Basic Electrical Technology
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Lecture - 29
DC Motor – 3

Hello everybody. In the last session we were discussing about the DC motor. We discussed about the various characteristics, the various types of excitations the series, the shunt, the compound excitation and we studied the characteristics of the shunt and the series motor in some detail. Today we shall continue from there and complete our discussion of the DC motor by studying the compound motors and other issues like modeling of the DC motor.

Now we discussed about the shunt and the series motor and there were few unique features which were representative of these two motors that is the shunt and the series motor. Now, if you look at the shunt motor, in the case of the shunt motor the generated torque T g is proportional to the flux field or the excitation into I a. In the case the series motor the generated torque T g is proportional to the flux into I a but the flux itself is proportional to I a and therefore you have a proportional to I a square.

In the case of the shunt motor let us say in both the cases R a is equal to R a is approximately equal to 0 R a is approximately equal to 0 the back emf will be equal to the applied armature voltage and which will be equal to some proportionality constant into phi into omega. Now, as this is a constant we saw that if we decrease the flux the speed is going to increase or if we increase the flux the speed is going to decrease because this is a constant and these two are inversely proportional to each other to maintain this constant.

So when under no-load conditions if we suddenly remove the excitation winding or if the excitation winding gets cut then phi becomes zero the motor will the motor speed will increase to a very large huge value and the bearings may get damaged so there may be mechanical damage to the motor and such a situation is called run away of the motor.

In the case of the series motor the back emf E b is proportional to phi and omega and as phi is proportional to I a is proportional to I a and omega. If I a is 0 that is at low speeds if I a is 0 when the at the time when the shaft is not rotating the E b is 0. So even if there is an I a and the shaft is rotating is not rotating and omega is equal to 0 E b is 0; under no-load conditions when let us say I a is close to zero then also E b is equal to 0.

Now let us say you apply the full applied voltage. The full applied voltage is applied, the shaft is not rotating then the I a is going to be very high the torque generated is going to be I a square it is going to be a huge torque and under no-load conditions the speed may accelerate very fast and again it may result in this run away in the case of the series motor and result in mechanical damage. Even in the series motor because at omega is equal to close to zero speed there is no back emf, the I a will be very large and that large I a is also going to result in a large field because the field current is same as the I a and therefore as a consequence the speed will quickly pick up and try to run away.

But under the under loaded conditions the torque will develop and then settle down at the operating point depending upon the low torque requirement. So the runaway situations can occur in both the cases and the runaway here is the case when field winding gets cut; in this case under no-load when you switch on the armature voltage E a under such conditions it can run away. So here the runaway condition would be field suddenly goes to zero and here runaway condition would be and of course no-load no-load start startup of the motor where you apply the E a. So the I a starts increasing and then that will give you a torque which is proportional to I a square and then the speed picks up very fast.

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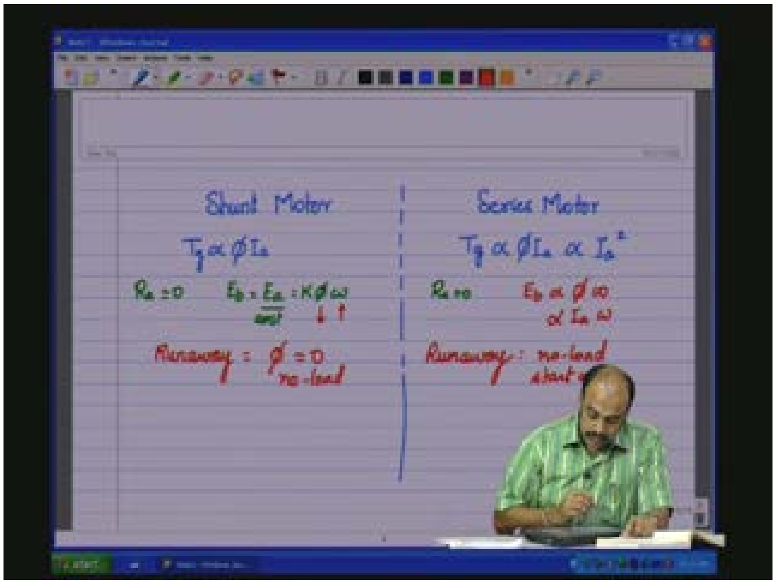

Now, in the case of the series motor as the torque is proportional to I a and during the startup the back emf is almost close to zero I a will be large and therefore torque as it is proportional to I a square the generated torque it has very high low speed torque in the case of the series motor whereas in the shunt motor the torque is limited because it is just proportional to I a and it is limited to I a which is the rated value. If I a is having a per unit value of 1 that is 100 percent torque will be having per unit value of 1. But in the case of T g which is I a square it is square times the rated value. So therefore you have a T g which is............ for example; if I am having T I a is equal to 10 amps rated for both the cases T g will be proportional to 10 amps whereas T g will be proportional to 100 amps for a 10 amps rated, this makes a torque which which will be much much higher than the shunt motor torque for the same armature winding rating of the currents. So this makes series motor special in some kind of an application where you need very huge torques especially at low speeds.

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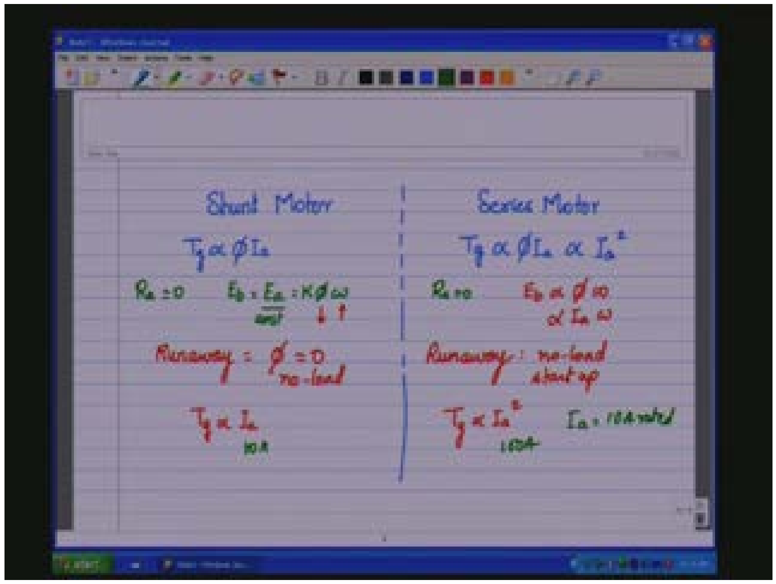

Now some such applications would be like in traction in electric traction; a series motor will be able to generate very high torque in starting in overcoming the initial inertia. Or in the cases like cranes where you may need huge torques in lifting a particular load now these are applications where a series motor would be ideal.

Now a compound motor; a compound motor is a combination of these two that is you have the motor; we have the brush the brush is connected to the electrical wires. Let us say we have an R a the armature winding resistance. Now the brush brushes are connected to the terminals of the motor as shown like that. So across the terminals of the motor we apply E a and there are two windings: one will be the winding we will call it as the shunt winding and then let us say there is another winding let us call it as the series winding. So the shunt winding and the series winding are connected in a fashion as shown that is we have the shunt winding which is connected across the applied source and of course we need to have a R f here, R shunt.

