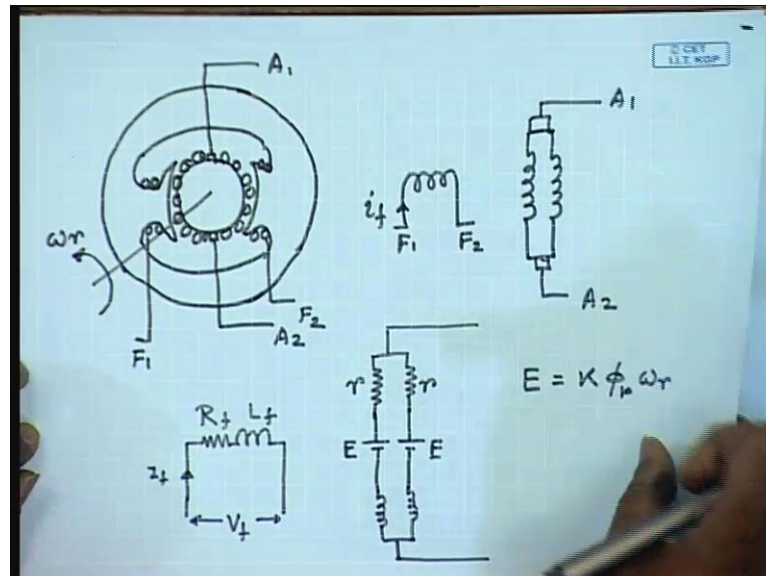


Electrical Machines - I
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Lecture - 26
Separately excited DC generators

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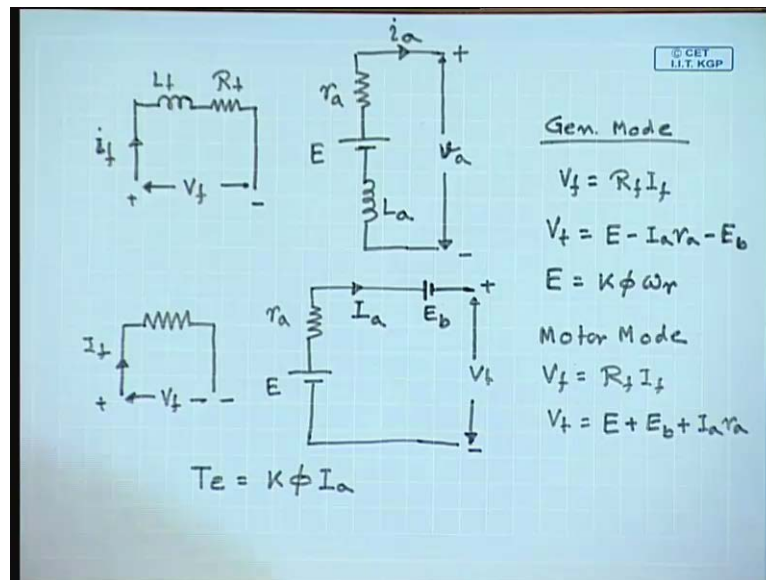


The cross section of a two pole DC Machine will look somewhat like this. These are the armature terminals, you also have field winding. These are the field terminals. schematically this is the shaft, can be represented as the field winding with the current i_f and armature winding, it is to be noted that although you have a physical single field winding the armature winding represented in this schematic diagram does not really exist in the actual machine. In the actual machine as the armature rotates the constituent coils of these two parallel paths keeps changing, but overall the structure looks like this therefore, it is reasonable to represent the armature of a DC machine by a parallel connection of several coils. The individual constituent coils may change, but the number of coils between two brushes remains always constant number of parallel paths being equal to the number of poles for lap connected machine and equal to two for wave machine.

Now, if this armature is rotated at speed ωR then we have seen that each of this parallel path will have a induced voltage. And of course, the windings will also have

their resistance, as well as inductance. Similarly the field winding will have its resistance and inductance, E as we have seen before is given by back $E M F$ constant k flux per pole ϕ into ωR , since these windings are identical the induced voltage are also identical.

