Electrical Machines
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Lecture 25
DC Motor: Speed Control
(Series and Compound Motor)

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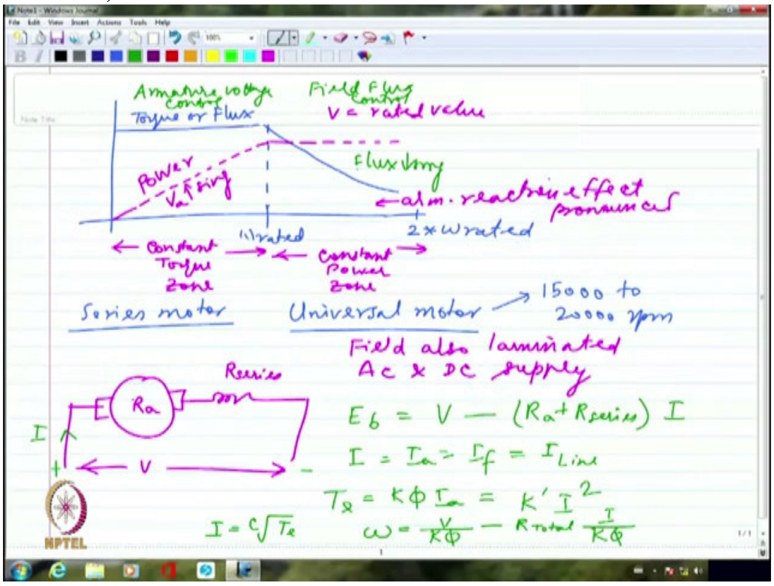

In the last class we had looked at the 3 types of speed control schemes for the separately excited or shunt motor drive, which are actually the armature resistance control scheme and armature voltage control scheme which are meant for below-rated speed operation. They will also have constant torque capability.

Whereas, if we are looking at the third type of speed control scheme, which is field flux or field current control scheme. It is actually looking at the flux going below the rated value because of which the torque capability will also come down, if I am assuming that the armature current should not go beyond normal values. So, because of which we are actually looking at the field flux control, only meant for above rated speed operation but the torque being below the rated torque value. So, both of them when multiply, we are going to have constant power.

So, we basically divide the region of operation of the D C motor drive into 2 regions. If I may call this as ω_{rated}, we are going to look at the flux remaining as a constant until ω . Beyond that I am going to have the flux actually coming down and so, also will be the torque. So, if I say that this is torque or flux, the same thing holds good as far as the torque or flux is concerned until rated speed, I can hold both of them as a constant if I want to.

But beyond that I would not be able to hold the flux or the torque as a constant, if I want to go beyond the rated speed. So, this is beyond rated speed. May be this is twice the rated speed, if I may say, so this is $2\omega_{rated}$. Even though the torque may be a constant or the torque deliverability of the machine is a constant, the power is the product of torque and speed.

So, I am going to have rather the power increasing linearly, like this, as the speed increases although the torque may be a constant the power will essentially increase linearly and I am going to see that I will have basically the power almost saturating to the maximum value or the rated value and it will not be able to increase beyond this because the torque is coming down whereas the speed is going up. So, this is essentially the variation of power. So, we call this zone as constant torque zone, and this is going to be constant power zone. So, these are the two distinct zones of operation.

(Professor – student conversation starts)

Student: What will happen to the torque when the speed goes beyond the rated value?

Professor: If I try to make the speed above ω_{rated} with the voltage is frozen at rated value, only way it can be done is by decreasing the flux. When I decrease the flux, the torque will also decrease although the speed increases. So, we are going to have the torque decreasing because the flux is decreasing. So, I should say that here voltage is frozen at rated value, whereas here the voltage is increasing. Armature voltage control if I am doing, voltage is also increasing.

(Professor – student conversation ends)

So, I should say, just like how the power is proportional to the speed, the voltage applied will also be proportional to the speed. I am not talking here about the armature resistance control. I am talking here about armature voltage control. So, the two regions distinctly are, this is armature voltage control, and this is going to be field flux control. So, I will have actually beyond a particular point when I am going to make the flux too low, so the flux is decreasing here.

So, because the flux is decreasing, I am going to have at some point, the armature reaction taking a heavy toll, on the main field flux itself. Originally, we had been neglecting armature reaction. Through and through that is what we have been doing. We just mentioned about the armature reaction, we never took care of including that in our calculations but when I make the main field flux itself very very small, because I am weakening the flux by and by, so, originally maybe the flux was 0.5 Weber. It has come down to 0.25 Weber.

