Electrical Machines
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Lecture No. 19
DC Machines- OCC & Load Characteristics, Classification

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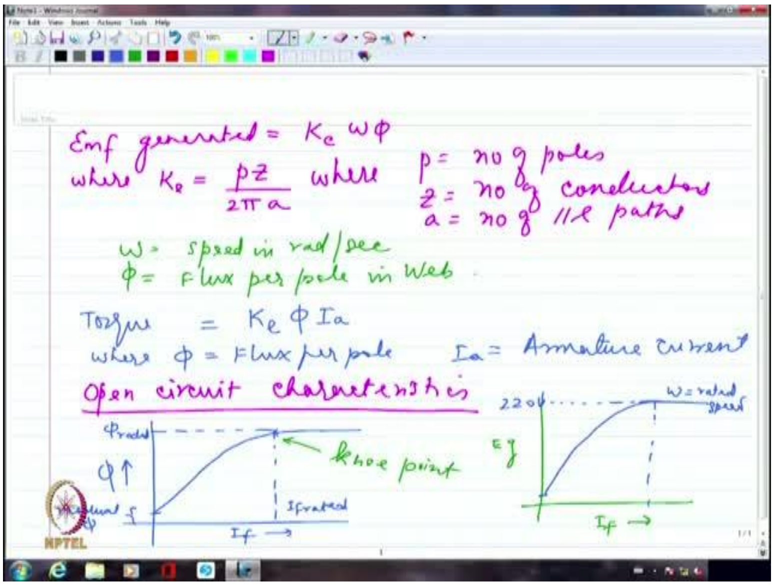

So, we actually looked at two major equations, after looking at the basic structure of the DC machine. We looked at lap winding; wave winding, and we said why one would have the number of parallel paths as many as the number of poles, and the other one will have only two parallel paths, we talked about that. Then we wrote the equation for EMF generated,

$$\text{Emf generated} = K_e \omega \phi$$

Where $K_e = \frac{PZ}{2\pi a}$ where P=number of poles, Z=number of conductors, a=number of parallel paths, ω=speed in rad/s, ϕ=flux per pole in wb.

We also said the torque equation,

$$\text{The electromagnetic torque} = K_e \phi I_a$$

The same K_e, back EMF constant, holds good in this case also. This is what we wrote as the EMF equation and the torque equation. Now, based on this we started discussing first of all what is the open circuit characteristics (OCC) of the machine. So, we were talking about OCC or Open Circuit Characteristics. This is valid when I am talking about the field excitation that can be changed, that means I am looking at the field system having only an electromagnet, not a permanent magnet. I am going to inject a field current and according to the field current I am injecting, I am going to get different values of flux because the MMF is changing, the flux will also change.

So, I can draw basically I_f on the x-axis and flux on the y-axis. If already the machine has been operated several times with a particular direction of the field current, then there may be some amount of flux leftover as residual flux. So, I may have some residual flux, may be to the tune of one 10th or one 15th or even less than that as the quantity that is leftover as compared to the related flux.

So, I am going to have this residual flux and as I increase the field current, I am going to see that the flux is increasing and then it reaches a particular value and almost saturates there that is it. There is hardly any variation of flux beyond this particular value. So, let us say this I call as I_{frated} which will also imply that I have a particular value as ϕ_{rated}. This is going to be the residual flux value. So, how will we define this I_{frated}, if we try to actually look at it generally, we tend to operate very close to saturation. Before it reaches completely the saturation point, we are going to operate it at a point which is known as the knee point of operation.

So, if I actually look at the characteristics as corresponding to my leg, where it is going to be bend near knee region. So, that particular point we call that as a knee point of operation. So, this is actually knee point of operation, so that is where normally we operate the DC machine. So, rather than now drawing the flux versus field current if I try to completely draw what is E_g versus field current.