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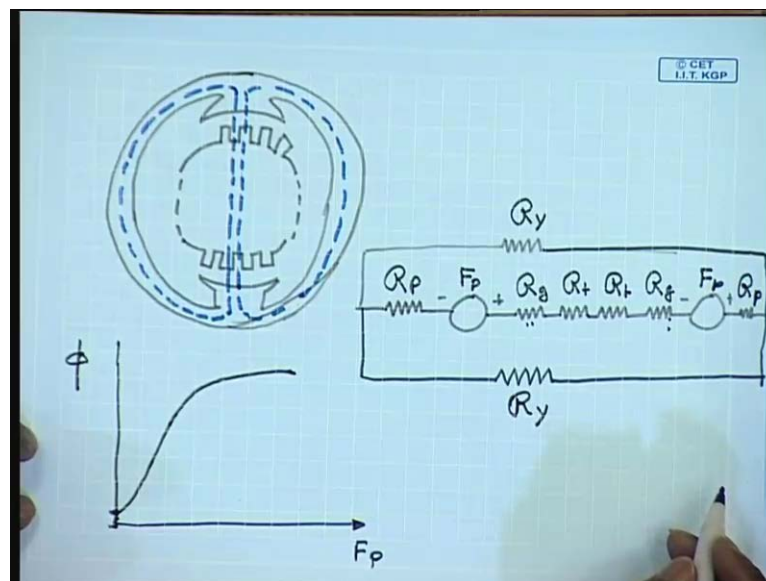
Therefore these two parallel branches of our DC machine can be replaced by a single branch. This is the field winding, this is the armature winding. Let the armature voltage be v_a this in plus this in minus and the motoring mode that the current, generating mode the current be i_a , it is resistance is r_a , this is E and this is the inductance L_a for steady state operation the currents i_a v_a i_a V_f these are all DC. Therefore, the inductance do not play any role in determining the steady state behavior of a DC machine therefore, we can neglect the inductance for steady state operation.

Hence the field circuit can be represented by the simply the field resistance and the armature circuit by the armature resistance and the induced voltage E . Sometimes the contact resistance of the brushes are also modeled there are different ways of doing it. It can be modeled as a resistance, but more often not the drop across the brush is more or less constant. Therefore, it is reasonable to assume the total brush drop as another voltage of fixed magnitude, which is independent of all other machines parameters or variables like armature current or rotational speed this is called the brush contact drop, normally is above two volts and this is the terminal voltage V_t .

Therefore the steady state equation of a DC machine can be written as $V_f = R_f I_f$, $V_t = E - I_a r_a - E_{brush}$, many a times this brush contact drop is neglected and $E = k \phi \omega_r$, where ω_r is the rotational speed of the armature. Now, this equation has been written with generator convention in mind that is assuming that the DC machine works as a generator. So, this is generator mode of operation for motor mode the direction of armature current will reverse. So, you will write $V_f = R_f I_f$, $V_t = E + E_b + I_a r_a$.

The generated torque is always given by $k \phi I_a$, in the motoring mode the torque assists the motion that is, it rotates the machine in the generating mode it opposes motion. So, these are the basic equations steady state equations of a DC machine and depending on whether it is operating as a motor or generator, we will take the appropriate set of equations. Now, we can see that, these are simple linear algebraic equation except the relationship between I_f and ϕ .