When it was 0.5 Weber, what I had as the armature reaction flux might have been 0.1 or 0.05 which would have been a much smaller fraction of the main field flux because of which I would not have seen much of impact of armature reaction flux on the main field flux. But when I have decreased the main field flux itself to original value, compared to that I am decreasing it to half the original value, then may be from 0.5 it has become 0.25 but out of 0.25 I am going to see probably the 0.05 or 0.1 will be a good fraction.

So, it will definitely take a heavy toll on the main field flux, when I compare that with the armature reaction flux itself. So, here probably I will have armature reaction effect is pronounced because I am not going to be able to really keep the armature reaction effect at bay. That is essentially going to cause some amount of reduction or at least a perceivable reduction in the flux.

So, that is about it as far as the speed control is concerned, so I thought probably I should just clinch the whole thing by mentioning this, that is it. We had started on series motor in the last class and we said in the series motor, if I have both AC and DC supply possible, then we call that as universal motor. So, we call that as universal motor, if it can work on both AC as well as DC. I told you that these can run at very very high speeds, because they can run basically at 15000 to 20000 r p m and they are specifically used for certain applications where we require this kind of high speed.

So, typically drilling machines or mixer, these things require very very high speed, so these two are typical applications of universal motor. But universal motor, the major difference between a normal DC motor and universal motor is that the field is going to be laminated in the case of the universal motor. So, we will have the field also laminated, because you are applying AC. So, this can work in AC and DC supply. They can work on both.

(Professor – student conversation starts)

Student: Is armature resistance control commonly used?

Professor: See armature resistance control only advantage is you do not have to have a variable DC supply at all. You can just simply include a rheostat. You can vary the rheostat value, that will be able to control the speed. So, simplicity definitely is one of the plus points of armature resistance control, which was being used when rectifiers were not in vogue. Now, that we use rectifiers quite a bit, slowly that is disappearing.

(Professor – student conversation ends)

There also you would be able to see that armature resistance control is probably used for very very small rated motors, because as it is we do not care about efficiency in many of the small rated motors. It may be for toys, it may be for camera, it may not be for the continuous running. Wherever, we worry about continuous running kind of application, that is where we worry about efficiency also much more.

It is only for a short duration, we do not worry about efficiency, rather we worry about 2 things, one is cost of the entire system, the second thing is how quickly it will respond, whether it will respond, responding very fast or not? These are the two concerns we will have for any system, which is not really going to be running on a continuous basis. So, in the case of series motor, let me first of all draw the diagram. This is going to be the field. So, let me call this as series field resistance (R_{series}) that I am going to have and I am applying a voltage V here. I am not showing this as V_a or V_f because it is common to both of them and please note that R_a and R_{series} are coming in series with each other. So, I have to write very clearly,

$$E_b = V - (R_a + R_{series})I$$
$$I = I_a = I_f = I_{Line}$$

If I say line current is I_L, whatever it is drawing, maybe this is plus and this is minus and the current is flowing like this, let me call this as I which is also equal to I_{Line}. So, I should be able to write, if I say $Te = K\phi I_a$, I should be able to write this as, if I assume that I am operating in the linear region of operation, I am going to have the flux proportional to the current. So, I am going to have essentially, this will be proportional to some K times I^2. I can directly write this as I^2.

$$Te = K\phi I_a = K'I^2$$

So, I should be able to write that, $I = C\sqrt{Te}$.

So, let us try to now, write the torque speed equation for this. $E_b = K\phi\omega$ so, I can write this as , $\omega = \frac{V}{K\phi} - \frac{R_{Total}I}{K\phi}$

That is the equation corresponding to the torque speed characteristics.

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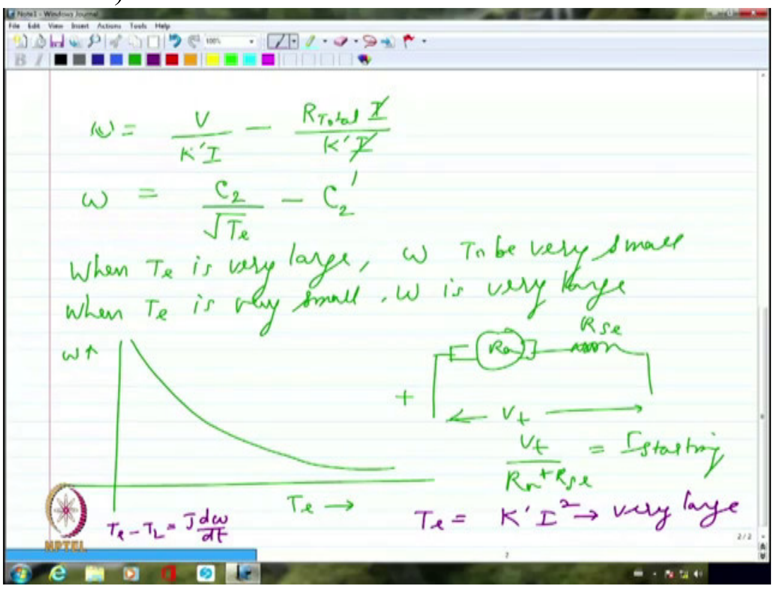

Now, we are going to have,

$\omega = \frac{V}{K'I} - \frac{R_{Total}I}{K'I}$. So, I can simply cancel these two. $\omega = \frac{V}{K'I} - \frac{R_{Total}\cancel{I}}{K'\cancel{I}}$, So, I can write this as $\omega = \frac{C_2}{\sqrt{Te}} - C_2{}'$.