What is the generated voltage versus field current, I am probably going to get some value of generated voltage even when the field current is zero, because there is some residual flux as long as I have rotation in the armature. So, I am going to rotate it probably at rated speed, if a machine is given generally it will be given the nameplate details, with what is the maximum current it can withstand or the average current that you can pass through the machine, how much is the voltage you can apply to the machine if it is operating as a motor. It will also tell you what is the rated speed, what is the rated power, all those things will be given.

So, in which case I should be able to say clearly whether I am operating at rated speed or not. So, the prime mover is going to rotate it at a particular speed. So, let me say may be ω= rated speed. I am operating this at rated speed, so if it is a 220 volts machine or something like that may be then I am applying the rated value of field current which is corresponding to rated flux, I will get 220 volts as the value of voltage, so this is going to be rated voltage. So, I am talking about 220 volts as the rated voltage in this particular case.

So, when I am running the machine at rated speed with rated field current been applied, I will get the voltage which is supposed to be the rated voltage of the machine.

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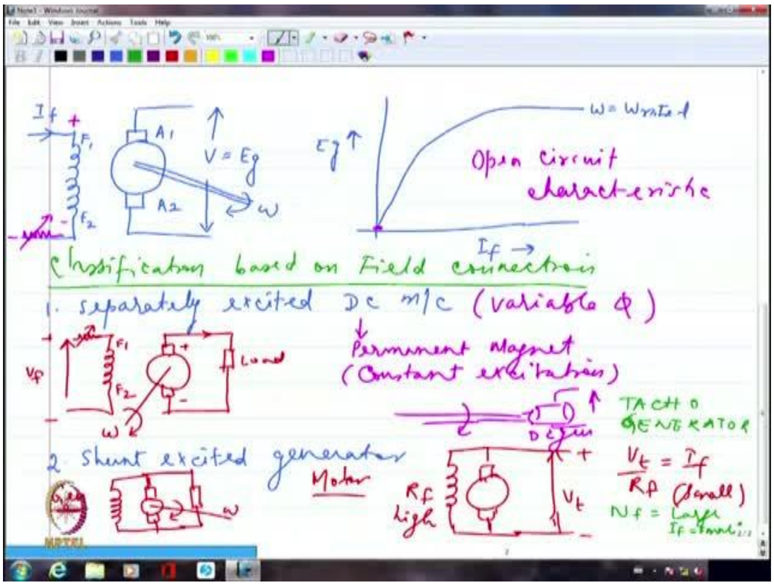

So, I can specify this as though if I am measuring it across the armature, please note that the DC machine will always be specified with the circle which is representing the armature with two brushes on the either side. This is the representation of the armature of a DC machine, always. You will never ever show a brush for AC machines, only for a DC machine we will show the two brushes, one will indicate the positive brush and the other one will indicate the negative brush and the circular thing indicates the armature.

So, this is the representation of the armature of a DC machine. I will have the field somewhat like this. So, I am showing the field in the form of an inductance because its primary function is to produce flux or magnetism, so I am going to show it as an inductance. This is my field winding, let me probably show the field winding as F_1 F_2. Let me show the armature terminals as A_1 and A_2. So, I am probably sending some current which is the variable current here.

So, this I_f can be varied and the variation in I_f can be affected either by varying the voltage, what I am connecting to the field winding, or I can connect the resistance in series with the field winding. Most of the times what we do is to connect the resistance in series, in most of the cases. So, I may have a resistance connected in the series and what I am doing is to measure the voltage here. So, I am calling this as E_g that is the generated voltage. So, at a given value of field current I will be able to measure how much is the generated voltage which will indirectly imply what is the value of flux that I have produced in the machine for this given field current.

Of course, I have to drive this machine at some omega (ω), if I do not have a prime over it is definitely not going to really generate any voltage. So, I am showing this as the shaft which is being rotated at a speed ω. So, there has to be a prime mover. So, the primary requisite for generator action is actually to have a prime mover which will impart mechanical power to the system and I should also have the field excitation. If I have only residual magnetism it is actually going to give very-very limited amount of voltage nothing more than that.