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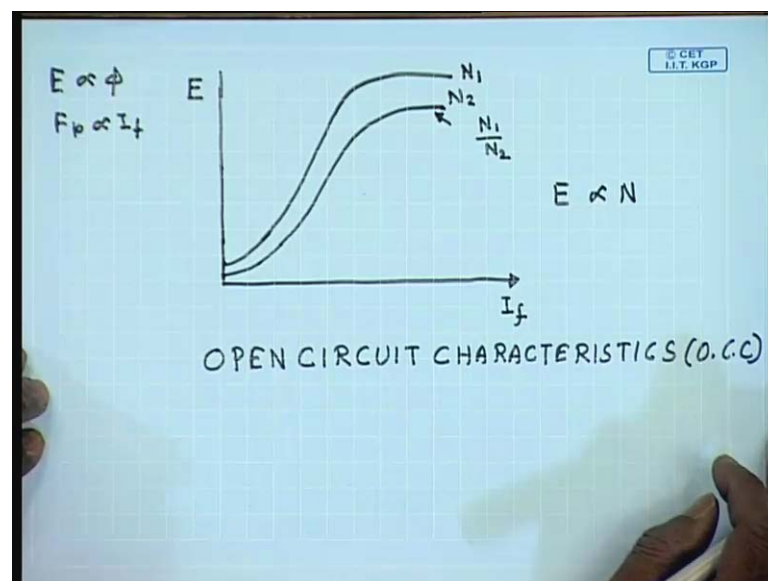


This relationship is not normally linear, because of magnetic saturation of the DC machine. The DC machine magnetic circuit can be drawn in a simplified way as given below. This is the armature which has slots and teeth on them, this is the pole. The flux path through the machine can be steps like this, the main flux path. So, the magnetic circuit of a DC machine can be drawn this manner. This is the m m f source due to the field coil on one pole, this is the m m f source on the second pole, this is the reluctance

of the first air gap, this is the reluctance of the second air gap, these are the reluctance of the armature teeth, this is the reluctance of the pole body and these are the reluctance of the stator core. As we see from this magnetic equivalent circuit that, in this except for the reluctance of the air gap, now all other flux path contains iron which is a ferromagnetic material and shows prominent saturation.

Therefore as the field $m m f F_p$ increases the field flux ϕ initially rises in a linear manner as long as the iron remains unsaturated, but later on it shows a predominant saturation characteristics and becomes flat. Not only that the iron body also shows a residual magnetism, which is present in the iron if even when there is no field excitation this characteristic is important for the operation of a DC generator. So, it is expected that the induced voltage in a DC generator will also follow similar pattern.

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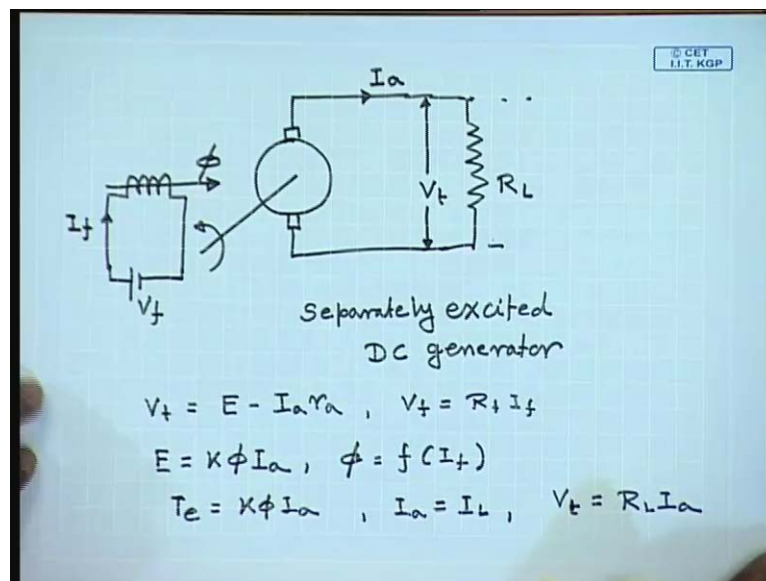


It is indeed so but it is customary to find out, since E is proportional to ϕ for a given speed and ϕ is proportional to F_p , F_p is proportional to I_f . It is expected that if the induced voltage of a DC machine is plotted with respect to the field current. It will be similar to the characteristics of ϕ versus F_p and operated at constant speed, these characteristics can be experimentally determined for every DC machine and is called the open circuit characteristics or O.C.C. In short. This is an important characteristic for every DC machine and can be obtained experimentally by exciting the field winding from a separate source and keeping the armature terminals open and operating the machine as a

generator at constant speed. and if the induced voltage is plotted verses field current at constant speed we obtain the O C C.