Now the series winding will be connected in series as shown where the armature current flows through the series excitation. So you have a phi series and a phi shunt. So the series winding the shunt flux will be the dominating flux in most of the cases so you will have the resultant flux which is the shunt flux plus or minus the series flux that is the shunt flux meaning the flux generated by the shunt winding plus or minus the flux generated by the series winding. If it is aiding then we say it is a cumulative compound cumulative compound. So in a cumulative compound motor the flux is the shunt winding flux plus the series winding flux they aid each other they add up and then you have a larger flux and the differential compound differential compound the flux the resultant flux will be the shunt winding flux minus the series winding flux so the resultant flux is going to be lesser in amplitude.

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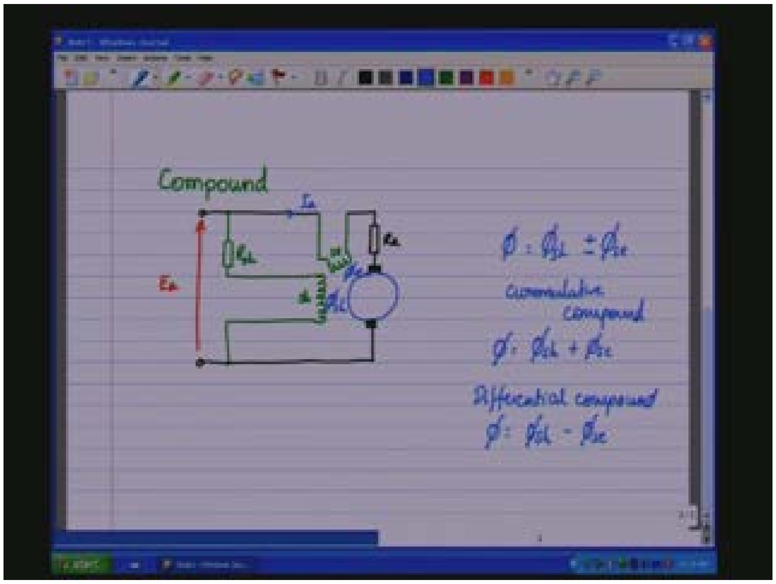

So in a cumulative component at initial startup condition, omega is equal to 0 there is no back emf, I a has not started but there is still I f that is I shunt which is going through the shunt winding so there is a shunt excitation which is there, so phi shunt is there is present inside the machine and I a is beginning to grow so during initial conditions the motor will act like shunt motor then once the gradually the motor is picking up speed you have I a also flowing because of the load and because of the load we have the series field contribution also. So under no-load conditions I a is going to be negligibly small. So even under those conditions you will have the flux contributed by the series small much smaller than the shunt field flux and therefore under such under no-load conditions it will act like a shunt machine and therefore under no-load startup condition where the series motor would run away in this case under no-load startup condition it would be like a shunt machine and therefore there will not be the possibility of runaway under such conditions.

the In the case of yeah in the case the cumulative component under full rated load the series field flux plus the flux due to the shunt they add up and they will reach the rated flux. Now, the under load conditions because I a is going to be large the flux is going to be higher than under no-load conditions where the series field flux is going to be less significant. So the flux in the machine is going to increase from let us say phi shunt value to phi shunt plus phi series value as the load increases from no-load to full load. So as the flux increases you saw that the back emf is connected across the armature winding and if you say the back emf is constant for a given speed then as the flux increases the speed will reduce so which means that as the load is changed from no-load to full load flux is increasing and the speed will reduce and in the case of the differentially compound as the flux as the load is increased from no-load to full load the field starts from phi shunt value and starts decreasing. As the as the flux decreases the speed will increase to maintain the back emf constant. This means that in the differential component there could arise some instability due to increase in speed and that could cause some runaway issues. So normally the compound motor is not wound for differential purpose it is normally wound as a cumulative compound motor.

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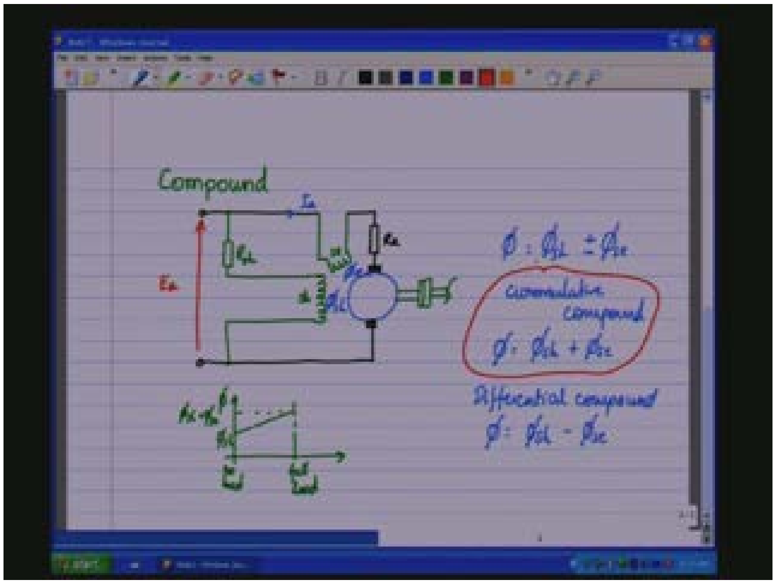

Let us understand consolidate with a couple of examples; one of the shunt motor. Now let us say we have shunt motor we have a shunt. Now if the shunt motor is rotating at 1500 rpm and it has a 120 volts dc as our E a applied to the terminals of the motor. Now I a is 51 amps and R shunt or R f or field winding is 120 ohms, R a is given as 0.1 ohms. Given this let us calculate I a, let us calculate the E b and let us calculate the mechanical power developed by the motor. Let us do these three things.

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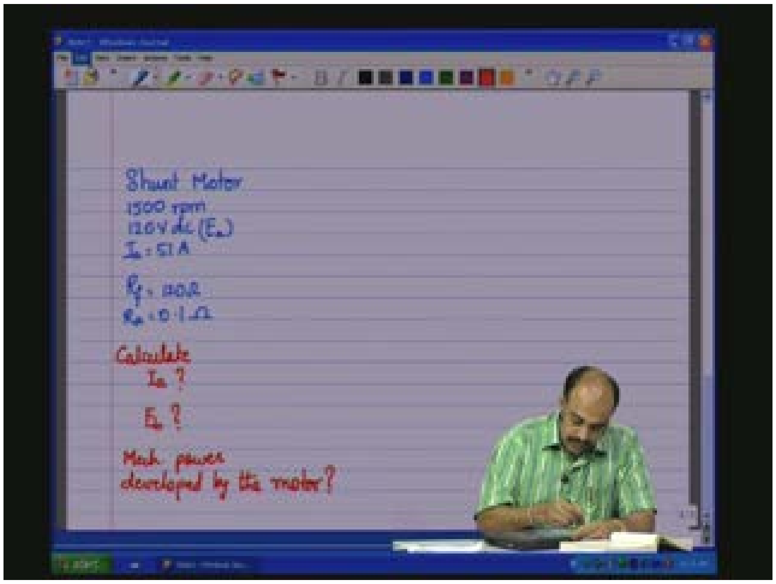

So let me have a copy of this so that we shift pages, we could look back at it. Now we know that the schematic is like this. This is the shunt field (Refer Slide Time: 20:11), we have R a, we have the field winding, the brushes; the mechanical load is connected in this fashion, terminals of the motor. we have E a which is applied here, we have I f flowing through this, there is also R f, there is I a which is flowing through this and let me just make a modification what we take from the current here is the let us say the source current is 51 amps; instead of saying I a is 51 amps let me take it as the source current as 51 amps so now what we have is this is 51 amps, we have 120 volts and this is rotating at 1500 rpm, now R a is 0 point 1 ohms and R f is 120 ohms so we have these things which are..........