So, with this I am going to have this graph been followed by the machine, this is $\omega = \omega_{rated}$. This is I_f and this is the voltage E_g. So, we call this as open circuit characteristics. I may have a resistance connected in series, if I want really, a variation in the field current. Maybe I should show a very-very small voltage, it is not starting from the origin I should have a small voltage if there is residual flux normally there will be residual flux, unless I repeatedly excite the field in two opposite directions which I will not do in a DC machine normally. I will try to excite it only in one particular direction. If I am trying to excite it once in the positive direction, once in the opposite direction, then if I keep that keep doing that repeatedly I am not going to have any residual flux leftover not much really. So, I would basically try to do only one direction excitation so generally the field coils will also be specified with where the plus should be connected and where the minus should be connected and so on.

It will generally specify the terminal as well, when you generally purchase a DC machine. It will tell you in what direction the current should flow in the field coil, generally. Whenever you do an experiment on DC machine the first thing normally we do is to make the open circuit characteristics, so that we know exactly what the back EMF constant is or what is the torque constant, so that you get feel for what is the kind of rated torque it will generate if I pass rated armature current.

Although everything is given in nameplate details nevertheless, we would also like to verify the back EMF constant of a machine to start with so that you get a feel for the characteristic of the machine. Now, the field what I have shown, I have shown it as though it is connected to a separate supply. But I can have different configurations of DC machine depending upon how I am going to connect the field along with the armature. So, let me try to look at the classification of the DC machine based on field connection.

So, I can have really a separately excited field, so the first one we are talking about is separately excited DC machine. When we say separately excited very clearly I am going to have a separate source for the field and if it is a motor I will have a separate source for the armature. Both of them will be completely independent of each other. So, to show the connection I should show it as though this is my field and I will apply V_f here, may be I can have a variable resistance here, if I want to vary the field. So this is F_1 this is F_2.

And I am going to have the armature, if it is a motor, I am going to connect the DC supply voltage to the armature as well which will be separate. So, I will say V_a, another voltage source probably. If it is a generator, I will only connect probably a load here. So, if I am talking about the generator this will be the load. So, I may have a plus here and minus here and the current will flow like this. Of course, if it is a generator, I should have a source for rotation so mechanical power has to be input.

So, the field and armature are not directly electrically connected to each other in this particular case and hence the name separately excited. They are not electrically connected at all, they are only magnetically coupled. So, it is like transformer action in one sense, they are not electrically connected at all, the rotor and the stator. Instead of having a separate excitation I can also have permanent magnet, which means I do not have to give any electricity for the field circuit.

I can simply have magnets which are permanent magnets like the normal magnets what we see naturally existing. So, I will have the North Pole and South Pole which are in the form of a permanent magnet. But I cannot vary this excitation, it is given that the flux is going to be so much, I cannot really vary the excitation. So, here it is a constant excitation. I cannot vary the flux whereas here it is variable flux, I will have variability in the flux. Generally, permanent magnet DC machine, especially if we are talking about permanent magnet DC generator or even permanent magnet DC motor, they are all small-scale toy kind of motors.

Very-very rarely we use it for a real motor in an industry, we normally use it only for some kind of toys or if we are talking about a generator, we use it probably in the case of tachogenerator where you may be sensing the EMF or speed. So, if you want to sense the speed, we already said that the generated EMF is proportional to the speed, so let us say I have a rotating mechanism, along with that I have coupled a small DC generator.

So, if I try to measure the voltage what is generated that will give me an index of what is the speed at which the shaft is rotating. So, there I can have a permanent magnet, so whatever is the speed of rotation correspondingly I will have a particular voltage generated. So, this is generally known as tachogenerator mechanism. So, tachogenerator is used generally for measuring the speed indirectly by looking at the voltage generated by the tachogenerator itself in which case it may be a permanent magnet.