If the O C C is obtained at any given speed, let us say for a speed of N_1 the O C C for a different speed N_2 can be obtained from the O C C at N_1 by simply multiplying by proportionality constant. This O C C is obtained at speed N_2 is obtained by multiplying the O C C, the ordinate of the O C C by a factor N_1 by N_2 . This is due to the fact that the back e m f, E induced voltage is proportional to N . It is to be emphasized that during the determination of O C C the field winding is excited separately and the armature terminals are kept open the machine is also operated as a generator at constant speed. A few other things, while determining the O C C the field current should be either continuously increased or decreased. It should not be, it should not alternate, because if it alternates then the flux in the core will show a local hysteresis and will introduce error in the O C C.

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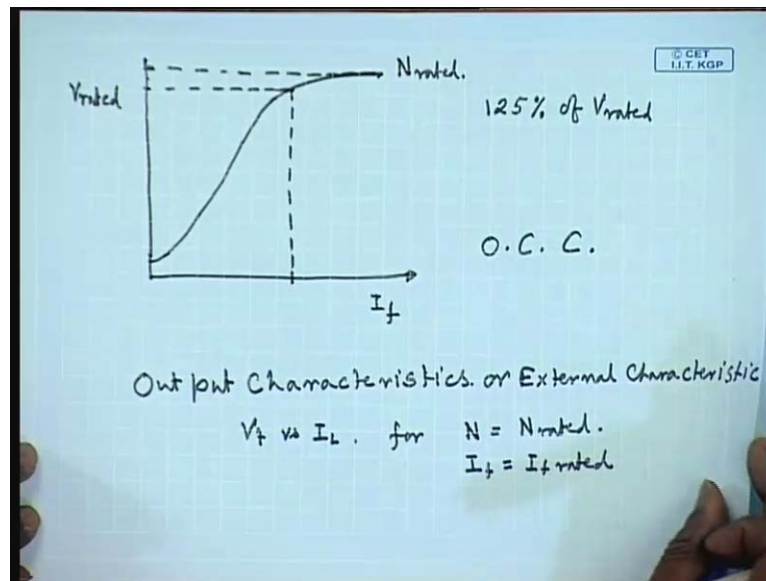


We have seen in our pervious class, that the field winding of a DC machine can be connected in many different ways. This is the armature terminal, this is the armature terminal this is the field terminal, when a field winding is excited from a separate DC source produce a flux ϕ , this is called a separately excited DC machine. For this separately excited DC generator, we can write the terminal voltage V_t equal to induced voltage E minus $I_a r_a$ and applied field voltage V_f equal to $R_f I_f$, E equal to $k \phi I_a$

and ϕ is some non-linear function of I_f . The torque generated T_e developed torque equal to $k \phi I_a$.

Since the armature terminals supplies the load. So, armature current is same as the load current I_L . It is to be noted that this generator can either supply a standalone resistive load R_L in which case we have the further relation V_t equal to $R_L I_a$ or it can be connected to a DC bus having a terminal voltage equal to V_t .

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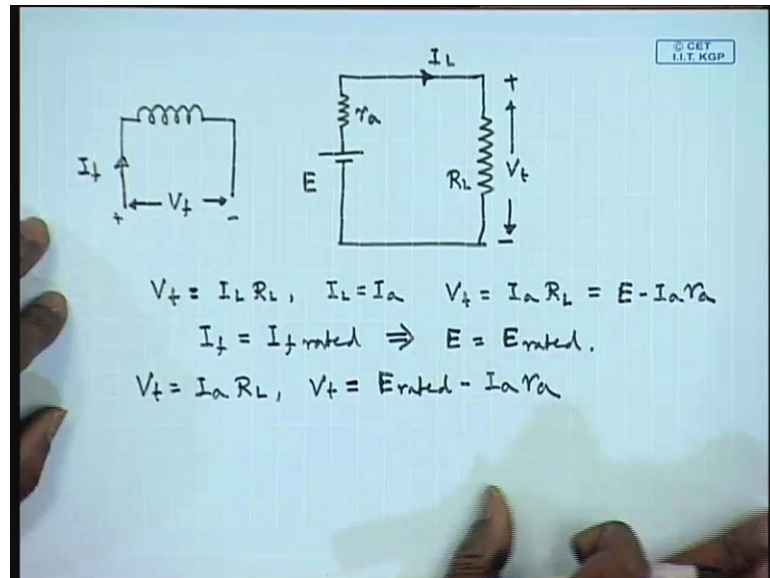


