Basic Electrical Technology
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Lecture - 28
DC Motor - 2

Hello everybody. In the last session we had started our discussion about the DC motors. Principally the DC motors and the DC generators belong to the same class with the structure of the machine or the structure of the equipment being similar in both the cases. The structure of a DC generator can be used even for a DC motor only that the flow of power is reversed. In the case of the DC generator the power flows from the mechanical side to the electrical side and in the case of the DC motor the flow of the power is from the side of the electrical to the mechanical side. All the equations and the principles involved are exactly similar to the case of the DC generator.

The DC motor's back emf which is equivalent to the lower end force in the case of the DC generator the induced emf in both the cases that is the back emf here and the generator emf in the case of the generator are having the same equations that is p N 5 Z by 60 volts the only difference being the flow of power; in the case of the DC motor it flows from the electrical to the mechanical side whereas it is the other way the round in the DC generator. So, in this session we shall continue our discussion of the DC motor. First let us review what we have learnt till now about the DC motor. We have the DC motor which is represented as a circle and it has two brushes. So the armature makes contact with the electrical world by the means of these two brushes and the armature winding resistance is represented as an equivalent resistance R a as shown here. There is a source which is applied a source voltage which is applied and we call that one as E a across the terminals of the motor and the armature as the motor is connected to a shaft and which may be coupled to a mechanical load.

Now this DC motor when it is rotating will generate a back emf or a counter emf E b which we discussed in the last class and on the mechanical side we have two variables which we need to consider that is one is the torque which is the potential variable and the other is the omega in radians per second which is the kinetic or the flow variable on the mechanical side and the flow variable on the electrical side is I a.

Now E b into I a is the power which gets into the armature power delivered to the armature and that is going to deliver the rotational power to the mechanical side. Now the torque here........ we saw that the torque here is given by p phi z I a by 2pi this you saw in the last session and we know the induced emf is p N phi Z by 60. So we see here that the induced dmf is dependent on this speed of the rotation the torque is dependent on I a.

If we rewrite this here E b equals p, now if it had been omega in radians per second I have to convert them into rpm so omega which is in radians per seconds to convert it into rpm 60 by 2pi where this is in rates per second. Now this whole thing is in rpm into phi into Z number of total number of conductors in the armature, phi is the flux per pole, p is the number of pole pairs divided by 60 which gives you p omega phi Z by 2pi and torque is also given by p phi Z I a by 2pi.

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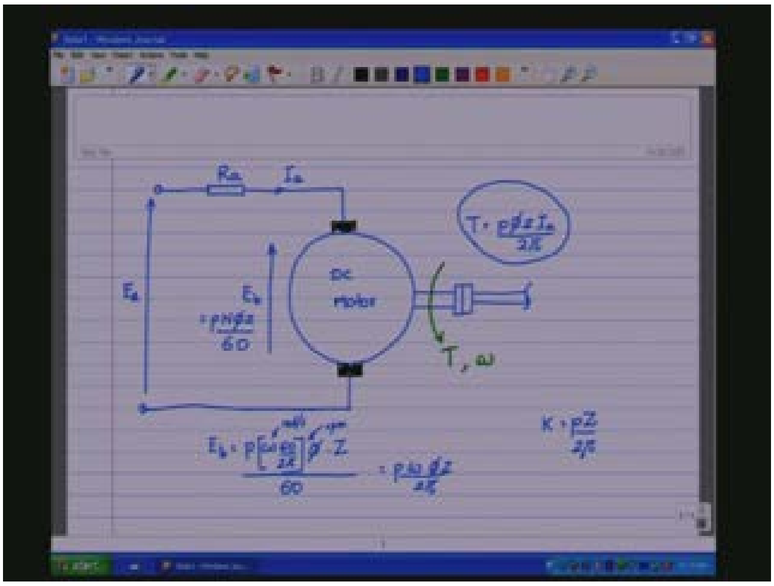

Now let us have a constant K which is defined as p Z by 2pi. This constant k is number of pole pairs, total number of conductors and 2pi which is a constant and therefore it is a constant for a machine constant for a machine. So therefore torque is equal to k phi I a and E b is equal to k phi omega.

Now these two are the important equations in modelling the motor and also in determining the flow of the power and the flow of the power and relations between the two sets of variables the potential variable on the electrical side to the potential variable and the flow variable on the mechanical side and vice versa.

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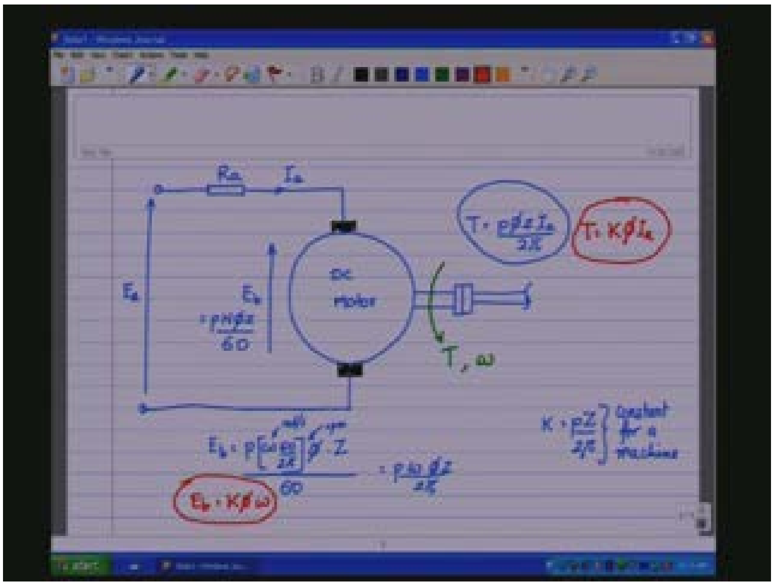

So we now have a motor with brushes as shown here and the mechanical port in the form of the shaft and the electrical port in the form of the black wires being taken out from the brushes.