So, I can write the speed torque equation somewhat like this. Some two constants I am taking and I can write it like this.

Very clearly this is not a linear equation, like what we had originally for the separately excited DC motor drive, I can say when T_e is very large, right, I am going to have ω to be very small. In fact, if you look at the equation it will come out to be negative. If T_e is infinity, I am going to have ω to be negative but obviously a motor cannot be driven in the opposite direction just by a load. That is not possible.

So, you should say that, rather the speed becomes almost 0, when I overload the machine, right. Similarly, if I try to look at when T_e is very small, ω is very very large. So, it is like, a characteristic somewhat like this. It is almost asymptotic in both the directions. So, if I say this is ω and this is torque.

So, if I am trying to start a DC series motor on a very light load, then what will happen actually is, the current drawn is going to be really really small, because the current drawn depends heavily upon what is the kind of load you have.

So, if I am having, actually if I am starting the DC motor on very very small load during starting, all I have is only R_a and series resistance (R_{se}), if I say this is R_{se}. These two are coming in series and I am applying whatever is my voltage here. So, I am going to have $\frac{V_t}{R_a + R_{se}} = I_{starting}$,as the I starting current, because I am not going to have any back emf at all. When the motor is starting ω= 0, so I will not have any back emf. There is no back emf, only limiting factor for the current will be the resistances, nothing else.

So, this is going to be the starting current. The starting current could be very very large in any DC motor for that matter when I am starting it with full voltage. I do not have back emf. So, there is nothing to limit the current other than its own armature resistance in the case of separately excited DC motor and its own armature plus field resistance in the case of series motor. So, I am going to get a very very large current passing through the entire field and armature system and what I get as the torque is $T = K'I^2$.

This is what we said as the torque. So, the torque generated is extremely large. If I say that the current is very large, the starting torque is also going to be extremely large. So, series motor is one motor drive, which can really generate a very very large starting torque, that too controllable. If I put a external resistance in series further, I can control that resistance also. Correspondingly, I would be able to control the starting torque quite effectively in a series motor drive.

So, if I have a very large starting torque, but what I have as the load torque is really small, the machine will go into extremely large speeds, because you are going to look at T_e -T_L, so this will be very large, because starting current is large, so I am going to have $T_e - T_L = J\frac{d\omega}{dt}$. I am going to have the rate of rise of the speed that is going to be really really large. So, I am going to see that the machine will literally reach to extremely large speeds in a very very short frame of time. So, generally it is dangerous to start a series motor on light load condition.

If I try to start a series motor on light load condition, eventually, the speed reached will be very very high, the shaft could break, because the mechanical strength of the shaft will be limited but if I try to start the DC series motor on light load or zero load I would see that the current drawn becomes so large during starting, unless I control it effectively, I am going to get a very large starting torque, because of which the speed gained will be enormously high and eventually the shaft might break. So, generally it is not prudent to start a series motor on no load or light load condition.

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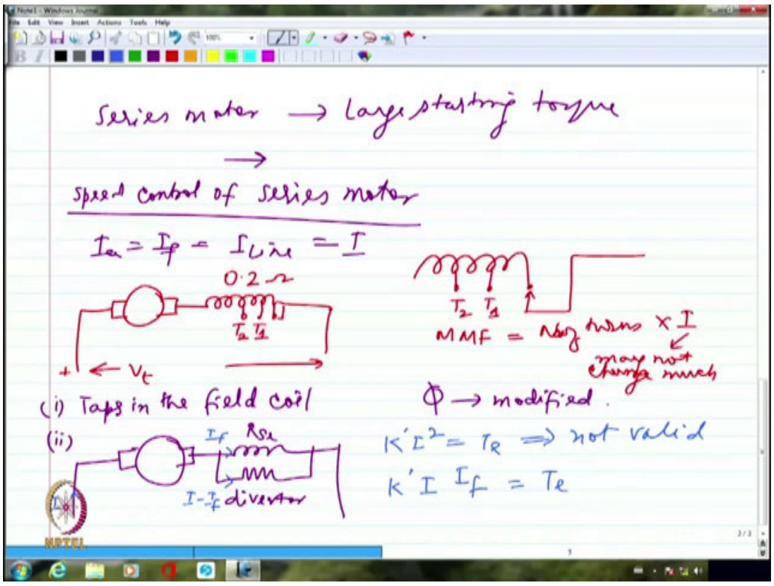

But, all the same, because the series motor inherently has a large starting torque. It is very very suitable for those applications, which require a very large starting torque right in the beginning. Like for example an elevator, lift, an electric vehicle because you cannot say that I will just rotate the engine then vehicle come and attach itself. That is not going to happen. You are going to have all of them attached together.