The O C C for separately excited machine generator can be obtained by running the generator at a constant speed and then increasing the field excitation slowly. So, that the terminal voltage when the armature terminals are open reaches a value which is larger than the rated value of the, if this is the rated value rated terminal voltage. Then the O C C is determined up to a value which is about 125 percent of V_{rated} , this O C C is normally obtained at the rated speed of the generator.

However as we have mentioned earlier O C C for any other speed can be obtained by multiplying the O C C of the generator at rated speed by the ratio of the speed. However, it is more important for at least a generator to find out, what is called it is output characteristics or the external characteristics? This one is the open circuit characteristic or O C C. For a DC generator supplying a load as shown here, it will be more important to find out its external characteristics or the output characteristics. This is a plot of the terminal voltage V_t verses the load current I_L , which is same as I_a in this case for

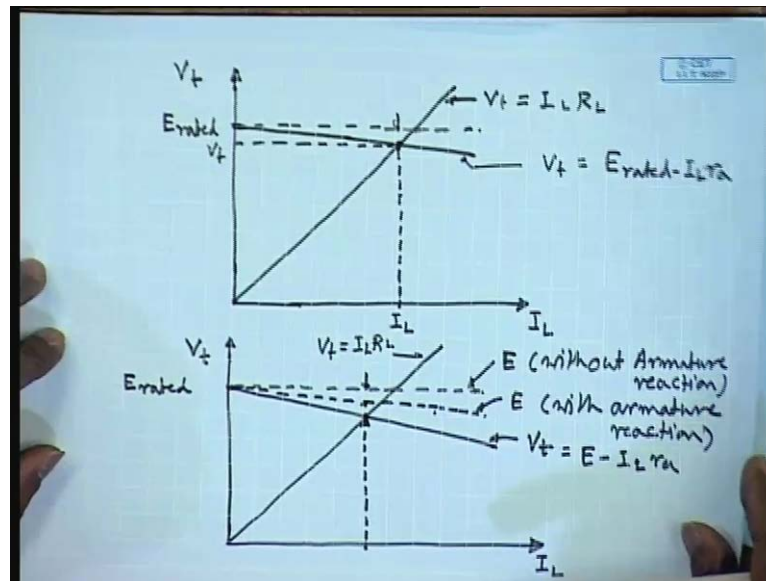
constant speed N equal to N rated and I_f equal to I_f rated, where I_f rated is the field current required to produce rated voltage at no load.

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So, under load condition, this is the equivalent circuit of the DC generator. From this we can easily say V_t equal to $I_L R_L$, I_L equal to I_a hence, V_t equal to $I_a R_L$ this is also equal to E minus $I_a r_a$. Now, these set of equations can be if I_f equal to constant would imply, if the machine is operated at constant speed E equal to constant at E rated. So, the operating point can be found out from this relation V_t equal to $I_a R_L$ and V_t by the intersection of these two straight lines E rated minus $I_a r_a$.