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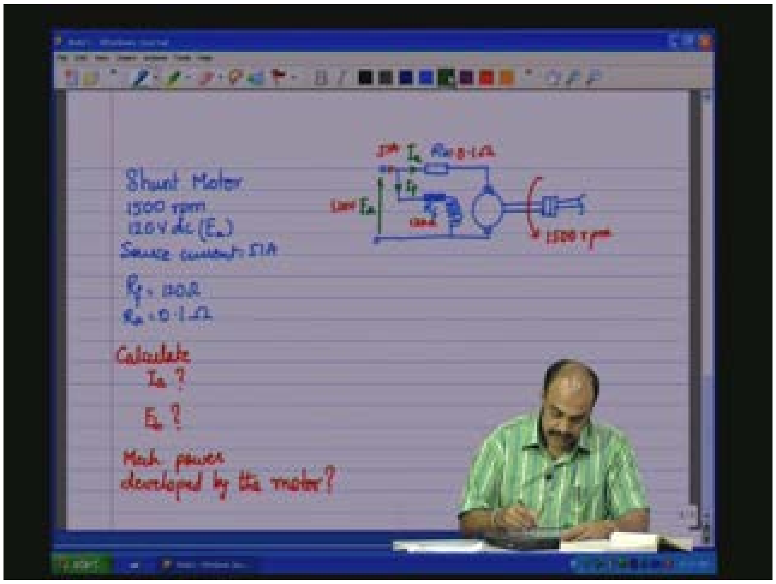

Now let us calculate first I a. now I f is known, easy to calculate which is 120 volts by 120 ohms which is equal to 1 amps. So 1 amps flows through I a, 51 amps is coming from the source so I a is equal to 51 amps minus I f which is equal to 50 amps because I f is 1 amp.

Now what is E b?

Now E b is the back emf which is across the brushes that is E b, it is E a minus I a R a drop E a minus I a R a drop which is 120 minus 50 amps into 0.1 ohms which is 115 volts is the third.

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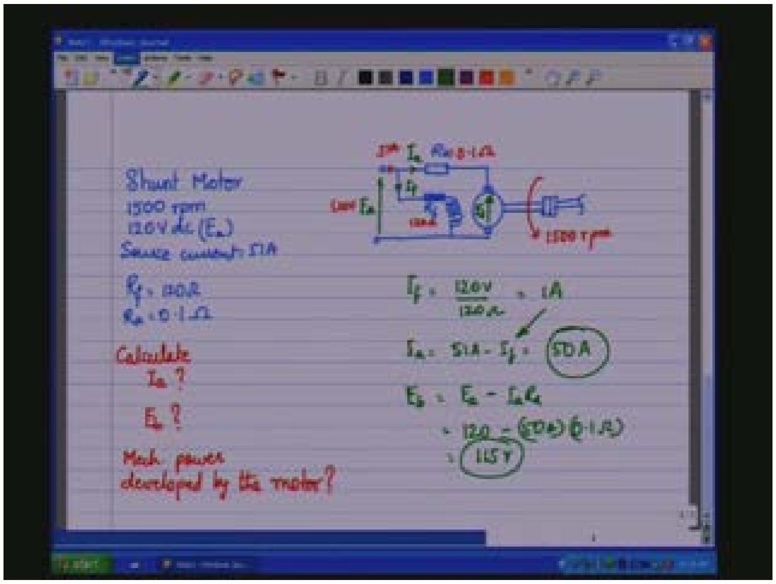

Now the final point in this problem is that we need to find we need to find the mechanical power which is given to the load. So, if we look at what is the power that we actually delivered to the load what we get here is E a I a R a drop I a square R a drop goes off and what is given is ultimately the power which is......... so the power let us first find what is the power which is drawn from the source P source or P a so P a will be E a into 51 amps which is 120 volts into 51 amps which is equal to 6120 watts and what is the power absorbed in the armature the power absorbed in the armature P armature will be E b into E b into I a watts. So E b into I a watts is nothing but this voltage which we calculated which is 115 volts into this current which is 50 amps which is 5750 watts. So this is the power that is delivered to the armature and given as which will appear as the mechanical power that can be developed by the motor. So this your final the third point in the question which can be answered.

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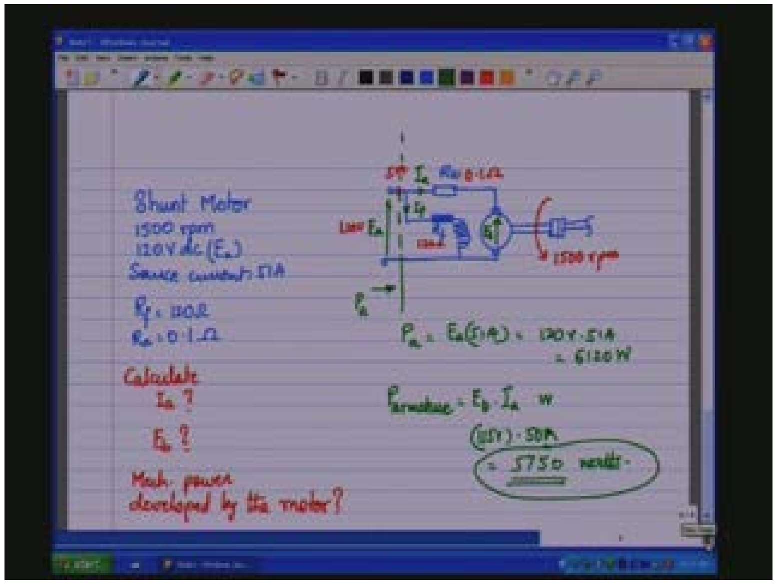

So let us take up just one more example on the series motor. So let us say we have a series motor which is rated for 15 hp 240 volts, 1780 rpm and rated current of 54 amps 54 amps. Now let us calculate the current and speed when load torque is 224 newton meter is 24 newton meter. Let us further say that there is a torque speed curve there is a torque speed and torque current curve which is given for the series motor which looks like this. This is torque (Refer Slide Time: 28:22) and on the x axis you have the speed N and also the I a both these. So the torque speed curve this is torque verses speed, so as the speed is increasing the torque is reducing and at very low speeds the torque is going to be very high I a square and there is torque verses I a let us so when I a is equal to 0 it is like that and then it is taking a square form because torque is proportional to I a square so it goes in this fashion. And let us say this is our rated load. So this would be the rated load and this would correspond to our per unit 1. So, if we say these are all in per unit values this is also in per unit values and this would be 1.0 1.0. So at rated current 100 percent current there is a 100 percent torque. So this is the condition that is this is the graph which is also given to us. So now let us calculate the various things asked.