I would not like to have several connections in a tachogenerator because it is a small one, it is a secondary mechanism. So, generally I will have permanent magnet there. So, this is one of the applications of permanent magnet generator. The second type of connection I may have is called shunt excited generator or shunt excited DC machine. Shunt excited means I am going to have actually the DC armature is connected in parallel with the field, and I am going to have probably the load connected here if I am talking about a generator.

If I am talking about a motor, I will have a common power supply, supplying the field as well as armature, so I definitely need to have a mechanism for rotating this if it is a generator. If it is a motor, I am going to have basically a DC armature here which is connected to the field in parallel and together I am going to connect a V, let me call this as terminal voltage rather than specifying this as field voltage or armature voltage.

I am essentially looking at the whole thing as a terminal voltage. So this terminal voltage is going to supply both the field as well as the armature. Please note that if the armature is designed for 220 volts the field will also be designed for 220 volts here, which means the field winding is supposed withstand a large voltage in this particular case. So, it is generally rated for small currents and large voltage, which means we are going to have high resistance in the field winding. So, in this particular case R_f , if I may look at this will be high because I am looking at $\frac{V_t}{R_f} = I_f$, it is small.

So, the shunt field will be carrying normally very-very large number of turns with small amount of current. So, large number of turns means I am going to have thin wires made into huge number of turns which is going to make the MMF actually high, because of the number of turns being high not because of the current being high.

Student: Are the field and armature windings electrically connected?

Professor: Yes, that is what I am saying in the first case separately excited, they are electrically isolated. In this particular case they will be electrically connected but they are in parallel, but please understand that the field winding comes separately. The armature winding comes out with brush connection, so external to the machine I will connect them in shunt. Not inside the machine. So, generally the field terminals are brought out, the armature terminals are brought out through the brushes, then you connect them in parallel or in series or in whatever fashion you want basically external to the machine not internal, internally they are never connected.

So, always the field terminals will be brought out, armature terminals will be brought out and they will be connected external to the machine normally. So, if I want shunt configuration, I will connect them in parallel to the same voltage supply, that is it. So, generally shunt winding is going to be characterised by N_f being large and I_f is small, this is how it will be. So, I am going to have N_f, that is the number of field turns, will be large thin wire which will be wound over and over to make huge number of turns. And I_f is going to be small so $N_f I_f$ anyway which is making for the MMF of the DC machine that will be pretty much large.

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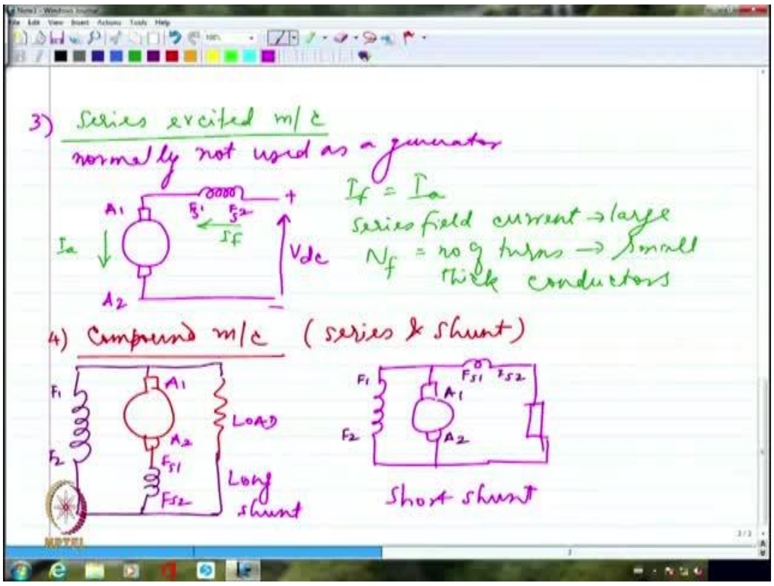