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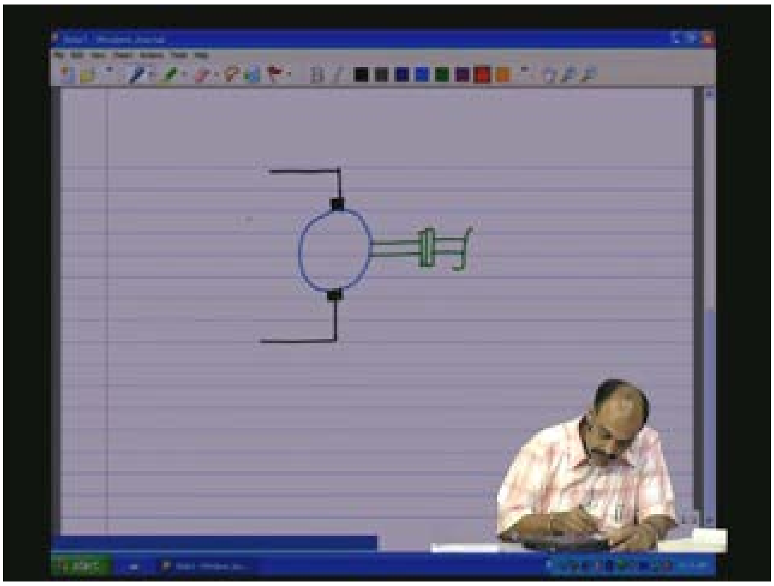

Now E b, back emf which is induced here is K phi omega torque torque okay sorry I will use that is given by generated torque is given by K phi I a is it not? That is what we just now, saw in the previous discussion.

Now what is I a?

I a is the current that is flowing into the armature or the armature current and what is omega here; omega is the speed in a radians per second and where k is equal to p Z by 2pi. Now you see that we have E b and I a on one direction on one side on the electrical side and you have generated torque and omega on the mechanical side.

Now E b is linked, the back emf E b is linked with the speed of rotation on the mechanical side angular speed of rotation in radians per second that is omega and I a is linked with the generated torque as shown by the equations here and the linking variable is K phi is same for both the cases. So therefore this is a GYRATOR. We have already said that the motors, generators are GYRATORS but this equation here emphasis our point that it is a GYRATOR and not a transformer.

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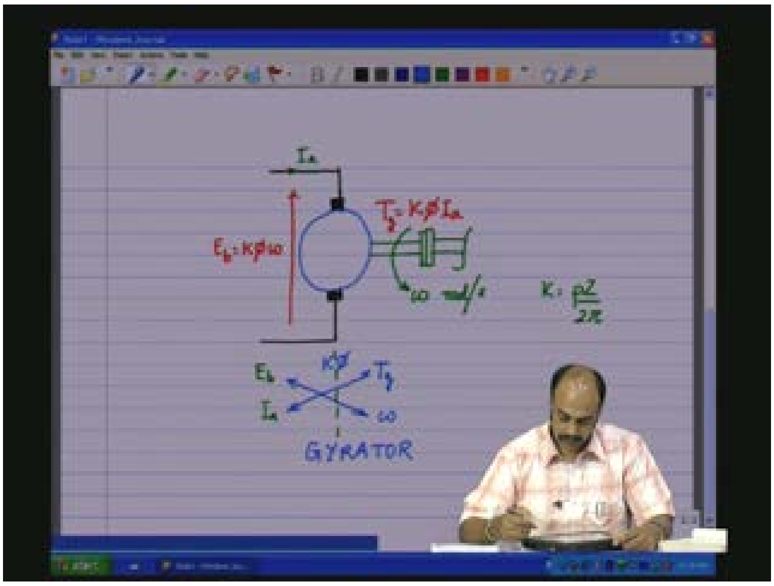

Now, looking at this equations here the torque generated torque is proportional to two quantities phi and I a the armature current; phi the flux the excitation in the machine. So if we vary I a the armature current the generated torque is going to change and for a given load if the generated torque changes the speed is also going to change. So one could control the speed by changing I a or one could also control the speed by changing the generated torque by changing the excitation or control in the excitation.

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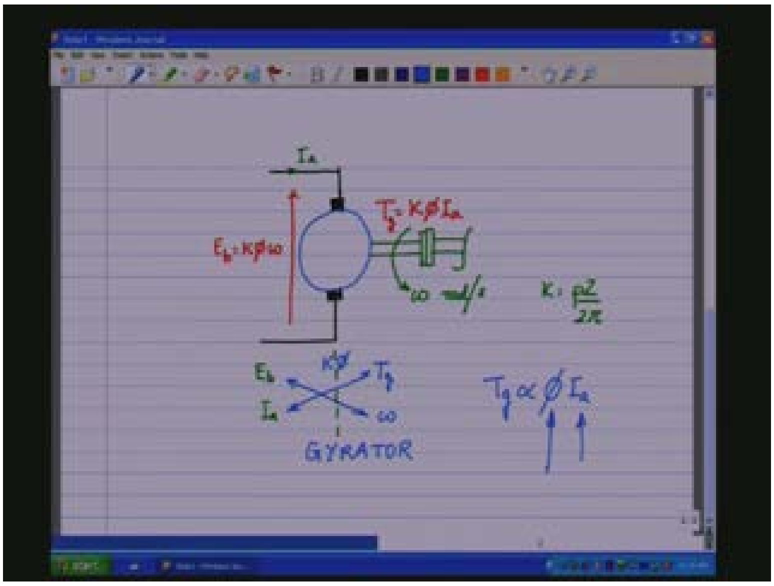

So, generated torque generated torque which in turns which in turn is going to affect the speed of rotation is affected by two variables main variables which is the field or excitation phi and the other variable is armature current I a. So, by controlling the armature current I a or by controlling the field or the excitation phi or both one can change or control the generated torque and for a given load that is going to change this speed. This means that the speed of the DC motor can be controlled by changing these two parameters by controlling these two parameters to achieve speed control.

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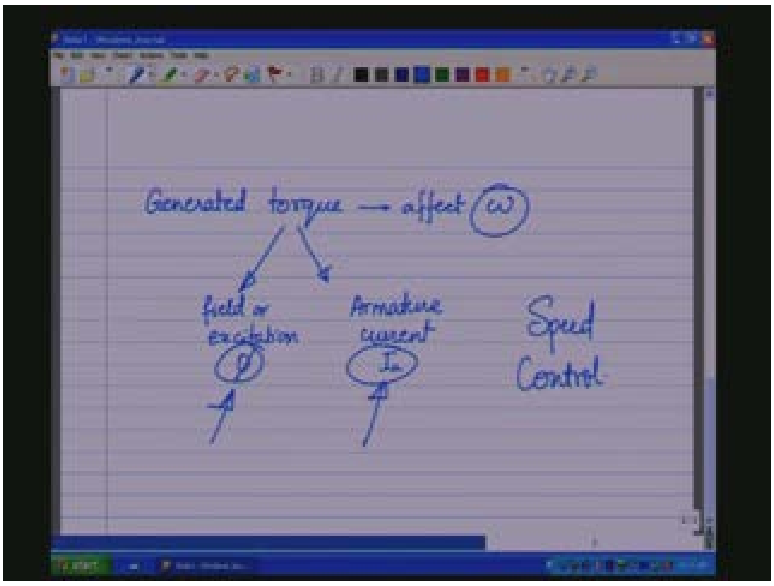

So let us get back to the equivalent circuit and see how we go about achieving speed control. So first let us do control from the armature side armature side speed control. So we have the motor, we have the brushes here (Refer Slide Time: 15:35) and the brushes are connected to the terminals of the motor, they are brought out to the terminals of the motor and we have a resistance R a which is the equivalent resistance that we apply to the motor.