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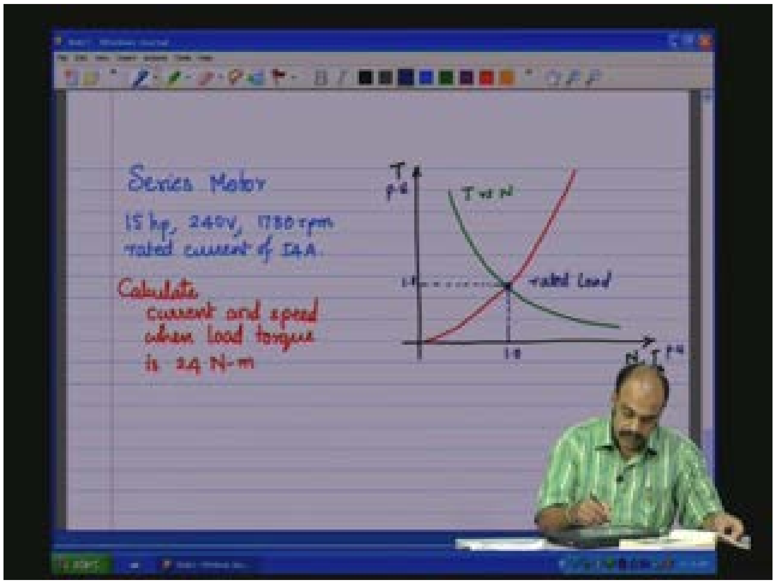

Now what is the power?

The power or the base power we will call it as P b which is 15 hp and let us convert it into kilowatts which is 15 into 746 which will be 11190 watts this is the conversion that we have assumed for the conversion from hp to watts 746 watts is 1 hp, then the base speed is 1780 rpm and the base current is 54 amps given.

Now the base torque is given by the relation which we worked out before which is let us say power base power divided by speed in radians but we have the speed in rpm N rpm into 2 pi by 60 would be in radians which will be 60 into 1 11190 watts divided by 2 pi into 1780 rpm which is 60 Newton meter, 60 Newton meter is the base, T b base.

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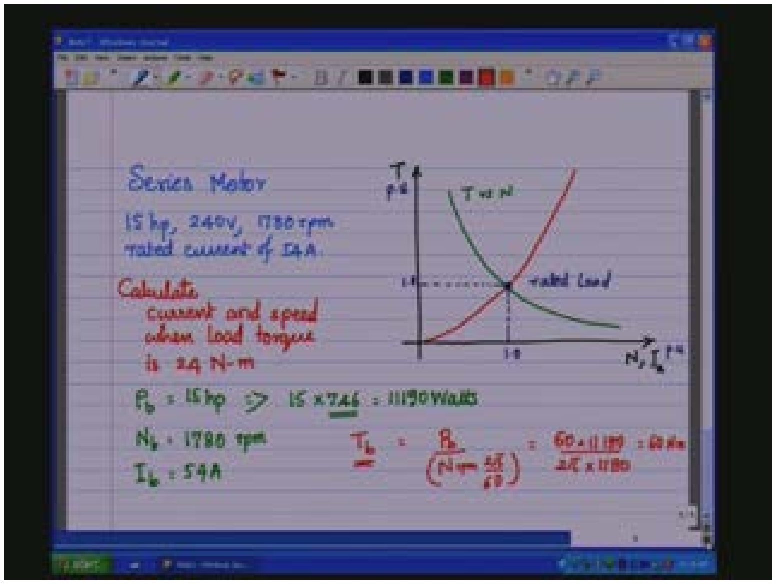

Now the torque load torque is 24 Newton meter. This means per unit value wise per unit would be 24 by 60 which is 0.4 p. u so all should be calculated at 0.4 per unit value. So when we look we go back to the characteristic (Refer Slide Time 33:18) let us say if this is one and this is and somewhere here is our 0.4 per unit so at that we have speed which is 1.4 per unit let us say as given.

So the speed now would be, the speed at 24 Newton meter torque is equal to 1.4 into 780 that is this is obtained from obtained from torque verses speed characteristic. Now this is equal to 2492 rpm.

Now the current I at that is at I a at 24 Newton meter will be will be whatever the current in per unit obtained from torque verses I a characteristic into I base so which will be.............

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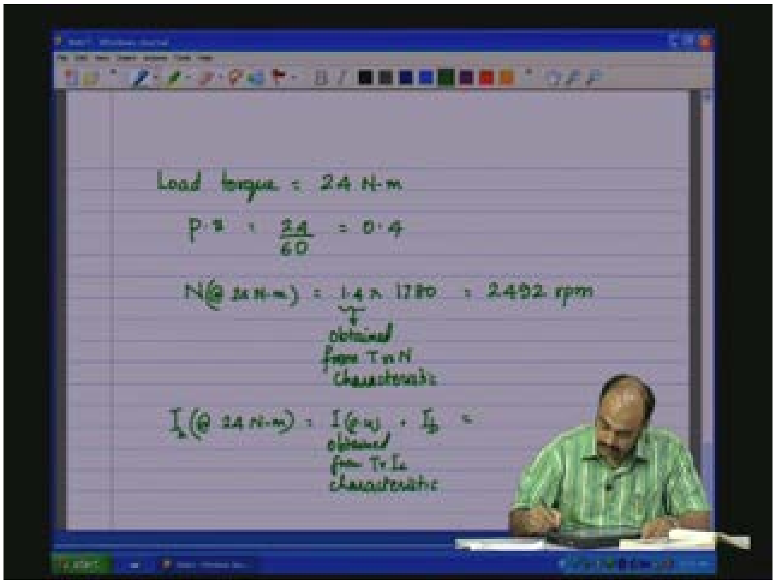

So going back to the characteristic here (Refer Slide Time: 35:35) you will see that the it cuts the torque verses I a curve the torque verses I a curve around 0.6 let us say 0.6 per unit so this will be 0.6 into 54 is equal to around 32.4 amps so this would be the I a and the speed at a torque of (Refer Slide Time: 36:14) 24 Newton meter for a characteristics as given like this for this particular machine. So this how one goes about calculating.