The third type of connection which is actually series. This is hardly ever used as a generator. Most of the times it is going to be used as a motor. Hardly ever it is used as a generator so I should say normally not used as a generator. Only as a motor it is used but it is commonly used as a motor very-very often, in fact, all our cars contain a DC series motor for cranking up mechanism. IC engines have to be cranked up, they cannot start otherwise, the cranking up is normally done with the help of a DC series motor inside most of our cars. Whether it is Maruti, Volkswagen or any of them gasoline-based cars all of them generally use a DC series motor for cranking up.

This is one of the major applications of DC series motor. So, in the series machine as the name indicates I am going to have this as the armature, so let me again mention this as A_1, A_2 and I am going to have the field which is actually F_1, F_2 and if it is a motor I am going to connect the common DC supply here, which is being applied to both the field and armature together. And armature currents will be normally of the order of at least a few amperes or few tens of amperes.

Most of the times because armature is the major power handling hub, so if I talk about 200 volts or 220 volts and the overall capacity of the machine is 2.2 kilo Watt, then at least 10 A has to flow through the armature. So, 10 A of current is flowing, the same current would flow through the field as well. If I call this as I_f and this as I_a I am going to have $I_f = I_a$. So the current is going to be large so series field current is large as against what we saw for the shunt machine. Shunt, we said the current is very small whereas series the current is large so I will have large ampere turns for this even by having smaller number of windings, smaller number of turns.

So, generally series field is characterised by thick coils which are just wound for fewer number of turns, which are carrying very large current. So, we are going to have large current and in this case. N_f, that is the number of turns is going to be small. But thick conductors because I am looking at this carrying a large number of current. Finally, there is something called compound machine which will include both series and shunt. So, compound machine includes series and shunt, the primary flux provider is shunt.

Minor adjustments are made by the series, that is what is done. What I mean is, the shunt is going to provide primarily the flux that is required for the machine. But, series, depending upon how much is the armature current carried by the machine correspondingly because if I do not have enough torque been developed in the machine or enough power available in the machine. If I do not have sufficient load then there is no point of generating large number of power, the voltage will be generated but the current will depend upon what kind of load I have connected in a generator.

Similarly, I may have the motor freely running depending upon how much of impediment I am putting on the shaft I am going to rather look at how much is the torque developed by the motor. So, for example, if I have an elevator, if only two of us get in, the torque developed will be very less. If 15 of us get in, the torque developed will be definitely more because it has to go against the gravity for 15 people together, it has to lift all of us up. So, the torque developed is going to depend upon what is the demand from the load side in the case of a motor, if the mechanical load demand increases, I am going to have more and more current.

If I am going to have a generator depending upon what kind of resistance or what kind of load I have connected I am going to have more or less demand of current basically from the machine. So, please understand this again and again if I am talking about actually armature and if I am connecting a small resistance, I am going to demand more current, for a given voltage. If I connect smaller resistance, I am demanding more current that means I am loading the machine more. If I am connecting a larger resistance, I am going to demand only a smaller current so larger resistance means loading less.

Smaller resistance means loading more, in the case of a generator. Please understand this right, it does not mean that I increase resistance I increase the load, no, when I increase the resistance, I decrease the load, I decrease the power demanded. Because I am always looking at a generator developing rated voltage, never ever you will find a power station generating something like 300 or 350 volts. It is rated for 400 volts 415 volts, it has to generate that. That is how it is, that is how it is adjusted. So, it will always run at rated speed, it will always generate rated voltage because I will always provide rated excitation, that is how it is generally.

