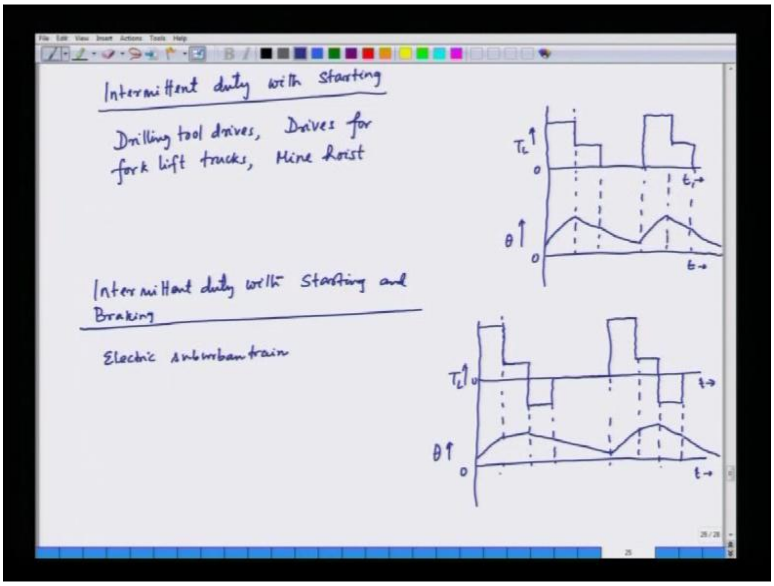

And we call that intermittent duty with starting. So, we have the load and the temperature rise curves are like this. So, we have t here, and we have t here in this case and T L in the y axis and theta here. So, when the motor starts large load is applied; it has to overcome the inertia, and then the motor runs. Then it is switched off, and then again it starts. A large load is applied; it runs, then again it is switched off. So, what about the temperature rise? How does the temperature of the motor change when this kind of load is applied? So, this is the temperature of the motor theta. So, the temperature increases when it starts. Then when it is loaded the load is little less than the starting load. So, the motor begins to cool somewhat, and then when it is completely switched off it cools down to the normal ambient temperature.

So, here the cooling process stars, because this load is less than the starting load, and then finally it cools down. And before it cools down to the zero value again we have to have starting here and then it cools down we have the running. The roaming load is less than the starting load, and then finally, it reaches a minimum temperature before the next load is applied. So, an example of this kind of thing is drilling tool drive. We have drives for fork lift trucks, mine hoist. Now think of a mine hoist. Mine hoist is a heavy drive; in the sense that it is basically lifting man or material from underground mine. So, first of all it has to accelerate to start, and then it goes down. And then finally, it has to lift some material and then it comes to arrest. So, starting and then lifting the material and then stopping.

So, all this loads include starting, running and stopping, and the temperature rise changes accordingly; when it starts the inertia is large. So, it has to accelerate against the large inertia. And then sometimes in the loading condition the inertia become little less or the load become little less; the temperature rise or the temperature reduces somewhat, and then when it stops the temperature further reduces before the next cycle begins. So, this has got starting, and then we have some loads in which both the starting and the braking have also included; the braking is also quite important. For example, a locomotive, the suburban train; a train is moving, and the train has got large kinetic energy when it is moving.

And when it stops it has to be braked, and we prefer to brake it electrically, because if we brake it mechanically there will be wear and tear of the wheels and the track. So, electrical braking is not only efficient but also good for the wheel and the track. The motor starts from rest. It runs at a steady speed, then it is braked. So, we have the starting, running and braking. So, this is one type of the motor, and we can show the corresponding torque and the temperature raised diagram. So, we have intermittent duty with starting and braking. So, we have the classifications like this. We have the load torque, and we have the temperature rise.

So, how does the load torque change? The starting it requires large torque for starting; the inertia of the drive is very large, the locomotive has a large inertia. So, it has to start against this inertia. So, the starting torque is very high, and then it runs as the running torque is comparatively less. So, we have a high starting torque and then somewhat low running torque, and then the braking is also quite significant. So, we have the braking torque, and this repeats it is intermittent type of loading. So, starting, running and braking. What about the corresponding temperature rise? So, let us see the corresponding temperature rise here. T is in the x axis the time, the theta here in the y axis. So, during the starting it takes a large current.

So, the temperature rises and then running condition it rises but very low. Then the braking will be as high as running. So, it slows down little bit, and then finally, when it stops or it is switched off, it cools down. So, this is starting, running, braking and then finally rest. So, this is the temperature rise; in this case also the motor does not reach the steady temperature. Of course, if it runs for a very long time the temperature will be steady and then it brakes. For the braking also there is some temperature rise, and then in between the two loads there will be a considerable amount of cooling time when the motor cools down. An example as we have already discussed that one of the examples of this is a local train or suburban trains.