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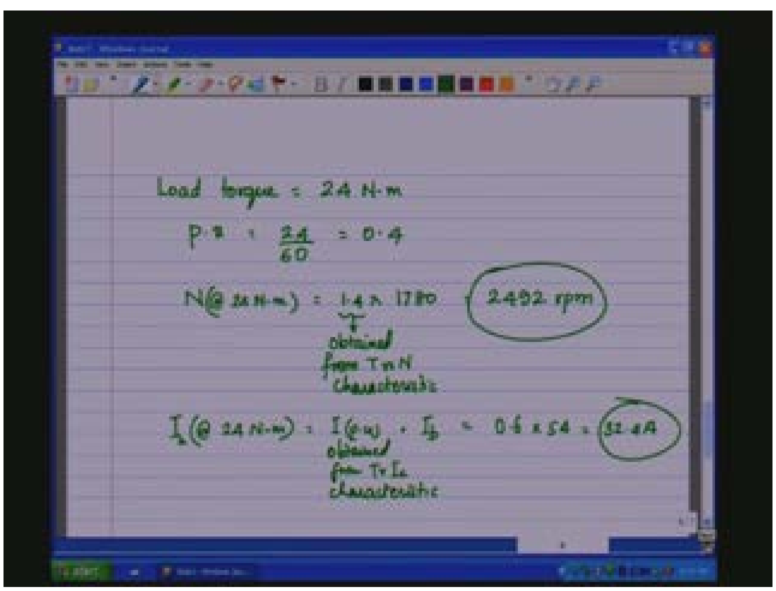

So now we have one more major issue in the motor and that is how to stop the motor that is braking, how do we stop the motor. So the braking is accomplished by 4 by 4 methods; can be accomplished by four part methods 1 2 3 4. First one is the simplest; we call it as coasting let us say. The second one by applying mechanical friction by applying the mechanical friction on the mechanical side. The third one on the electrical side you are applying a load which is called the dynamic breaking and the fourth one is called plugging. These are the four methods in which one may try to stop the motor.

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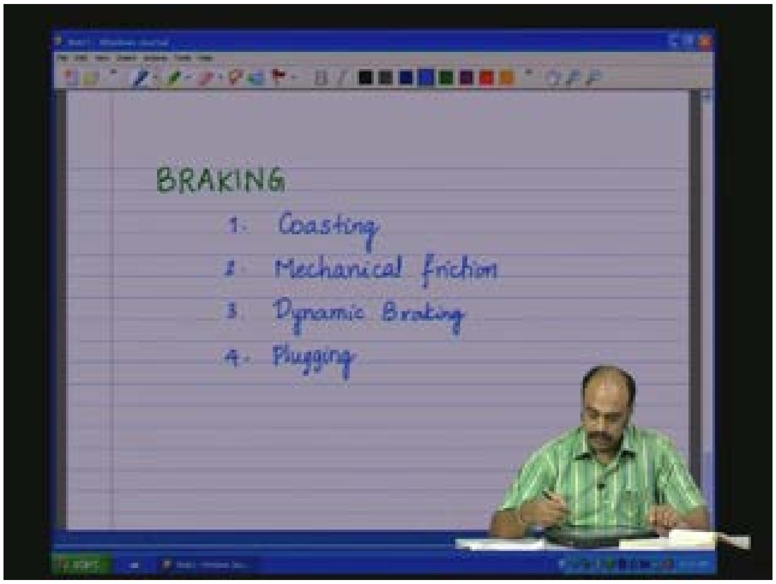

So, if you look at the schematic of the motor system, let us say we have the DC motor, brushes, the brushes are connected to the brushes are connected in this fashion (Refer Slide Time: 38:30). Let me now make a small modification the way we normally draw the schematic. now So I am going to have these three positions here. Now here I am going to....... let me take another colour so here I am going to put our E a E a now there is of course a field winding which is also going to be connected to E a so this is R f and there is going to be a I f field so this is going to generate your phi. Now this is your I a armature current.

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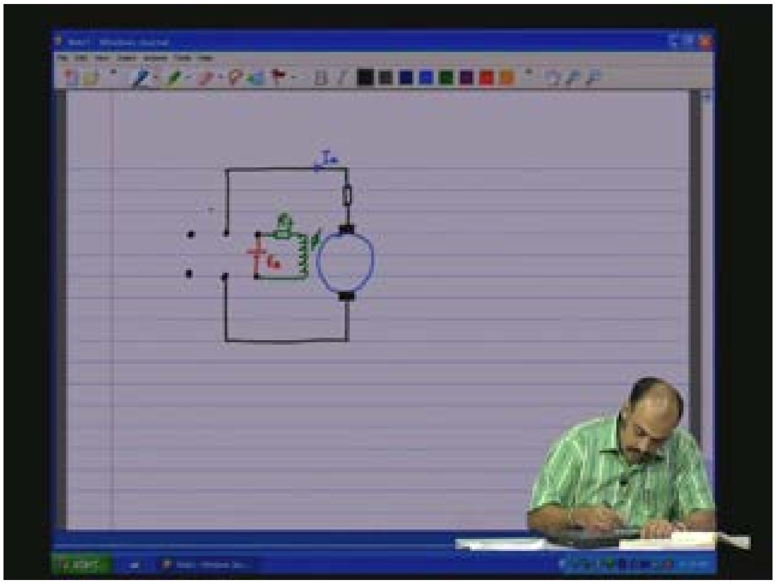

Now I am going to have a double pole double throw switch. This is a double pole double throw switch. Let us give some names, let us say a b c d e f e f. Now what we supposed to do.... this is the DC motor. Let us have the back emf E b here and we are going to connect the shaft to the load. So this is the system that is right now existing. I will make a copy of this for future, copy (Refer Slide Time: 41:13).

Now the motor is rotating which means we have a generated torque and it is rotating at some speed omega, now we want to bring it to a stop. So what do we do; now when the motor is rotating that is let me call it as motoring, so when it is motoring a c b d are connected connected, a and c are connected, b and d are connected that is here we put these double pole double throw switch two positions c and d. So a and c are connected b and d are connected so which means the armature voltage is applied to the brushes of the motor. So this will cause I a to flow and therefore motoring will happen and then there will be generated torque and therefore the speed.

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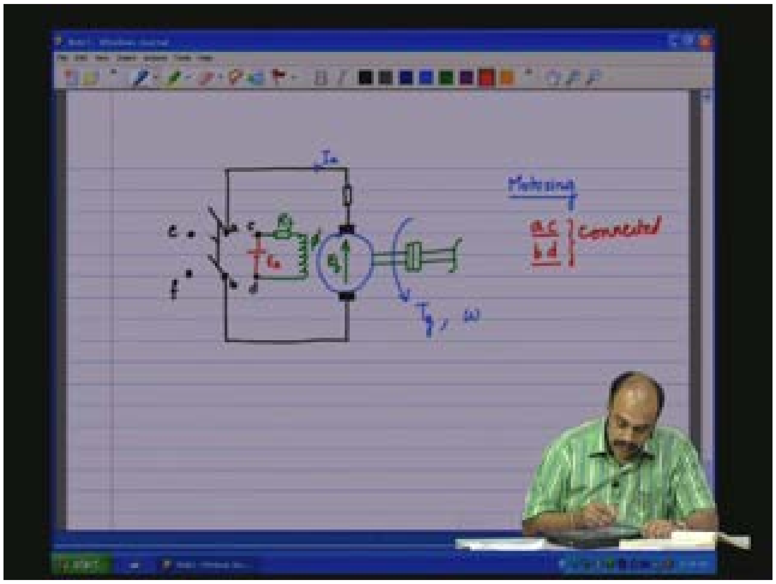

Now if we open this switch that is disconnecting the switch such that a and c are open, b and d are open under such condition there is no I a flowing which means I a is equal to 0; I a is equal to 0 means generated torque that is if a c b d are open I a is equal to 0 forced to zero what happens to T g; T g being proportional to phi I a T g also becomes 0 there is no generated torque but there will be inertia in the mechanical side which will make it to continue to move; like if you are travelling in an automobile if you switch off the engine it will still continue to move because of the momentum because of the inertia which is stored in the mass of the vehicle. So we just allow it to gradually die down, there is no torque applied so on its own because of the frictions associated in the bearings and so on and so forth the shaft will coast and gradually come to zero. Now that may take quite a long time depending upon the amount of inertia which is there on the shaft. Now that is called coasting mode.