And especially if you look at the traction system that is the suburban train service and so on, it will have a huge friction with the rail. There is huge amount of friction with the rails. So, it has to overcome that friction and start moving, for which you require a very very large starting torque normally. That is the reason why DC series motors have been conventionally used for all the traction systems or suburban train system, tram, car and things like that. All of them had been originally driven only by a series motor.

So, series motor is really ideal for electric vehicle applications. It is also good for cranes. It is also good for hoists. It is very good for lifts or elevator, where you are going to have the load right from the beginning. You will hardly ever start it on no load. So, that is the reason, why you would normally see that series motors are conventionally employed in all these applications. So, so much so for the series motor but there also, how to do the speed control of series motor. I will just touch upon this. I am not going to get into great details of this. Series motor speed control is a little too tricky because in the case of shunt motor and separately excited motor we have a distinct field system, distinct armature system, we should be able to control the two currents independent of each other, most of the times, whereas here I am going to have $I_a = I_f = I_{Line}$ or I may call this as the common current I.

So, very difficult to control the field current and armature currents independent of each other, it will not be possible for me to control those two. So, most of the times what is done is to control basically the flux. So, if this is the field coil and here is the armature and I am going to have the supply here, what I can do is to have many taps in the field coil. May be at some point I will connect all the turns. I may connect it to tap number 1 (T_1), which may include less number of turns; T_2 if I connect it to, it may include even lesser number of turns.

So, I can have multiple taps in the field coil. Of course, it will disconnect and reconnect the taps, which is actually dangerous, because you are looking at an inductive current. Field is always inductive coil. So, you are looking at an inductive current being interrupted and again reconnected. So, it is not really a very good proposition but we do not have any other option. That is the reason why if this is the field coil, we are going to have normally this is connected here, may be another tap, another tap and so on. This is how I will have multiple taps in the field coil.

So, depending upon this I am going to vary the MMF. Please understand that the resistance of the series field will also be 0.1, 0.2 ohms, nothing more than that. So, if I include probably part of the field coil only, the resistance will come down from 0.2 to probably 0.15, 0.1 and so on. The major player in limiting the current is the back emf, not really the series field resistance or armature resistance. So, that is essentially going to only modify the current very very slightly by adjusting this series field either in tapping 1 or tapping 2 or the initial position.

So, the resistance will not change grossly. The current will not change grossly. Because of that we are essentially only playing around with MMF because the number of turns is getting modified. So, I have the number of turns originally as may be N, now it will become N-10, N-5. So, I am going to have essentially the number of turns getting modified with the current almost remaining as the constant. This may not change much. So, because of which I am looking at the flux getting modified. MMF is modified; the flux will also be modified.

So, if the number of turns are decreased, the flux will get decreased. If the flux gets decreased, it is like field weakening zone. So, it is going to have an increase in the speed. So, I would be able to get an increase in the speed, if I go for lesser and lesser number of turns. So, one of the methods is actually taps in the field coil.

The second method what is normally used again is the diverter. The diverter actually is a resistance which will be connected in parallel. So, this is generally known as diverter resistance. This is the series field. So, we are going to have the diverter resistance comparable to that of the series field resistance itself. If the series field is going to have the resistance of 0.1 or 0.2 ohms the diverter might have 0.3, 0.4 Ohms or 0.1 itself depending upon how much of current I want to get it diverted.

So, if I say that the current flowing here is I, I will have, this is I_f whereas this will be $I-I_f$. So, I am going to have essentially this $I-I_f$ whatever is the current that is not going to contribute towards MMF production. It is only meant for dissipation, nothing more than that. So, what we are trying to do in the second case, that is the diverter case is to divert some portion of the current away from the field coil, so that again we are reducing the MMF.

So, when we reduce the MMF, we are going to reduce the flux, again field weakening takes place, which means the speed can increase. So, that is what happens in this case. So, please note that, in this case I cannot write simply KI^2 or $K'I^2$ is equal to torque is not valid because I am going to have whatever is $K'II_f$. So, I have to take this as the overall torque, that is being produced because the flux is proportional to I_f, not proportional to I as it is. So, this is going to be the torque that we get.