So, electric suburban train is one of the good examples of drives which require both starting and braking. Now when we have so many types of duty of the motor, how do we select the rating of the motor? So, primarily we can classify them into two broad categories. One is continuously rated motor or continuous duty, and the other is intermittent or shorten duty. In continuous duty whatever is the load or whatever is the power which is being delivered, we choose the higher available power when we choose the motor. And what about the intermittent load? The intermittent load we have to find out an equivalent torque to find out the rating of the motor. So, let us see how we decide on the rating of the motors in general.

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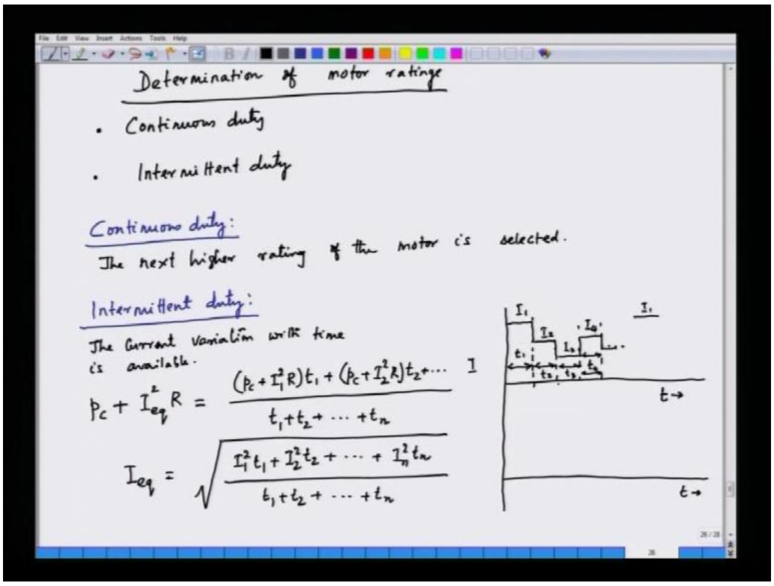

So, we have determination of motor rating. So, primarily what we have? We have continuous duty, and we have intermittent duty. So, in the continuous duty if you take this first one what we do here is the following. We take the power the maximum possible power of the load and choose the next available rating of the motor, very straightforward. If suppose a fan is delivering a power of, say, 60 watt. So, we choose the motor which is 60 or higher watts; if the load is let us say 85 watt, we choose the motor which can deliver 85 watt or higher; the next higher rating is selected. So, this is very straightforward. So, what we can say here that the next higher rating of the motor is selected.

What about the intermittent duty motor? If the load is constant it is fluctuating; it is not constant. It may be a periodic, or it may be periodical let us say. If it is periodic but it fluctuating we need to find out an equivalent rating of the torque or current or power. So, for intermittent duty we have to do some calculation before arriving at the current or the torque of the motor. So, we will be discussing about the rating of intermittently rated loads. So, let us say that we have a motor in which we know the currents. The current is varying like this; say for example we can recur the current, and for simplicity let us say the current profile is available, or the current variation with time is available. And this variation is given like this.

So, we have I 1 current here, and then we have I 2; say for example, we have I 3 here, I 4, and then after that we have again I 1. So, this is I 1, and this I 1 is applied for the time t 1, and this is I 2 is applied for a time that is t 2. I 3 is applied for a time that is t 3, and I 4 is applied for a time that is t 4 and so on. And this is again I 1; it is periodic. So, if we have the periodic variation and the variation is like this and so on. So, what about the losses? The loss in the motor primarily consists of two losses. We can assume that core loss and the copper loss. Core loss is almost constant irrespective of the load. Core loss is not a function of load; it is constant.

So, p c or the core loss is constant, and the copper loss is the function of the load. So, we can say that the loss here is p c the core loss, and we know the resistance of the motor. We say we have equivalent current I e q square into r. This is the copper loss, and then we have each intervals here may be t 1 to t n. So, we can say that it is p c plus I 1 square r for the time t 1 plus p c plus I 2 square r for the time t 2 and so on divided by the time t 1 plus t 2 up to t n. So, if we simplify this we can calculate or we can evaluate what is I equivalent. I equivalent is given as I 1 square t 1 plus I 2 square t 2 plus I n square t n divided by t 1 plus t 2 up to t n. So, this is a very interesting derivation in the sense that we can find out an equivalent current for a fluctuating load.

So, when we know I equivalent we can select the motor with the next higher current. And this is one of the ways in which we can find out the ratings of the motor if the load is fluctuating. Now in this lecture we have derived the thermal model of the motor. We have seen various duties of the motors, and we also have discussed how to select the rating of the continuous rated motor and intermittently rated motor. So, in the next lecture we will see more about the selection of the ratings, and we will also see when we have the highly fluctuating load, how do we distribute the load so that the motor ratings is reduced; those things we will be discussing in the next lecture.