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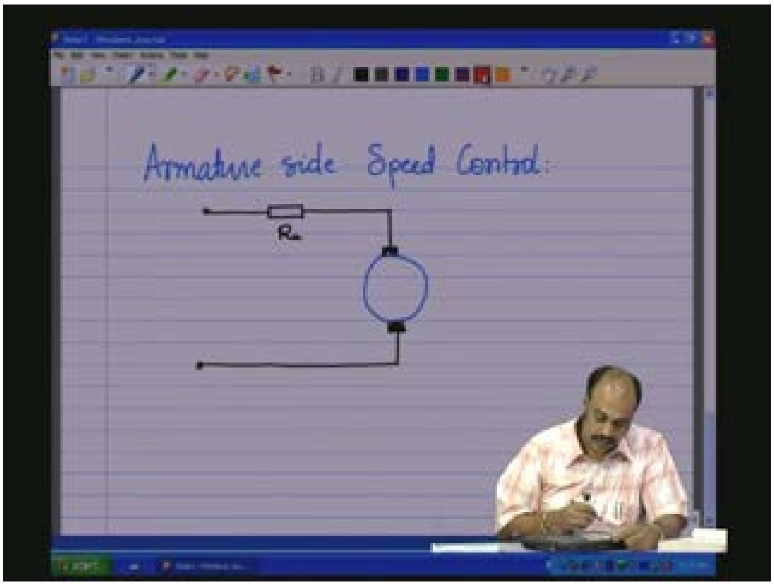

Now this to this motor we are applying a source E a and this motor mechanical shaft is connected to whatever load mechanical load that one wants to connect and this has the generated torque and omega the two parameters, and on this side we are having E b the back emf and I a the armature current which are two corresponding variables the potential and the kinetic variables and this is the DC motor.

Now, to control the speed we need to change E b. Of course the speed is going to affect the induced emf E b and we saw that T g was proportional to these two main things the main parameters phi and I a. Let us first look at how we go about changing phi I a. I a

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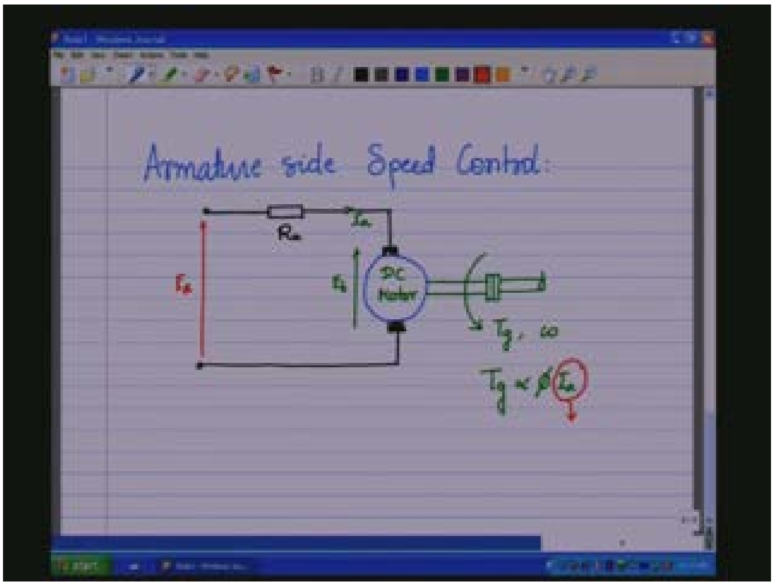

Now the armature current can be changed by either changing this or by changing I a itself by interposing a resistance in series with R a and making that variable as R that is the R s series. So therefore when E a is varied I a is equal to E a minus E b by R a R s is still not putcome in to the picture. Now if R s is put then it is plus R s.

So let us say right now R s is equal to 0. So if R s is equal to 0 we have this equation. Now as E a is decreased as E a is decreased what is going to happen E b is still not decreased, I a is going to reduce because E a minus E b is going to reduce and as I a reduces T g the generated torque is going to reduce because it is proportional to phi I a and all this while phi we are keeping constant and because the generated torque has decreased for the same load omega the rotational speed also reduces and because the rotational speed has reduced this is going to affect E b and E b is going to reduce because E b is proportional to omega so it will come and settle at the new equilibrium point or the new operating point. So this is how the sequence of parameters that will get affected if you reduce E a.

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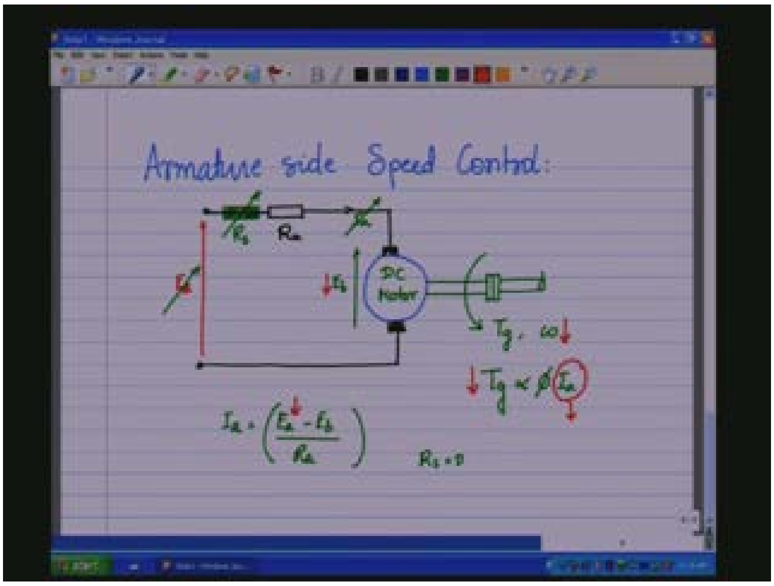

Now if E a is not reduced E a is just gets fixed which means we introduce a series resistance R s. if a series resistance R s is introduced here R s is finite no longer zero. So E a is fixed E b is fixed for now we are increasing R s, moment R s is increased I a is going to reduce, reduction in I a is going to result in reduction in the torque T g generated torque which is going to reduce the speed omega for the same load and that is going to reduce the back emf E b and that will come and get settled in a new operating point. So now E a minus E b is going to get distributed between R s and R a by their values by the ratio of the values. So in this way the speed can be controlled by either controlling the armature voltage or by controlling the armature current by way of a series resistance or rheostat connected in series with the armature.