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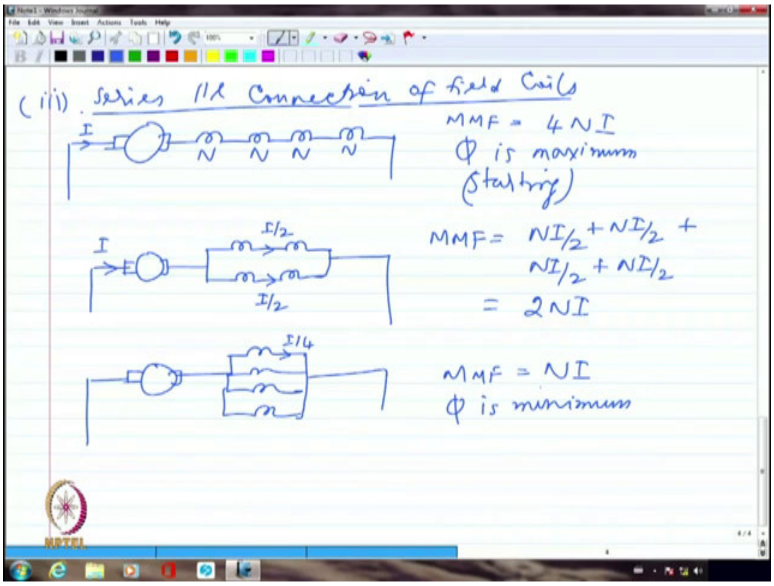

The last kind of again operation that is adopted for the speed control is, if this is my series motor's armature, I may have several field coils in series or parallel. If I have all the field coils are in series, imagine them to be lumped together that is what is the total series field coil. So, let us say each of them is having a number of turns to be N and let us say the current that is flowing is I. I am going to have the MMF = 4 N I.

Rather than this, if I connect it in such a way that I am going to have 2 coils in series, 2 more coils in series and both of them are in parallel. So, if I am going to have the two field coils, actually connected in series and two of them are in parallel. Let us say this is I. I am going to have I/2 flowing here and I/ 2 flowing here. And because it is I/2, if I try to look at the MMF in this case, I am going to have $MMF = \frac{NI}{2} + \frac{NI}{2} + \frac{NI}{2} + \frac{NI}{2} = 2NI$.

This is what will come out to be my MMF. Because the resistance is really comparable in each of field coils, the current would hopefully divide itself into 2 halves. So, I am going to have a reduction in the MMF for sure and that is going to be actually halved compared to what I had in the previous connection. But of course I have to disconnect and reconnect the field coils. And this is normally done. At least for sure I know that in Chennai the traction system, the old traction system uses this still for increasing the speed.

And of course the last type of connection, I can have all 4 of them coming in parallel, right. I can have 1, 2, 3 and 4; all 4 of them can come in parallel. So, I will have I/4 in each of this. So, I will have (NI)/4 multiplied by 4 because 4 such coils. So, I am going to have essentially

MMF in this case to be just N I. So, in this case flux is maximum out of the reconnections and in this case flux is minimum because I am looking at the MMF also getting minimum.

So, if the flux is minimized, I am going to have in all probability the speed increasing. So, generally we would use this during starting condition, so that we get more torque, more flux, less speed. Here, we will have it slowly changed over from the first connection to the second connection to the third connection as we go along increasing speed direction. So, we are actually going to see that the series-parallel connection of field coils generally is a very very commonly used technique to change the speed of a series motor.

Now, that we have seen the series motor operation, so these are the three techniques that are used for the speed control of DC series motor. So, tapping of field coil, diverter resistance and series parallel connection of field coils. These are the 3 different types of techniques that are used normally for the speed control of a series motor.

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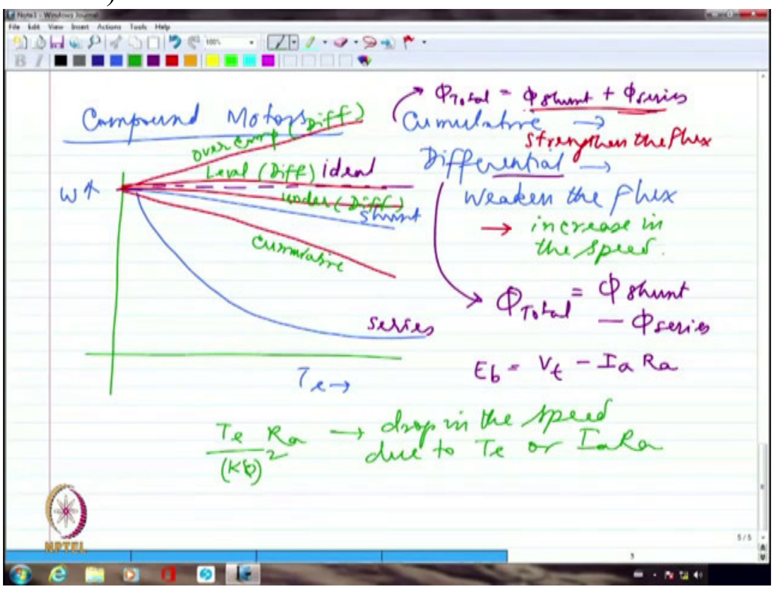