So, if it is our compound machine, I am going to have series field and I am going to have shunt field, both. So, I am showing both of them and then they are connected like this, this is how it is. So, let me call the shunt filed as F_1 F_2, maybe even here let me change this to F_{S1} and F_{S2} to show the series field. So, let me write this as F_{S1} and F_{S2}, this is the series field, and this is going to be the load. This is, of course, A_1 and A_2. Please note in this particular configuration the shunt field is coming completely across A_1 and A_2 along with the series field as well, so we call this as a long shunt, it is coming across A_1 A_2 plus F_{S1} F_{S2}.

I can have instead a short shunt I will show you just by a difference, so I am going to have the armature here, I can have the shunt just coming across like this and then I am going to have the series feel beyond this. So, this is generally known as short shunt whereas this is known as long shunt. So, long shunt comes across both armature and series field together whereas short shunt comes across only the armature nothing more than that. So, I can put the series and then the load here. So, please note that here my F_{S1} and F_{S2} have come here.

This is my F_1 F_2 this is A_1 A_2, of course, please note that the field is coming only across the armature here, not across the series field as well. Series field is going beyond parallel connection of the shunt and armature. So, this is generally known as short shunt. We will start off with first generator operation having seen the different configurations, we will look at the implications of these connections as and when we discuss the characteristics. When we load the machine what happens, so we will look at the implications as and then we look at the characteristics of the machine.

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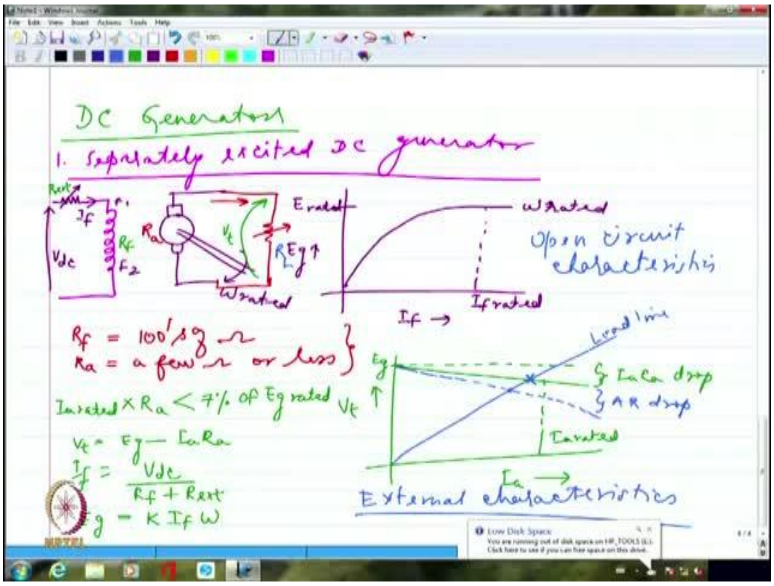

So, first of all we will start off with the separately excited generator. So, I am going to first discuss DC generators, and out of that the first thing that we are going to discuss is separately excited DC generator. So, most of the times in the laboratory as well as in many of the industries, if it all I am using a DC generator which is very rare again. We are going to have invariably the same voltage supply available for armature as well as field. If I am using it as a motor, I might have the same voltage supply, may be to 220 volts or 400 volts the DC value is fixed because of which the separately excited field will also be in a position to withstand a large voltage normally.

Whereas series please note it is having a voltage division between armature and field whereas here there is no voltage division I am having the entire voltage applied here, so I may apply may be with the help of another resistance to adjust the current I may have some V_{dc} applied here and that V_{dc} may be whatever is the rated voltage in my factory or in my laboratory or whatever. So, I will have here this resistance as a rheostat or the variable resistance that I am going to have so variable resistance that I have.

So, I can adjust the current definitely, so this is F_1 F_2 and the current is flowing in this direction and let me call that as I_f, and here is going to be my armature. I can initially plot the open circuit characteristics just by adjusting the rheostat value or I need not even switch on the field to start with and then I can just measure what is the voltage that is developed when I am rotating this at ω_{rated}, I can measure how much is the voltage. Once I measure the voltage, I will get the residual EMF that is generated. So, I will be able to plot what is my OCC, so this is going to be my OCC by adjusting the field rheostat and accordingly I am going to get different points in the OCC.