Now, between the two methods if you see if we introduce a series resistance the whole I a current the armature current is going to flow through the series resistance and there is going to be a I a square R s drop. So, for a power which is E a into I a that is going to be taken from the source and E b into I a that is going to be delivered to the armature I a square R s and I a square R a gets lost as heat out of which I a square R a is inevitable and unavoidable because R a is the armature winding resistance so what is avoidable is I a square R s the series resistance that we have put here to achieve speed control.

So if I a is large for a very high loads then there could be significant loss in the series resistance and therefore the efficiency of the motor will suffer because the efficiency is basically p out by E a I a minus I a square R a minus I a square R s so this going to reduce the efficiency of the sorry plus E sorry I am just going to rewrite this p out divided by E b I a the power delivered to armature plus I a square R a plus I a square R s and we see that it is going to reduce the efficiency of the motor. So it is preferable to do armature voltage control rather than rheostat control.

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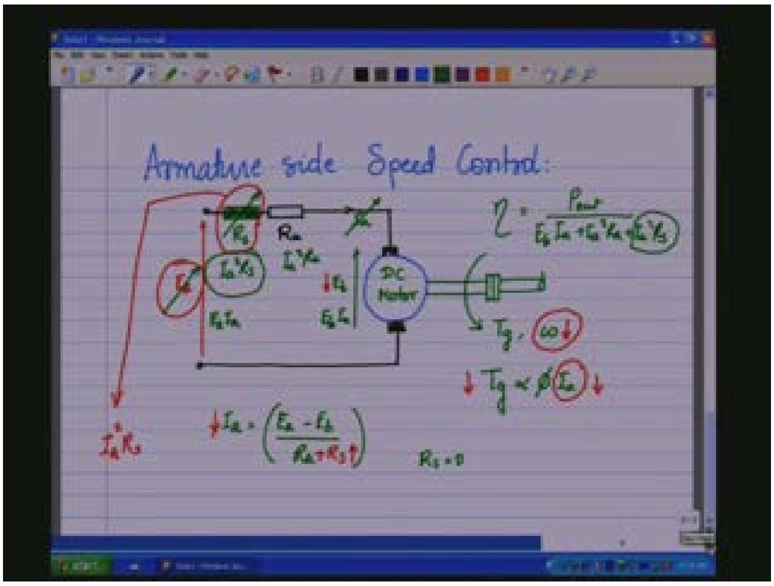

So, in the armature voltage control one could have two machines connected back to back as shown here (Refer Slide Time: 24:30). Now let us say that it is one machine, this is the actual motor which is going to the mechanical load and there is a R a here as shown in the circuit and these are the terminals of the motor so this is the motor. Now here we have the field coil also which I am going to show here and I will indicate that there is a field current I f which is flowing through the field coil to give a flux phi. So phi is set up in the........ now this can be coming from some other source so there could be a resistance here and probably a battery connected here so this could be R field R f and this is f let us say R f; we have been using E everywhere so we will use E f so this is the field coil coming from a separate source. So this is the separately excited motor this is a separately excited motor just like in the case of the generator a separately excited generator case.

Now we need to apply an armature voltage E a that is capable of being varied, a DC voltage. So to the terminals here let us connect a generator here which has its own R a which comes from again another machine another similar machine but it is being operated in the generator mode, so this is a DC gen DC generator and this is a DC motor and the shaft of the generator is being driven by a prime mover and this generator also has a field coil of course as explained before, there could be a resistance, there could be of course a battery some other separate source so you have an R f and an I f which is going to generate phi and this is an E f. So this is going to excite the generator this is also a separately excited generator. So the speed of the shaft or the torque supplied or the energy supplied through the mechanical domain this could be moved by a prime mover, it could be an AC motor or some other prime mover like a IC engine that is the internal combustion engine or any of those things. This prime over is going to supply the mechanical energy through the generator generates the E g here across the generator then after the drop what you get here is E 0, E 0 is the armature applied voltage to the motor. So here you have the motor here you have the generator so E 0 and E a are same.

Now for this generator the load is this motor. So this A is applied to the motor and this is going to deliver again the energy back to the mechanical domain. So if we control the speed of the prime mover the generated voltage here because this is again dependent on the speed here, if the this is rotating at N rpm, what you are going to get here is E g which is equal to p N phi Z by 60 so N here is going to affect E g so by changing N E g changes, E 0 changes and therefore E a changes which is going to change the torque generated torque here which is phi I a which is going to affect omega.

So the speed of this mechanical shaft of the motor side is controlled by controlling the speed of the mechanical shaft of the generator. This type of speed control system is called Ward - Leonard system. This is called the Ward - Leonard speed control system. This is for speed control. This is a very rugged method of very rugged and useful method of controlling the speed of the DC motor especially high power systems.

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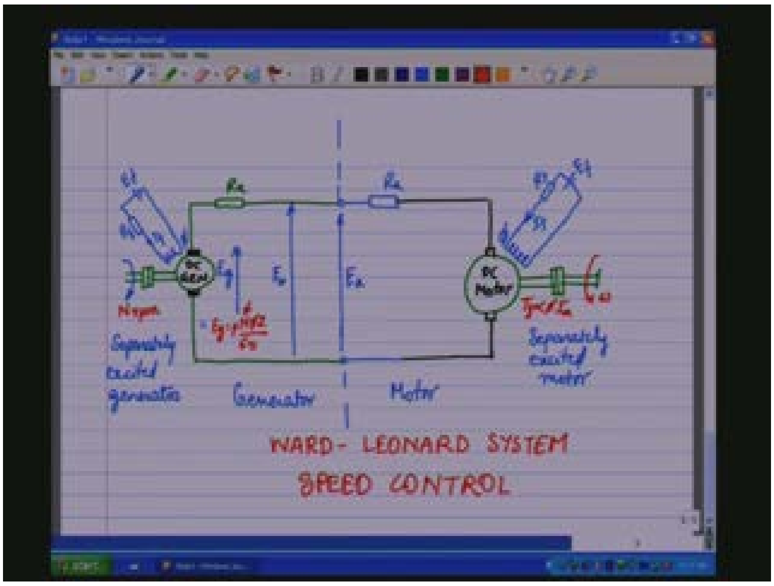

The other method that we saw that we said could affect the speed of the mechanical side and the omega is by controlling the excitation of the flux of the field because T g is proportional to not only I a but also to phi. So if we are able to change phi then we should be able to affect T g and thereby the speed for a given load.