So, now that we have seen the series motor as well as shunt motor, if we have a combination, if we have compound motors, how are the speed torque characteristics going to change? So, we have again cumulative and differential. Please note that differential compounding is equivalent to having field weakening. Whenever I have differential compounding, I am essentially subtracting the flux that are created by the series field coil from the overall main field flux.

So, the flux gets decreased. So, I am going to have basically differential will weaken the flux, whereas cumulative is going to strengthen the flux. So, whenever I am going to see weakening of the flux, I will have increase in the speed. We already said field weakening will generally increase the speed. $E_b \propto \omega\phi$. So, if I am keeping E_b at a constant or applied voltage as a constant but I am going to reduce the flux, automatically the speed has to increase, so that it gets back to the original value of back emf.
So, differential and cumulative, if I try to look at the characteristics, let me first of all draw this is the shunt, let us say. This is ω, this is the torque and this is the shunt machine. If I am talking about a series machine, we drew it as though it is somewhat like this. This is what a series machine's characteristics.

Now, if we have a differential compounding, just like what we had in the case of the generator, whenever we had cumulative compounding, we said that every time there is an increase in the armature current because of an increase in the power delivery, we are going to have maybe the voltage building up further. So, I_aR_a drop may be nullified, I_aR_a drop may be actually over-compensated or under-compensated.

Same thing is true here with respect to differential compounding, because if I do differential compounding, the moment I increase the load torque, the speed falls. That is what this is indicating. If ideally the motor had not had any resistance, this would have been the ideal characteristics. But because of the I_aR_a drop, I am going to have a fall basically in the speed, as the torque is increased.

As the torque increases, the current will increase. Once the armature current increases, I am going to have definitely the series field current also increasing correspondingly, whether it is long shunt or short shunt, it is immaterial. But I am going to have essentially as the armature current increases, I will have the current through the series field also increasing.

If the series field current increases, I am going to have in the case of differential, more and more depletion of flux will take place, because I am looking at $\phi_{Total} = \phi_{shunt} - \phi_{series}$. That is what happens in differential. Whereas in cumulative I am going to have $\phi_{Total} = \phi_{shunt} + \phi_{series}$. Please realize that $E_b = V_t - I_a R_a$. If I_a is increasing, I am going to have less value of E_b although the difference is not much still, I am going to have a little bit less value of E_b.

But in the process if the flux is already increasing because I_a has increased, then the speed has to come down. Because E_b is proportional to $E_b \propto \phi_{Total}\omega$. ϕ_{Total} have increased because of which I am going to have definitely a reduction in the speed. So, if I talk about cumulative, it will actually be falling even below the shunt motor characteristics in the case of motoring operation when I talk about speed versus torque. It is just the converse or inverse of what we had in the case of our generator.

In generator, cumulative was becoming flatter or higher in terms of voltage and so on whereas here differential will essentially behave that way. So, I can have again under-compounded differential DC motor or flat compounded differential or I can have over-compounded differential DC motor. So, please understand that just between the generator and motor, this particular behavior is completely opposite.

All these 3 correspond to differential compounding. So, this is over-compounded but very clearly this is also differential. This is level or flat compounded but this is also differential. And this is under compounded but this is also differential, whereas this is cumulative. Depending upon how much is the series field influenced on the overall flux, that will decide whether the speed will come down almost to 0 or whether it is going to remain somewhat higher.

(Professor – student conversation starts)

Student: Why is differential compounding causing an increase in the field?

Professor: See if I am having I_aR_a drop, I am essentially looking at,

$$\frac{T_e}{(K\phi)^2} R_a \rightarrow \text{drop in the speed due to } T_e \text{ or } I_a R_a$$

This is the drop in the speed due to torque or I_aR_a. If the torque had been 0, I_a also should have been 0. This will not be there at all. I should not have had any drop in the speed. So, when I am having a drop in the speed, if I want to compensate for it, I have to somehow try to increase the speed and increasing the speed for a given voltage or a given back emf can be done only if the flux is weakened because flux multiplied by the speed is going to give me the back emf.