When the rheostat almost become zero value then whatever is the inherent resistance of the field circuit that is going to limit the current and hopefully that will be the rated current, because of which I am going to get probably at rated value of speed. I am going to get what is the rated voltage generated. So, this is going to be I_{frated}, this is how I_f changes this is E_g so this is going to be E_{rated} or V_{rated} whatever. Now, I am going to actually connect a load.

So, after I have checked up what is the value of back EMF constant and so on, I am going to connect the load. So, this is the load again load probably is variable because I want to see when I draw more current how is the terminal voltage, when I draw less current how is the terminal voltage. Because it will be very similar to what I had as voltage regulation in the case of transformer. A transformer also be initially started assuming without any resistance and without any leakage. So, we said E_2 and V_2 will be equal to each other if it is ideal transformer. But when I am talking about nonideality in any machine I am definitely going to have some inherent resistance for the armature.

Although they are all copper conductors, thick conductors, no doubt but I will still have some amount of resistance so if I say that the feel resistance is generally hundreds of ohms, armature resistance will be generally of few ohms or less. So, it can be even milli-ohms, or it can be just 0.1 ohm 0.2 ohms and so on and so forth depending upon what kind of rating I am talking about. The larger the rating the current carried will be larger because of which the conductors will be thicker. So, the resistance will fall, so larger the rating of the machine R_a will be smaller and smaller.

Because the conductors will be thicker and thicker normally. So, I am going to have these as some ballpark values, estimated values, I am telling you I am not asking you to memorise these things this should become your second nature eventually when you read through so many problems in DC machine invariably we will see that the field resistance will be given as 50 ohms, 100 ohms, 150 ohms whatever. Whereas, armature resistance will be given as 1 ohm 0.8 ohms, 0.01 and so on and so forth that is what you would see.

So, the armature resistance is generally very small but when a current is flowing in the DC machine, although 220 V were probably generated originally when it was under no-load condition. I am definitely going to have a drop which will correspond I_aR_a, if I_a is let us say 10 A, and let us say I am going to have my armature resistance as 0.5 ohm then 10 multiplied by 0.5 I will still have 5 V drop. So, from 220V I will have a drop of 5 V, so the terminal voltage if I try to measure now this may be only 215 V.

So, this I would call as the terminal voltage V_t. V_t will keep falling further and further as I increase or as I draw more and more current from the generator. So, if I try to plot how V_t is as compared to what my armature current is. Please remember or notice that you are going to have I_a and I_f independent of each other because they are supplied from two different entities. So, I have generated voltage which is supplying the load, which is also the armature current. I am going to have actually whatever is the field current that is decided by what is the field resistance and what is the field supply.

So the two are independent of each other so I am going to have this as I_a this as V_t, when my I_a is zero, I had this value to be E_g, at rated speed. Of course, I am talking about rated condition of speed, rated excitation when I provided rated excitation and rated speed I had E_g as my value of generated voltage. Now, as if it had been an ideal generator, this should have been maintained as a constant. But it is not ideal, clearly so I am going to have definitely a fall in the voltage.

But the fall in the voltage is not much normally in a separately excited machine because the armature resistance happens to be generally very very small. So I will have generally the drop in the voltage I_aR_a drop as compared to what is E_g, the original generated voltage, it will be less than 5 to 7 percent. It will not be definitely more than about 7 - 8 percent, so this is really really small. So, this is, actually if I say this is the rated current, so this is I_{arated}, I am going to have this drop what am getting as I_aR_a drop.