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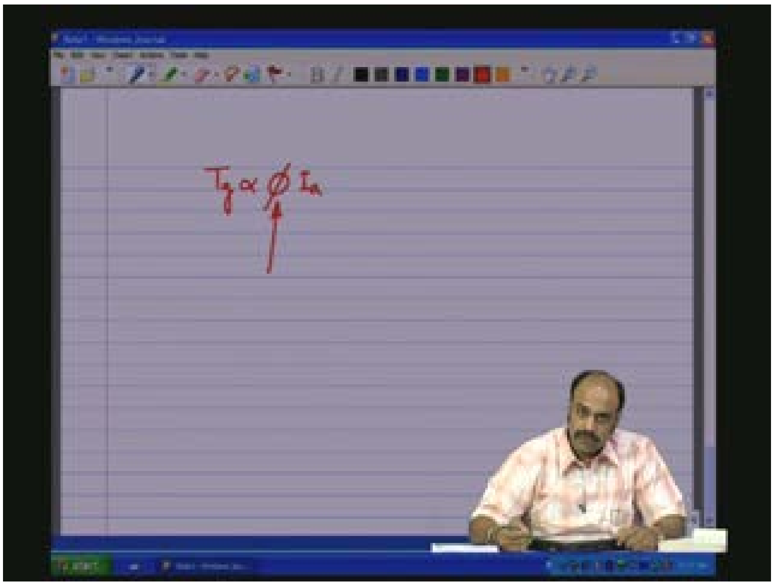

Now how do we change phi?

Changing phi is not a difficult issue. You see that we have a circuit here which is generating the field or the excitation (Refer Slide Time: 31:49) so there is a source a E f and that E f is passed through R f and the current I f or the field current is flowing through the field coils. So two possible ways of controlling I f; so, if we change I f because phi is proportional to I f so if we change If phi is going to change. So I f can be changed either by adjusting this resistor or by changing this voltage value of this voltage source. Both these will change phi which will lead to change in T g which will go which will affect the speed of the motor. But the manner in which we are going to change phi is going to depend also on the way the motor is going to be excited and the motor is excited in the following ways.

Generally we have three main categories for the motor for excitation motor field excitation. So, first method is called the shunt motor. So the name shunt motor is got from the fact that its field is excitation by having the field coil connected in shunt or across the motor terminals. The series motor the series motor is a motor wherein the field coil is connected in series with the armature winding and thereby the armature current flows through the field and third is the compound motor. So in the case of the compound motor as the name suggests it is a mix of both, you have two sets of coils: the shunt coil and the series coil; the shunt coil is connected across the motor armature, the series coil is connected in series with the motor armature. So that is the compound motor and these are the three main types of motor that you would come across, general categories.

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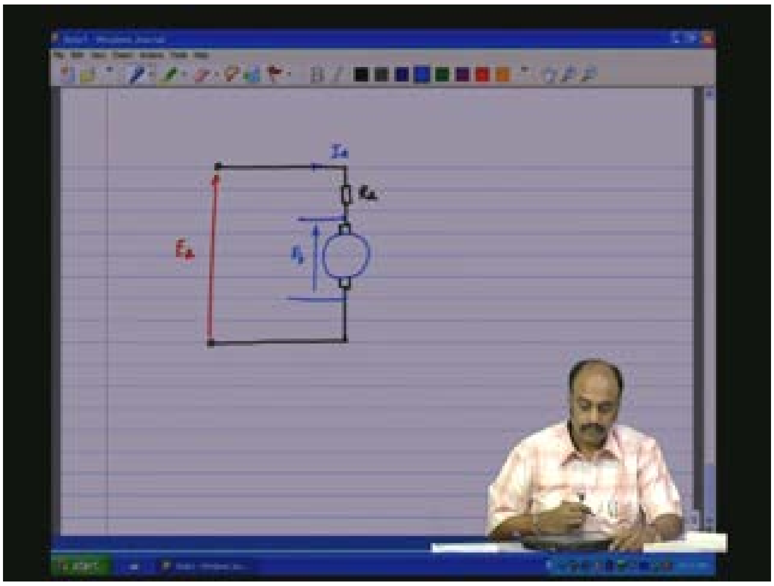

So the field current is generally is very small compared to I a; I f is very small compared to I a and therefore the field coil can be rated for a lower current and therefore the gauge of it that is the thickness of the field wire will be very small in general compared to the armature winding thickness. By varying R f that is by making R f variable the field current can be controlled and therefore I f can be controlled or the flux can be controlled as a consequence and therefore the T g can be controlled.

So, in the case of let us say a constant let me constant field motor let us select this, copy, paste (Refer Slide Time: 40:14). So in the case of a constant field application, phi is a constant then T g becomes proportional to only I a. So therefore as a result as T g is proportional to only I a the torque varies linearly with a load. So let us have a graph of torque versus I a and let us say torque, so the torque would vary linearly with the load so this is T g versus I a this would give you the load characteristic.

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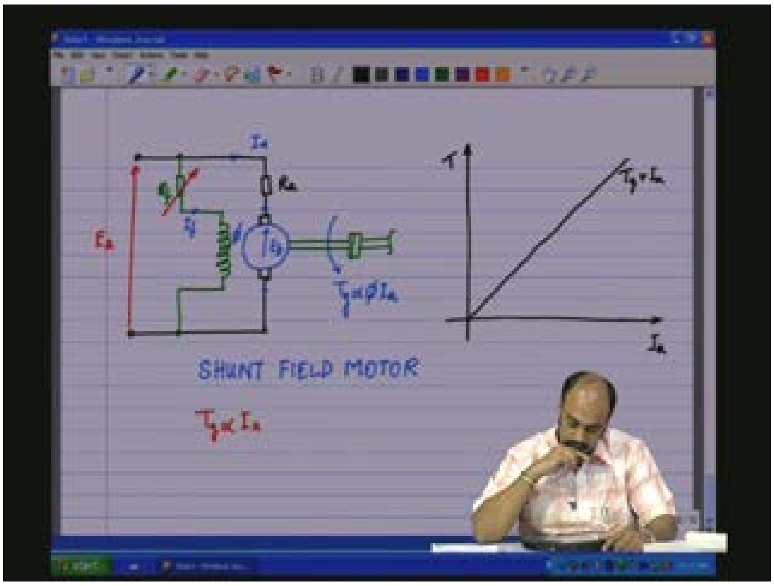

Now if we look at the shunt motor curve with respect to the torque with respect to the speed what happens?