In the coasting mode we are not doing anything, there is no extra circuitry we are just opening out the armature such that the I a is 0, the generated torque is 0 and it will gradually come it will gradually come to zero. What will come to zero the mechanical speed the omega will gradually come to zero.

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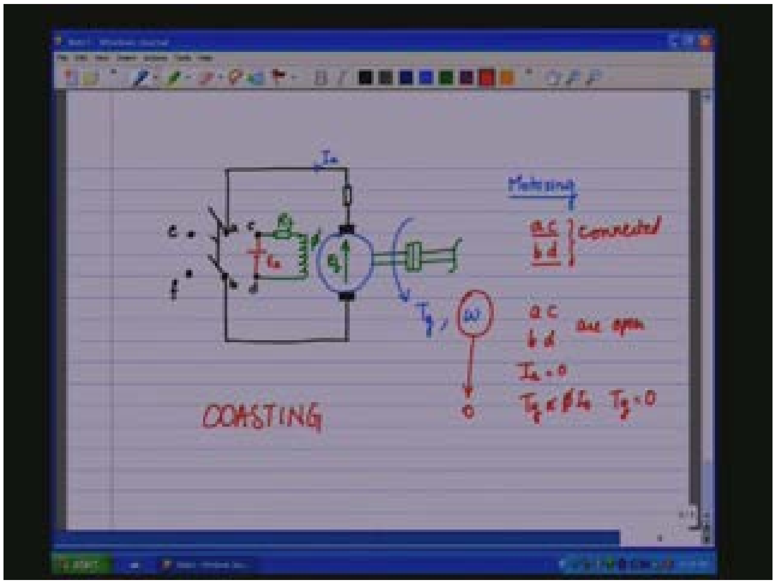

Now if the inertia of the mechanical system whatever is connected as a mechanical load is very high then it can take quite a long time for it coast for it to coast down to zero. So what can be done, we could take the second method which is applying mechanical friction. So let us say to this system which we have here (Refer Slide Time: 45:18) let us apply bricks like in a vehicle. So let us say at this point I am going to put something here and let me call that one as brake shoe. Now I apply a force F to the brake shoe so which means the mechanical shaft is rotating and you are going to apply force on to the brake shoe and the brake shoe is going to hold on to the shaft and then due to the friction between the brake shoe and the rotating shaft the mechanical system is going to come to halt which means the mechanical energy which is stored in the inertia is going to get dissipated as heat in the friction. So therefore you have the loss the loss of the energy through the heat developed because of the mechanical resistance of the heat in the friction. Now this is called mechanical braking.

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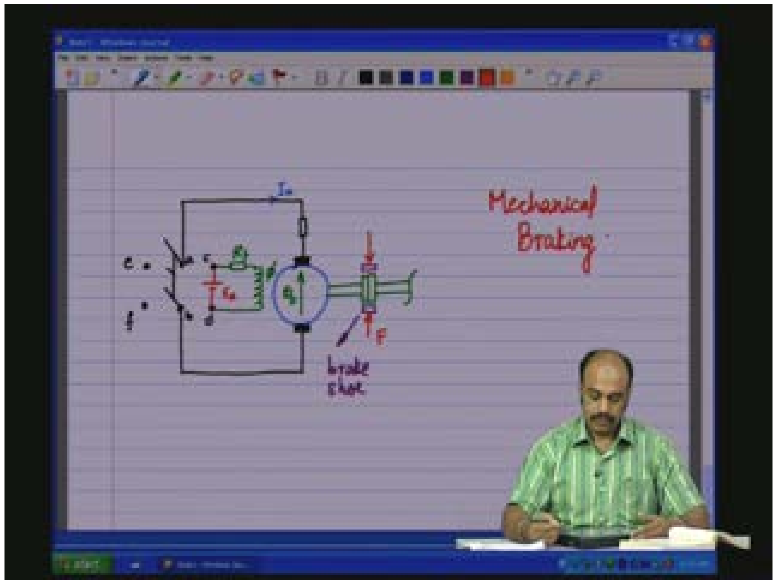

Now we could also try to brake it not only in the mechanical domain because we say that there is an electrical domain and the mechanical domain and we can move through any of the domain because energy is domain invariant. You can apply the brake or try to remove the energy which is there in the inertia or in the mechanical domain by dissipating in the resistor in the electrical domain that is also possible that is called dynamic braking.

So, in the dynamic braking what we do, the inertia the energy stored in the inertia of the mechanical domain is going to get reflected as E b it is a generator. Now that E b we will try to remove it by connecting a resistor here now I will say R b. So when it is motoring the switch here is connected to c and d so which means a c is short, b d is short it is motoring, I a is flowing. Now, during braking we open the switch and connect it connect it to e and d which means a and d is short, b and f is short which means now the whole system is acting like a generator. The inertia is rotating the shaft, there is a generated voltage E b which is going to be seen as a voltage across the terminals of the motor here and then applied to a load R b so there is a current which is going to flow in the reverse direction I a or if the current is already flowing in I a that is going to decay pretty rapidly because that gets because that gets dissipated in R b as I a square R b. So therefore the energy stored in inertia instead of being dissipated in the mechanical friction here is going to be dissipated as electrical heat in the resistor or the braking resistor R b shown here due to the armature current now flowing through the resistor. This will bring down the speed pretty quickly just like in a mechanical brake. Now this kind of braking is called dynamic braking.