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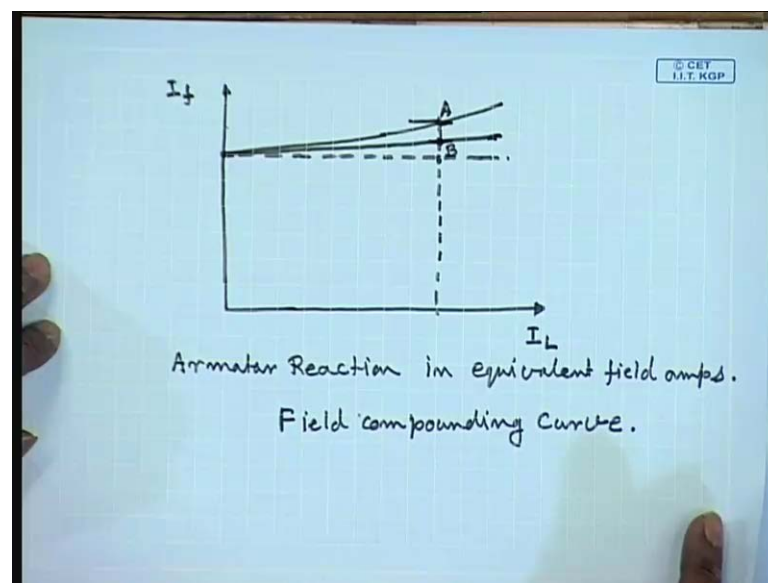
This is, if it is E rated and this is I_L , one would expect that as the machine is loaded the terminal voltage will fall linearly. For a given load resistance, the terminal voltage also obeys the first equation, the load line equation. So, this equation represents V_t equal to E rated minus $I_L r_a$, while the load line equation is given by V_t equal to $I_L R_L$. So, for a given resistance R_L the operating point is given by the intersection of these two characteristics. This is the operating V_t and this is the I_L and this is the drop due to armature resistance. The characteristics of V_t versus I_L is called the output characteristics or the external characteristics of the generator.

However this simple model neglects the effect of armature reaction, we have seen before that due to current flowing in the armature, the field flux is distorted the field flux at one half of the pole tip increases and in the other half it decreases. Now, if the machine is operating near the saturation zone, near the saturation point that decrease of the field flux due to armature reaction is more than the increase in the second other half of the pole due to increase in a peak. Therefore, there is a net reduction in flux per pole and hence due to armature reaction in a practical machine the value of induced voltage does not remain constant with increase in armature current. In fact, the armature voltage the induced voltage tends to drop.

So, without armature reaction with a constant field flux, the induced voltage would have remain constant at a value of E rated, but due to armature reaction there will be some

drop. This is the induced voltage E without armature reaction and this is the induced voltage E with armature reaction. On top of this there will be a drop due to armature resistance therefore, this is at any, this is V_t equal to E minus $I_L R_a$ and this is the load line V_t equal to $I_L R_L$ the intersection point is here, there are two drops as we can see the first one is due to armature reaction and the second one is due to the armature resistance. Now, the drop due to armature resistance can be due to armature reaction, can be found out experimentally by operating the machine at constant speed and by gradually loading the machine with change in the field excitation current.

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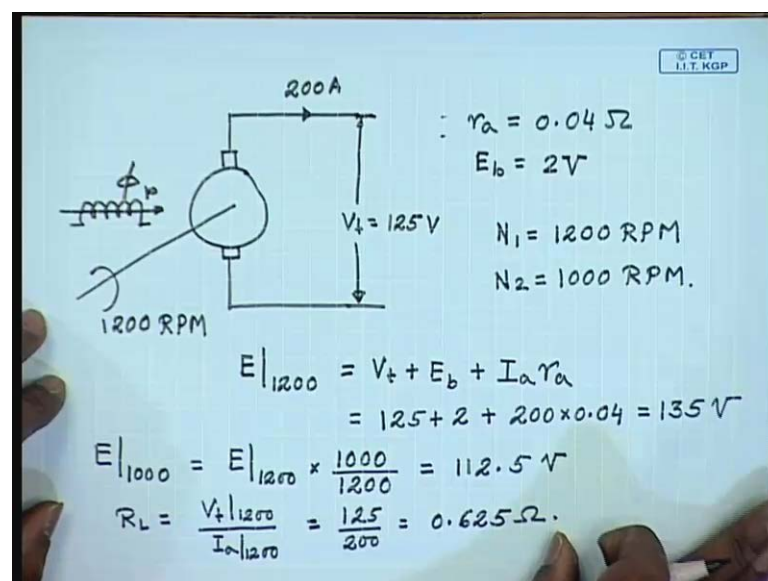
So, that so as to keep the terminal voltage constant at any desired value for any load current so this is a plot of I_L versus I_f . If there was no armature reaction then in order to keep the terminal voltage constant at any load current. You have to compensate only for the armature resistance drop and the characteristics would have been a straight line, but due to armature reaction some more increase in the field current will be required to overcome the drop due to armature reaction.