Now T g T g into the omega will be the power; T g into omega is the power. Now let us say we want to the keep the power constant power constant. So, when the power is constant then T g is inversely proportional to omega that is T g is proportional to 1 by omega. So with speed, so if we have speed as one of the axis then T with respect to speed is going to decrease, T is inversely proportional to........ so T versus omega. So as omega increases torque is decreasing. So this is T g generated and let us say this is T g which is load dependent the T g value which is load dependent or the torque value which is load dependent therefore we will say this is the load line, this is the load, this is the generated torque by virtue of its rotation and therefore this is the operating point operating point.

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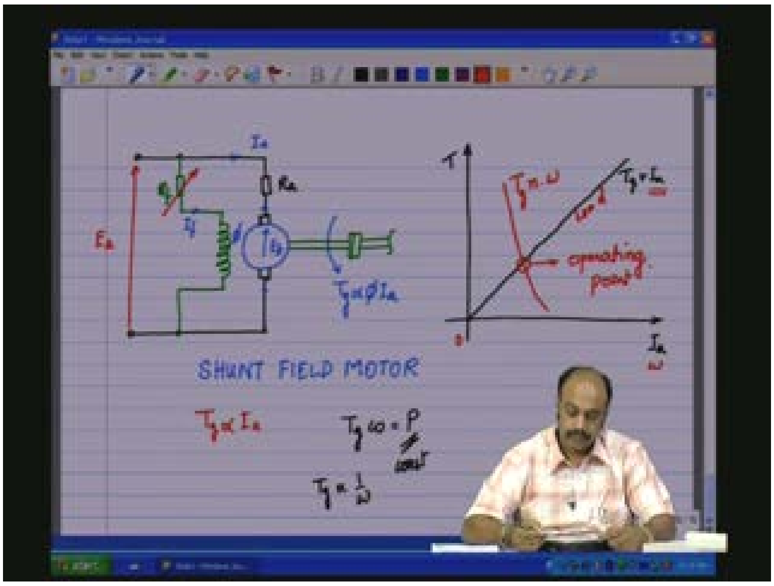

And because the power is constant meaning we are at let us say the maximum power p max let it be constant and let us say P max then this would indicate maximum or rated load this particular operating point. So the torque at rated load and at rated speed or the nominal speed so that would be your I a rated, omega rated in radians per second.

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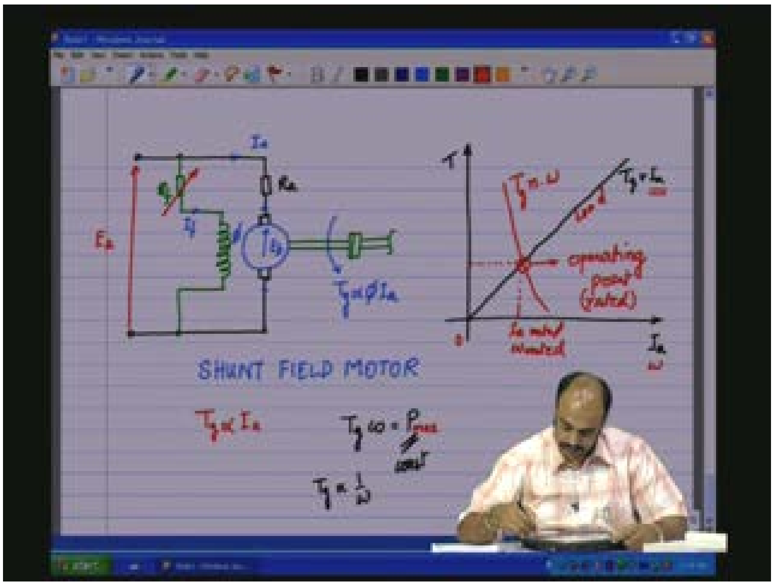

On other hand, what if we are not keeping power constant. So let me draw a graph with respect to the speed omega in radians per second, this is the torque so this is in Newton meter. Now let us say let us say I keep on increasing the voltage. As the voltage is being increased the voltage will keep on increasing as shown let us say up to a certain point. So this is the….. beyond that the voltage cannot increase because we would have reached the rated value for the voltage for the machine E a rated. So this is the E a curve this is E a with respect to speed.

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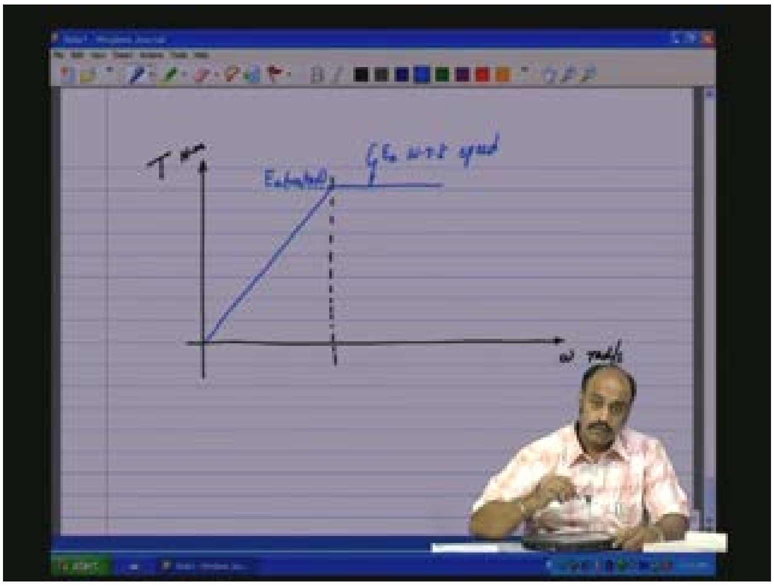

Now let us for the moment take R a equal to 0 so which means E a is same as E 0. So this is actual the back emf also because we are saying R a this is the back emf E b because R a is equal to 0. Beyond a particular speed the back emf has reached the same value as rated voltage we cannot apply a voltage more than the rated voltage otherwise the machine will saturate so it has to get clamped at this beyond a particular value of the speed. Now what is happening to the power the power that is delivered to the armature is E b into I a or A into I a because R a is equal to 0 so the power curve is E b into I a which is the power which is put into the armature.

Now as E b is 0 the power here is going to zero and that is going to increase. So let us say the power curve increases in some fashion up to this point. So at this point this is the power curve P in watts. Now at this point torque rated has been reached, omega that is the speed rated or the nominal has been reached whatever is given in the name plate and I a is also rated beyond let us say we want to still increase the speed, what happens?