So, I am going to have $I_{arated}R_a$ is going to be less than most of the times about 7 to 8 percent of E_{grated}. So, R_a is generally, really-really small that is what I am trying to emphasise. So, I should be able to write some of the electrical equations based on whatever characteristics I have drawn, I can say

$$V_t = E_g - I_aR_a$$

I should be able to write also that,

$$I_f = \frac{V_{dc}}{R_f + \mathrm{R}_{ext}}$$

What I have connected as the external resistance I am calling that as R_{ext} .

I should be able to say

$$E_g = KI_f\omega$$

So, in this particular case there is no correlation between I_f and I_a. R_f is the inherent field resistance which will be of the order of 150 Ω, 100 Ω or 150 Ω whatever.

So, this is field resistance, so these are the equations which govern the operation of separately excited DC generator. K is actually the constant, I cannot write this as K_e because, $E_g = K_e\phi\omega$, but now I am not writing ϕ. I am writing I_f because I_f is an electrical quantity. Whereas, ϕ, I have to bring in magnetic circuits.

So, that is why that K still corresponds to the back EMF constant. But if actually I eliminate ϕ and instead I put I_f, then the proportionality will change. There will be reluctance inclusion, number of turns, and so on and so forth. So, that K still related to the machine constants which are like parallel paths, number of conductors and so on and so forth, poles, all those things definitely.

So, these are going to be the equations that govern the operation of separately excited DC generator, by the way because this whatever we observed here is the load terminal voltage and the load current it is external to the machine. So, we call this as external characteristics of the machine, whereas this is open circuit characteristics of the machine.

Now a small twist I have to introduce in the external characteristics. All along we are assuming that the flux is unaffected by any armature current that is drawn, but the armature current is not going to keep quiet. It will also establish its own flux, because it introduces its own flux, the main flux which was created by the field will get modified. As long as the armature was open circuited, it was just developing the voltage, the main flux was just hail and healthy, there was no problem.

But the moment I connect the load the armature is going to start carrying current. If the armature carries current, it is definitely going to throw its own spanner into the entire field of things. So, I am going to have some variation in the flux, in the form of something called armature reaction. So, we will have to look at what is the reaction of the overall flux to the armature flux that is known as armature reaction. The net effect of armature reaction would be to reduce the flux to certain extent.

But there may be some saturation involved, there may be some other crossover involved because of which it is not a linear reduction as compared to the armature current been increased. If armature current is 5 A, if the flux is getting decreased by 0.2 wb, it does not mean if the armature current is 10 A, I am going to have reduction by 0.4 wb. So, I will have actually if I try to look at it, the drop will not be linear. It is going to be a non-linear as far as the armature reaction drop is concerned, we are going to discuss armature reaction in a little greater detail.

But I am just trying to say that it is non-linear because of which I am going to have this as armature reaction drop. This is called as armature reaction drop. So, the armature reaction drop occurs in a DC machine in addition to I_aR_a drop. I_aR_a drop is because of the physical resistance of the DC motor's armature winding whereas the armature reaction drop is essentially due to the armature flux interacting with the field flux and maybe bringing down the overall value by some quantity.

So that is going to cause a reduction in the overall voltage that I am visualising at the terminal of the DC machine and this will definitely increase as the armature current increases because the reaction will increase definitely. But it is not a linear increase that is a little non-linear and that is why I am not showing this as linear it may be non-linear. Now, originally if I had considered where the operating point for a given load resistance, R_L. Let me show this as R_L. So, I have to draw basically the load line. If I am looking at the load line, this is the load line, load line is I_L multiplied by R_L or I_a multiplied by R_L (I_aR_L), what is the voltage correspondingly?

Where these two intersect? This would have been the operating point originally, but now because of the armature reaction they are intersecting somewhere else, so I am definitely going to have a little different value of the operating point that is the voltage as well as the current, both are going to be somewhat different as compared to what actually I visualised originally as the operating point. This was the original operating point, this will be the new operating point as per the armature reaction effect is also included. So, we will look at what is armature reaction in the next class.