(Professor – student conversation ends)

So, if the flux is weakened, only then I am going to see an increase in the speed, which means I have to have differential. I cannot have cumulative. So, only differential compounding will give me an increase in the speed or a compensation for the I_aR_a or $\frac{T_e}{(K\phi)^2}R_a$ drop in the speed . That is essentially the drop in the speed. So, that can be compensated for only by having differential compounding and not cumulative compounding.

So, this is an important difference between the compound machines, when they are operated as motors and when they are operated as generators. This is a very very important difference. So, if I am talking about the level compounded generator, it is cumulatively compounded. If I am talking about the flat or level compounded motor, it is a differentially compounded DC motor. So, much so for the compound motors.

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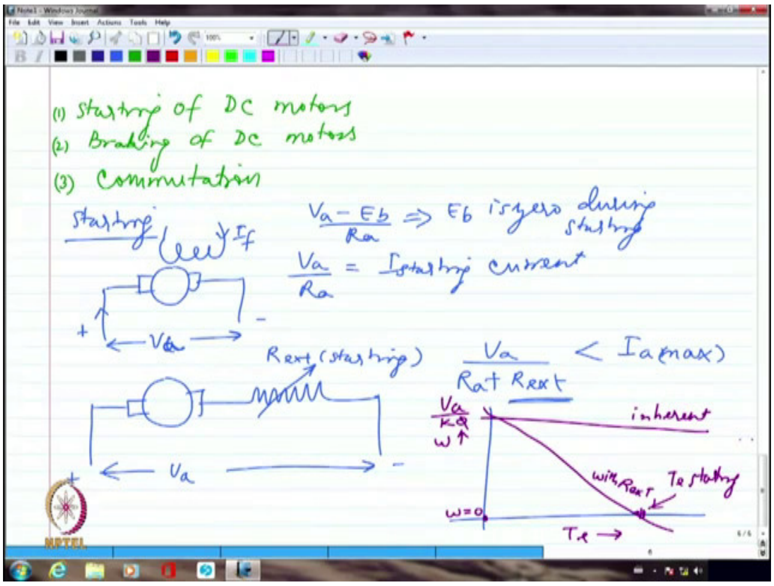

The last couple of topics, which we are left over with and of course commutation I have still not taken up. So, these are the 3 topics that are left over. One topic is about starting of DC motors. The second topic that we need to deal with but very briefly is braking of DC motors. And the third topic that is left over still is commutation.

So, these are the 3 topics that are still pending. So, let us try to look at starting pretty quickly, I am not really going to again get in depth into either starting or braking. But it is quite important for you guys to know that, if I try to start a DC motor with full supply applied to the armature without any resistance, extra resistance included in the armature circuit, the current is going to be enormously high, because the starting current in the case of a DC motor.

I am going to have basically, if it is a separately excited motor, I am going to simply apply V_a here. So, if I trying to look at what is the current, it will be $\frac{V_a}{R_a} = I \text{ starting current}$, this will be the starting current. Because back emf is 0. Otherwise normally we will write $I = \frac{V_a - E_b}{R_a}$. This is what we will normally write, but E_b is 0 during starting, because ω is 0. Even though I may apply full flux, I may still apply full flux and still whatever is the generated voltage may be, 0 because of the speed being 0.

So, I do not have any back emf which will play a vital role in limiting the current during starting of a DC motor. So, I necessarily need to include a large amount of resistance which may be available resistance. So, this is the starting resistance, which I include only during starting and I am going to essentially apply the full voltage. May be I do not have a variable voltage supply. If I have a variable voltage supply, I do not have to do this.

So, if I have only a fixed voltage, then I necessarily need to include an external resistance in such a way that $\frac{V_a}{R_a + R_{ext}} < I_{a\max}$ that can be withstood by the armature. I may have the normal current or carried by an armature to be 10 amperes but I may allow 20 amperes to go through my machine, probably because the commutator will be able to withstand that much amount of current for a short while.

So, it depends upon how I have really set the limit depending upon my commutator action, the commutator, the conductors, the I^2R losses in the conductor for a short while, the machine should be in a position to withstand these. Only if that is actually set, then I will be able to say what is the value of $I_{a\,max}$, my machine can withstand, then correspondingly I will decide what is the value of R_{ext} that I need to include.

So, this R_{ext} value will essentially depend upon what is the limit that can be withstood by my DC motor. But what will happen is, if I am going to have a large R_{ext}, may be my nominal characteristics are like this, but my actual characteristics is R_{ext} will be, you know much more drooped. So, this is with R_{ext} whereas this is inherent and this is the speed and this is the torque. I am looking at what is the current or the torque that is produced at 0 speed condition. This is ω =0.

So, under starting condition I am going to have this much is the torque produced, provided I give rated flux for the machine.
(Professor – student conversation starts)

Student: What is the influence of R_{ext} on the no load speed and starting torque?