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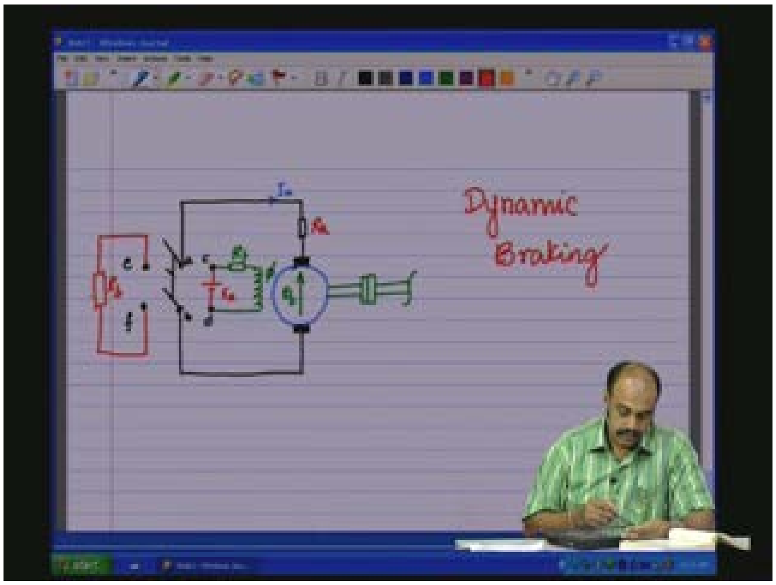

The value of R b here is chosen, equal probably to the rated current or sometimes even to twice the rated current depending upon how quick you want to have the braking effect. If it is twice the rated if the if it is chosen as E b by 2 I a is the value that you need to calculate for R b then it can handle twice the rated current for the same E b which is produced due for that particular speed the R b value is much lower and therefore more I a flows through R b and then gets dissipated much faster because higher the value of I a means I a square R b is going to be much higher and therefore the amount of energy that is drawn in unit time will be more and therefore the speed at which it will reduce and come to zero will be much faster.

Now in the fourth case called plugging what is done is we shall connect another source like this. Now I will call this one as E p or E plugging or E b; now E b is for the back emf E p is for plugging. So now what is done is when a and c are connected a and c are connected, b and d are connected then it is motoring. under such conditions I a is equal to E a minus E b by R a.

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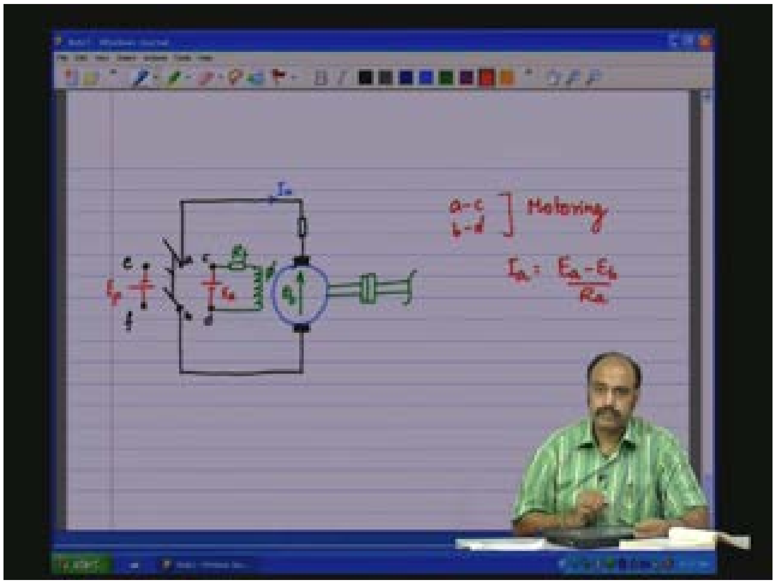

Now when we want to stop we open this double pole double throw switch and then connect it to e and f. So while braking a and e are connected, b and f are connected this is braking so under this condition what is I a; now you see the polarity here, we have applied a reverse polarity here as compared to E a so this would be in line with the generated back emf of polarity so I a would be E p plus E b by R a and that is in the reverse direction; immediately it is going to change the direction, you are going to have a reverse current flowing but it will be of pretty high value because R a is going to be small whereas here it was the difference in voltage between armature voltage and E b, here it is E b plus R p and E b can be any value up to E a and therefore a very huge armature current is going to flow during this braking time when you are putting the double single pole double pole double throw switch to e and f positions and this will try to make the motor; it is like applying the armature voltage in reverse which will try to make the motor rotate in reverse which means it immediately has to come to a stop and then starts rotating in reverse. So when it comes to a stop then you just remove the double pole double pole double throw switch such that I a becomes 0.

Now this can be pretty fast and this is called plugging. The value of I a can be very high something like fifty to hundred times the rated current so the armature windings may or may not be able to handle that so it has to be properly designed. Under such cases one will have to put a series resistance one will have to put a series resistance R p such that I a becomes during braking or plugging E p plus E b by R p plus R a. So you can adjust the value of I a to a required value whatever the armature winding gauge capability is for a very short time by adjusting the E p value which means this voltage and adjusting the R p value which is this resistance. This can be used to design the armature current value during plugging.

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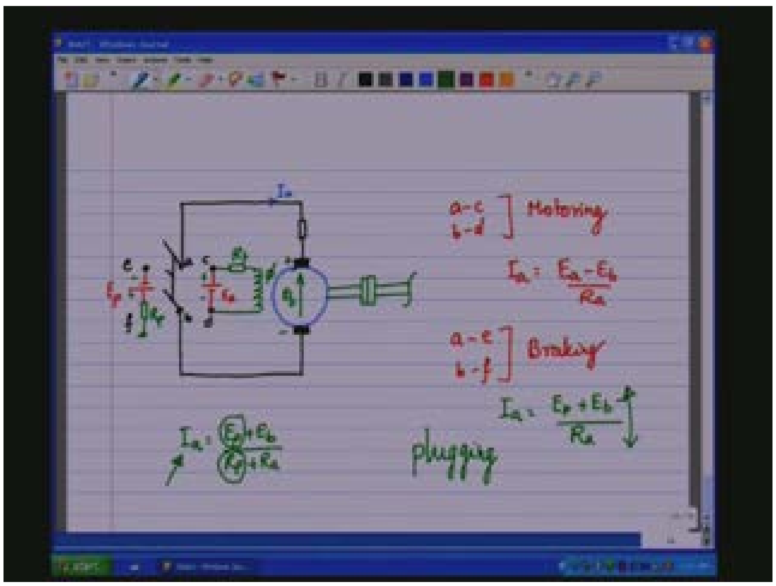

Now this can bring the motor to a very very quick start stop. So, to get a relative idea of let us say the speed omega and let us say the time t and let us say the speed is here at one per unit this is let us say per unit value it is 1 rated speed. So when we are coasting this is going to slow down gradually by its own internal bearing friction, windage loss and things like that and so this can take quite pretty long time to come to zero so this is coasting.