E a cannot increase any further, speed only can change and how can you increase the speed by keeping E a constant by decreasing flux only because T g is proportional to flux into I a, we are not going to change anything in the armature side because armature voltage now reaches its maximum constant so only other parameter to control is phi and phi you cannot increase more because already the voltage is in the maximum any increase in the voltage will saturate so therefore you have to only decrease the flux so we decrease the flux so which means T g starts reducing. So you can still go beyond the rated speed by reducing the torque. So the torque will start reducing in this zone and the maximum that can be available is T g is P maximum by omega.

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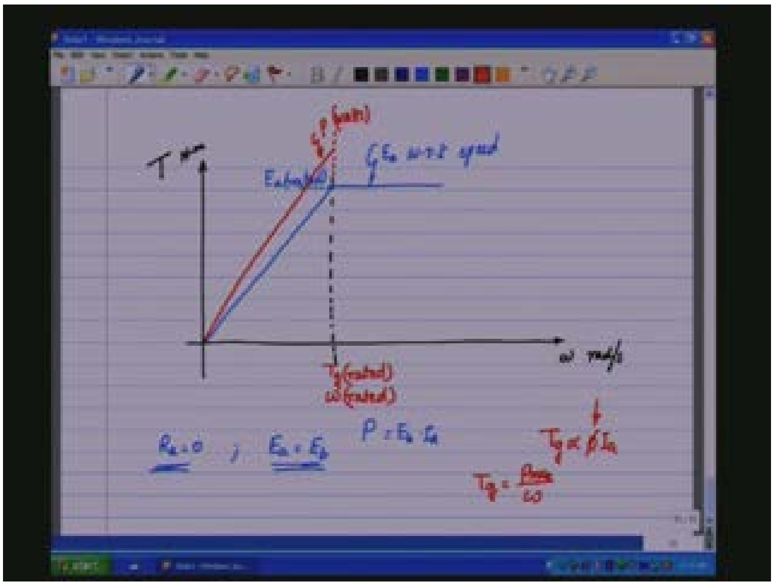

So if you say p maximum is constant for the machine then T g is inversely proportional to omega. So if I am having the T g curve so let us say this is T g max so that will start going proportional to 1 by omega as omega is increasing. But in this region you could achieve a constant torque up to maximum by changing these two. So there is possibility of obtaining a constant torque here because the speed is less than the rated and as the speed is less than the rated I a can take a lesser value and therefore for any load one could achieve a constant operating point below the rated. But beyond the rated there is upper limit for the torque which will take which will have a proportionality of 1 by omega. So this would be the achievable maximum torque curve the green line as I am showing here with respect to omega.

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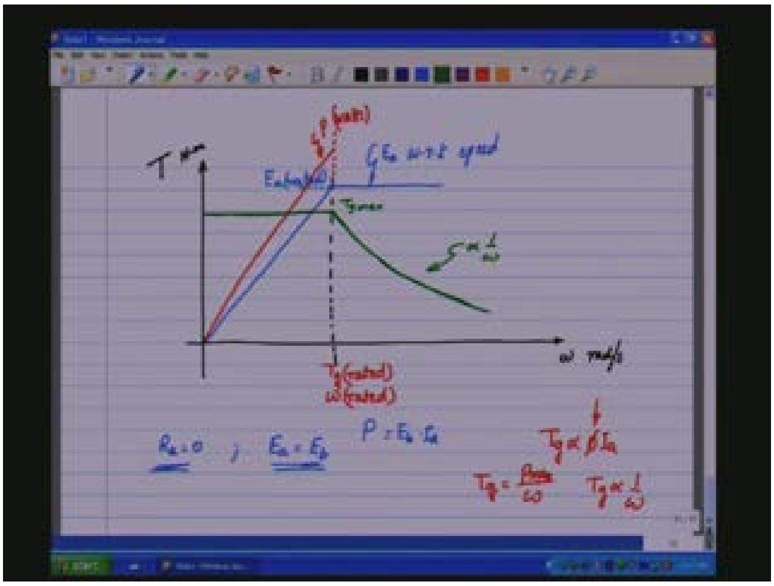

Now in the case of the series motor what happens?

So, in the case of the series motor we have let us say the same machine, we have the brush and I have the armature resistance R a as shown here across these terminals. This is the brush and this is the DC motor, this is R a and this is brought out to the terminals here and there is a back emf E b across the brushes, there is also an applied voltage E a across the armature and there is a current I a through the armature windings, there is now a field winding.

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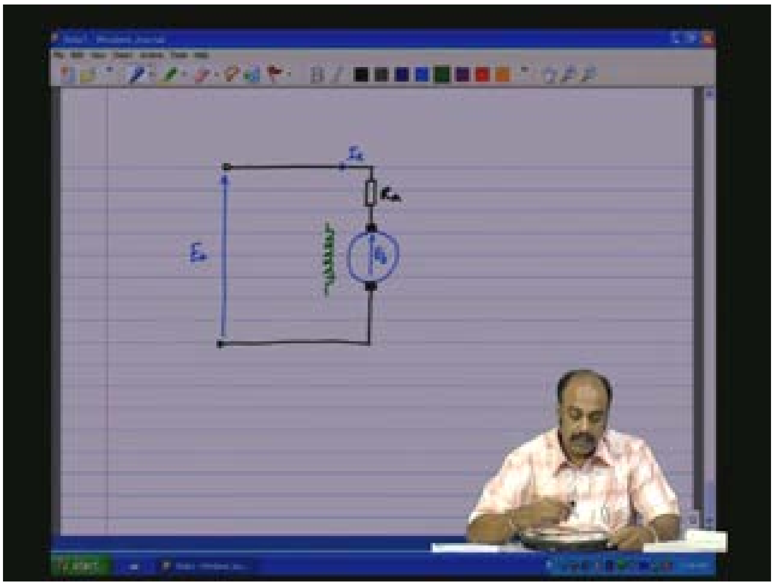

Now this field winding is not going to be connected directly across the terminals but it is going to be brought out here and connected in series with the armature. So what we do we make a cut here and then connect it like……….. so which means the I a flows through the field coil to produce also the flux and also the load and then what happens to the torque and the mechanical side; the torque on the mechanical side that is generated we know it is proportional to the flux into I a but the flux is proportional to the field current but the field current is same as I a so flux is proportional to I a and therefore T g is proportional to I a square in the series motor.