Professor: This is right, this is fine. Why should it be? I am applying the same voltage. See, this is $\frac{V_a}{K\phi}$. There is no R_{ext} in this. This is dependent upon what is the value of voltage that I have applied and what is the flux of the machine. Only these two are deciding what is the value of no load speed. In fact, we are not even in no load condition as yet. We are in the starting condition, which is ω equal to 0. So, when we are starting this is the operating point because the current that is being drawn corresponds to $\frac{V_a}{R_a + R_{ext}}$ and that current is being multiplied by the flux to give me whatever is the torque.

(Professor – student conversation ends)

So, this is the starting torque that I am going to get. So, this is the starting torque value. T_e starting. Imagine if I had extended this line, how much would have been the starting torque? Extremely large. Let me draw that as well.

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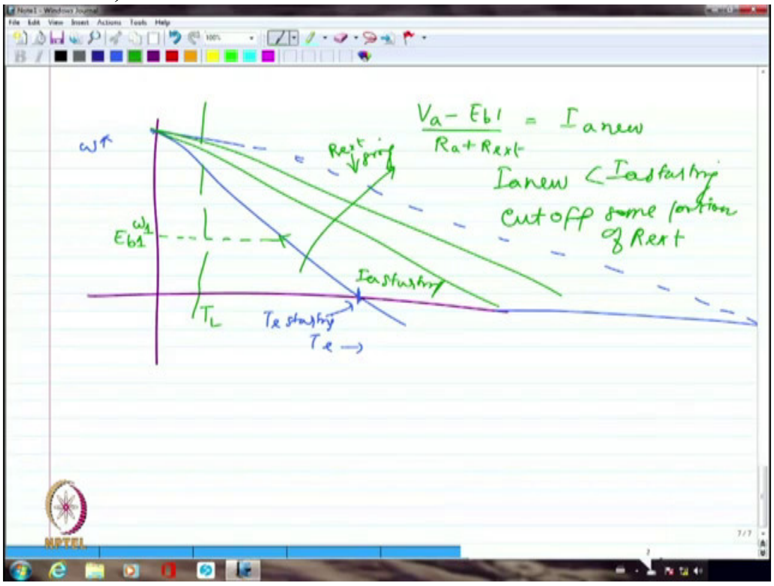

If I do not include any external resistance, I showed first of all with inclusion of external resistance, this is what is the starting torque. So, this is T_e, and we call this as T_e starting. If I do not include any external resistance, I have to just extend it further and further. It might intercept somewhere here, may be beyond the board.

Please imagine, if I had not included any external resistance this is really going to give me a huge value of armature current, a huge value of torque, if I assume that I have applied rated flux, the shaft will break for sure. So, it is really dangerous to start a DC motor with full supply ON without including any external resistance in the armature circuit.

So, normally I need to include a large resistance in the armature circuit and I will try to cut it off because what will happen is, this is the torque that is generated, may be the load torque is somewhere here. So, I have definitely an acceleration taking place. T_e-T_L is positive because of it there will be acceleration. So, as it accelerates I am definitely having the speed which is non-zero. So, I will have some E_b also generated.

May be this is ω_1; correspondingly, I have an E_b1. So, there is a back emf that is being generated. Now, this back emf will definitely play a role in limiting the current. I am going to have $\frac{V_a - E_b}{R_a + R_{ext}} = I_{anew}$. And $I_{a\ new}$ will be definitely smaller than $I_{a\ starting}$, because $I_{a\ starting}$, E_b was not there at all. Now, I have seen another E_b coming into picture.

So this, if I call this as $I_{a\ starting}$, I am going to have $I_{a\ new}$ less than $I_{a\ starting}$. This may not develop adequate amount of torque, maybe. I do not know what my load torque is, or I do not know what is the rate at which I want to accelerate. So, what I will do is to cut off the resistance. So, cut off some portion of resistance. Once I cut off some portion of R_{ext}, I will have now, the current will increase slightly. When the current increases slightly, I will have more torque. Then definitely another acceleration will take place.

As I cut off more and more resistance, I can show the characteristics in between. So, these are essentially R_{ext} decreasing. As I decrease R_{ext}, the characteristics will not be so drooping. So, this is how the starting is done. You start off with very large resistance, allow the motor to accelerate, as it accelerates, you cut off the resistance slowly but you cannot cut off the resistance really fast because it takes some time for the mechanical system to respond.

The mechanical time constants are always larger because of which, compared to the way in which I_a is increasing, that is going to be much faster as compared to the way in which the speed is going to increase. So, we have to take care of this. So, generally this method is known as resistance starting of a DC motor. So, the starter is basically a resistance, external resistance that is included in the armature circuit. So, we will start up braking in the next class.