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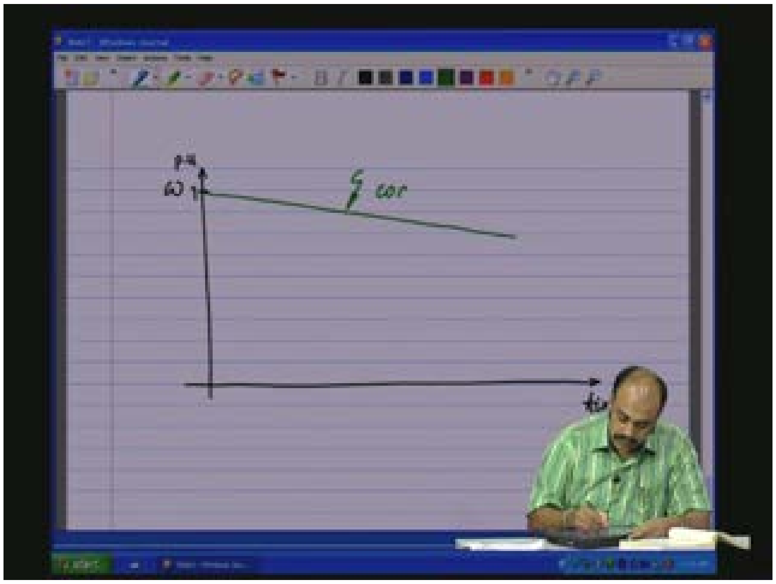

Mechanical braking dynamic braking are similar; only that in the mechanical braking you are applying mechanical brake by applying friction on to the shaft by means of brake shoes that is you are creating a mechanical friction where the heat is lost as heat in the due to the friction. Now in the case of dynamic braking instead of applying on the mechanical side lossy element we are applying the lossy element on the electrical side by putting a resistor and the braking effect can be something like that one it is a time constant. So this would be dynamic braking or mechanical braking.

Then the third one would be the plugging and that would be very fast and you should see that it comes to zero and then after it comes to zero because we are applying R p in the reverse direction it will try to change direct polarity and start rotating in the reverse direction but you have to switch off at the point when omega becomes zero. So this would be plugging. So plugging would be the fastest, you can control its speed the rate of decay of the speed by controlling the value of E p or the value of R p, dynamic braking is putting a resistor across the terminals of the armature and you can control the speed of decay by controlling by controlling the value of the resistor or which is being put across the terminals R b and it is the coasting it is slowest there is no control on that except that it keeps it will go to zero due to the energy which is lost in the bearing friction, windage and things like that so that can take quite a long time if the inertia is very high load inertia is very high. So that is about the braking.

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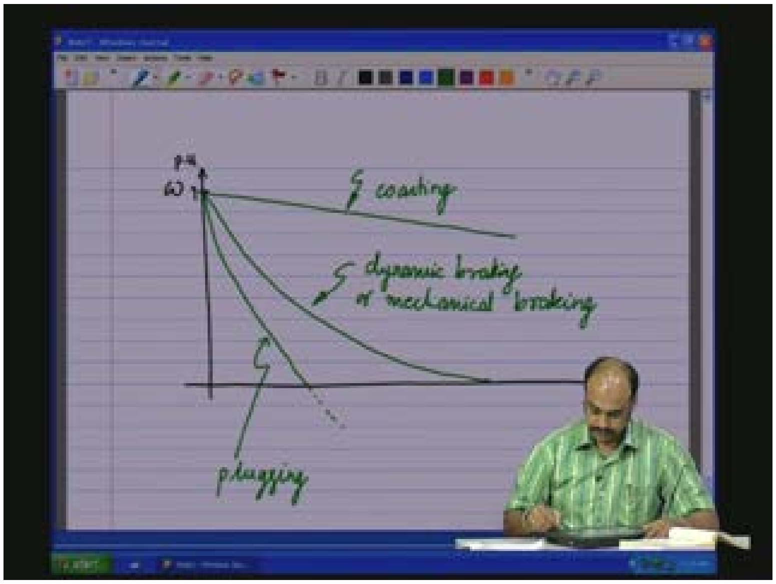

So now finally we would like to discuss about the state space model of the induction motor. It is very simple just like in the case of the generator. So we have the motor, we have R a; now I am going to include the dynamic element L a which is going to cause the decay up the rise time fall time of the motor so the L a is going to come in to the picture which is nothing but the armature winding reactants and we have the mechanical shaft. So here we have the T g and omega, there is reflected inertia, we have the back emf E b and the input E a.

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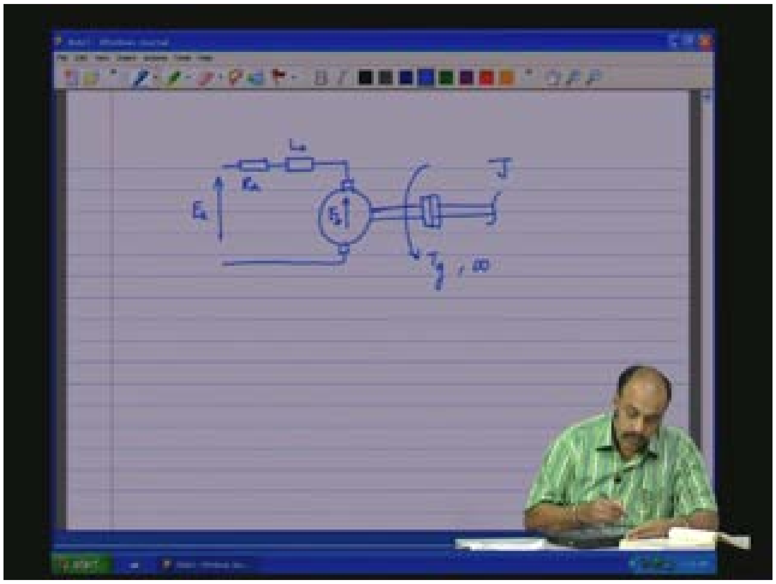

Now to get the state space model what you have to do I have to express it only as E a, there is an I a which is flowing in I a and another state variable omega just like in the case of a DC generator. So we have the equations here. So if we take this loop E a is equal I a R a plus L a d I a by d t plus E b is one equation. The other equation is T g will be equal to J d omega by d t plus friction into omega; same as in the case of a DC generator and this will be k into phi into omega. So this also is expressible in terms of state variables and input variables. Use these two equations to obtain the state equations.

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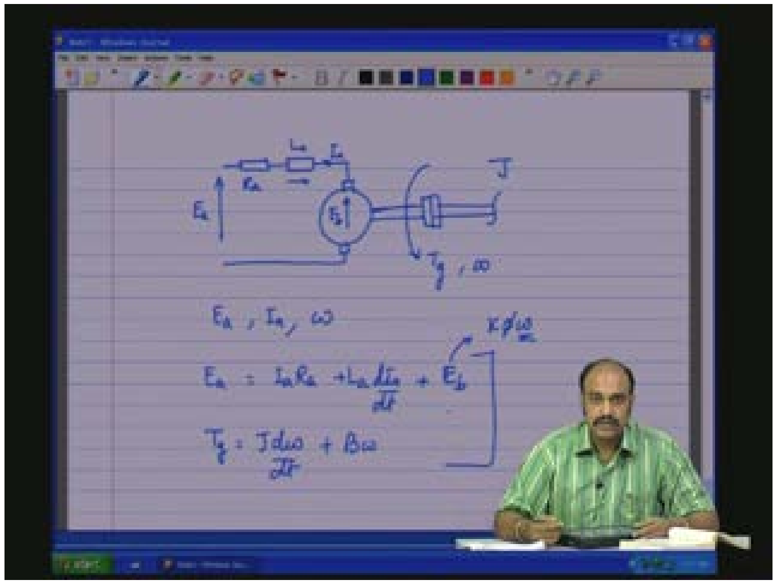

We stop here for the DC motor and continue in the next class. Thank you.