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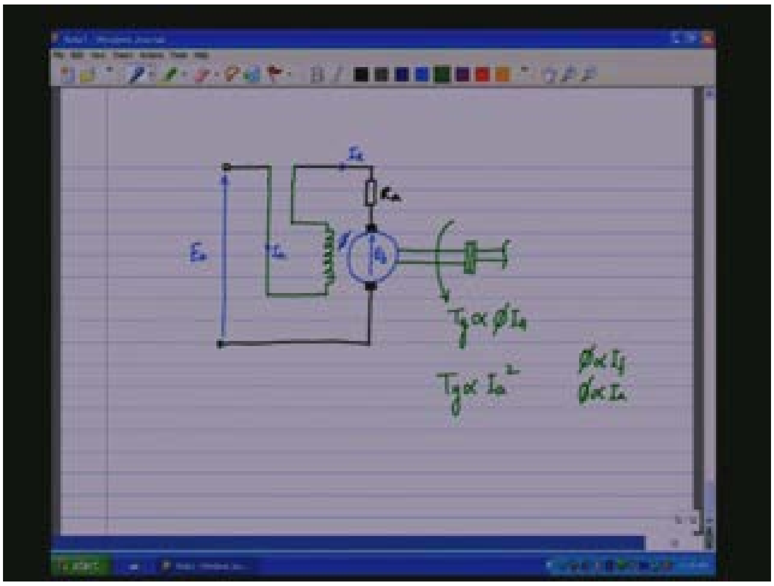

So in the case of the series motor we have the flux which is proportional to I a and therefore the generated torque T g is proportional to I a square. So therefore if we look at if we look at the load torque characteristics with respect to I a we see that this starts having a hyperbolic; T g versus I a in the case of series motor. Now let us see E b. Now E b is also proportional to phi I a sorry is proportional to phi omega phi into omega or E b is proportional to I a into omega because the flux is also proportional to……………

Now E b into I a is the power E b into I a is the power and therefore the power is proportional to I a square omega. And let us say we want to keep the power constant, then then I a square omega will be a constant. Of course I a square is T g proportionality is there in the factor and it is proportional to the torque is proportional to 1 by root of omega; in the case of T g is proportional to I a square and 1 by omega but T g is already I a square and therefore the armature current of the load current will be proportional to 1 by root of omega in the case of in the case of the series motor whereas in the case of the shunt motor I a is proportional to 1 by omega.

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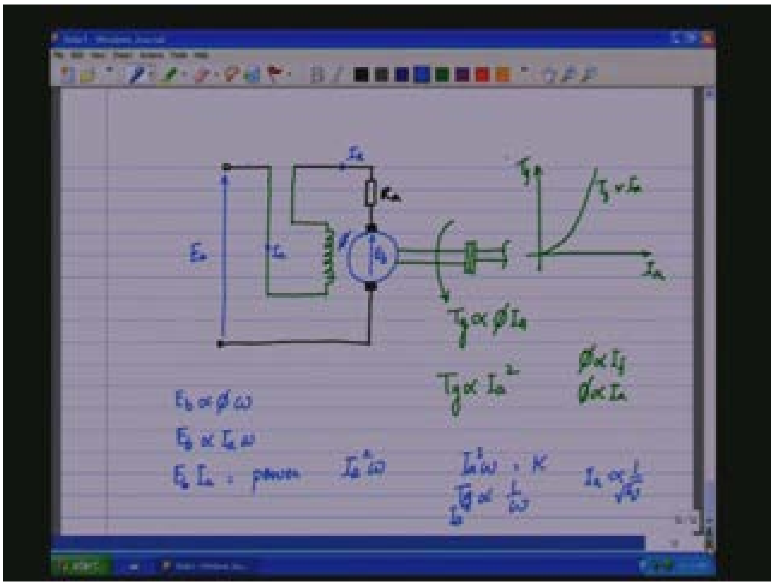

Now if we take this equation E b which is equal to p N phi Z by 60 or p Z by 2pi into phi omega where this is in rpm, this is in radians per second and this is K which we have defined so which is equal to K phi omega.

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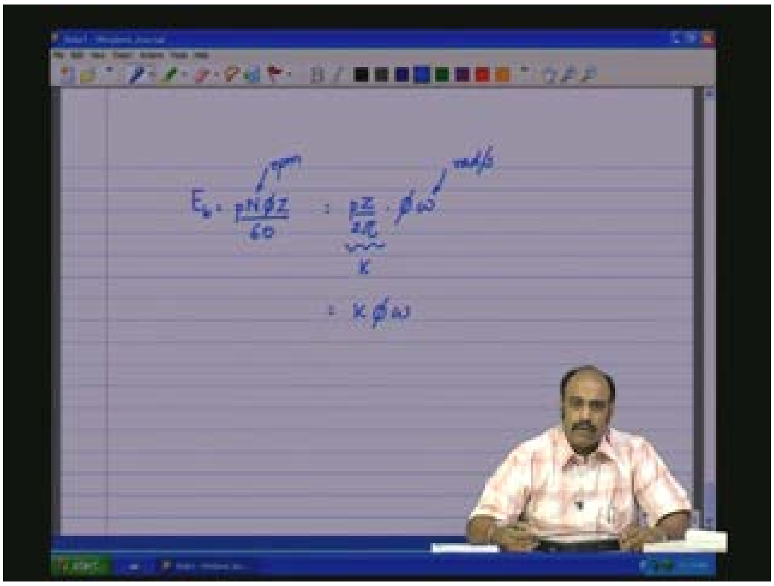

Now let us say in the case of the shunt motor. So in the case of the shunt motor let us say this is given by the applied voltage which is per therefore it is connected across the terminals and therefore it is not zero phi is not zero and E b is proportional to omega when omega is equal to 0 the induced emf is 0.

If the flux is brought to zero what happens?

Now E b is let us say approximately equal to E a and let us say for the moment for the discussion R a is equal to 0 then E b equals E a which is proportional to phi into omega. Now this if we keep it constant it is a constant DC source which is applied externally if you reduce the flux the field is going to increase so that the product is a constant. So, if this is suddenly made zero that is the shunt field winding coil is made suddenly zero then under no load conditions the speed here can increase phenomenally high and it may break away and damage the machine. But in the case of but in the case of the series motor when the field coil is broken I a is also 0 because I a is 0………. because this is proportional to I a and omega is also proportional to……… because we saw that omega is also a function of I a I a is proportional to 1 by root omega or omega is proportional to I a square. So when I a is made zero both the speed also will become zero because that is a function of speed and the motor does not run away whereas in the case of the shunt motor there is a possibility of running away. We will stop here and continue our discussion in the next session.