So, at any given load current one can find out the field ampere turns or field current required to compensate for the armature reaction drop from by calculating this magnitude $A B$. So, this way the armature drop in the armature voltage due to armature reaction can be expressed in terms of equivalent field current. Armature reaction in equivalent field amperes, this curve is called the field compounding curve. A field

compounding curve is a plot of the field current versus the load current at constant rotational speed and at constant terminal voltage. That is it plots the field current required to keep the terminal voltage constant for any given load current when the machine operates at constant speed. It is important to understand that, the amount degree of saturation at the due to armature reaction is somewhat dependent on the terminal voltage of the DC generator.

Hence if the purpose is to find out the armature reaction in equivalent field amperes, it is necessary to find out the field compounding curve at the desired terminal voltage. It is easy to understand that, this field compounding curve can be obtained at different speed and at different terminal voltage; however, in order to find out the equivalent field amperes for the armature reaction it is necessary to find out the field compounding curve at the required terminal voltage.

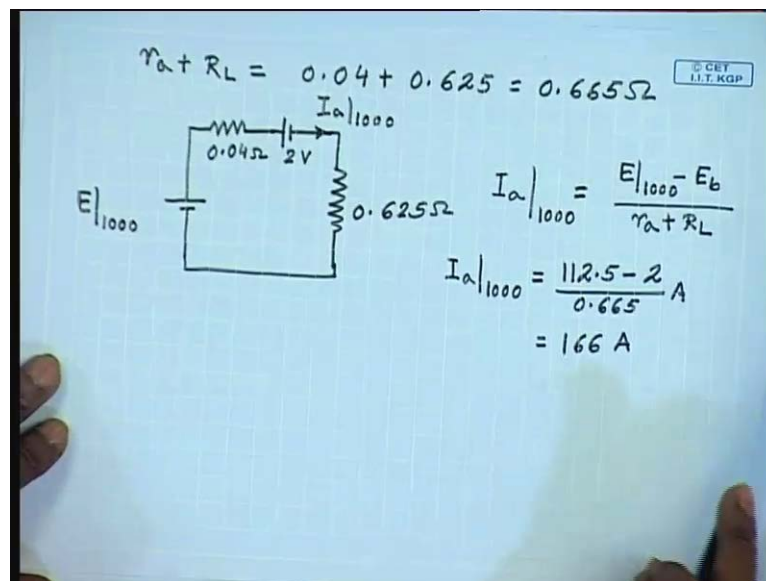
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So, let us see, solve few problems to understand what has been discussed so far. Suppose we have a DC machine, separately excited DC machine, this machine as a armature resistance r_a of 0.04 ohm, total brush contact drop E_b equal to 2 volts. It supplies a load current of 200 ampere at a terminal voltage V_t equal to 125 volts, when it is rotated at 1200 R P M. Question is if the rotational speed is reduced from 1200 R P M to N_2 equal to 1000 R P M, what will be the new armature current?

For this, let us first find out the induced voltage E at 1200 R P M neglecting, armature reaction E at 1200 R P M then will be terminal voltage plus brush contact drop plus armature resistance drop. Since back E M F is proportional to rotational speed E at 1000 R P M will be equal to E at 1200 R P M multiplied by 1000 divided by 1200 this comes to 112.5 volts. What is the load resistance R_L ? R_L equal to V_t at 1200 R P M divided by I_a at 1200 R P M this is 125 by 200 equal to 0.625 ohm.

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Hence, the total armature circuit resistance r_a plus R_L equal to 0.04 plus 625 equal to 0.665 ohm. At 1000 R P M therefore, you can draw the equivalent circuit as E at 1000 r_a 0.04 ohm then E_b equal to 2 volts then R_L 0.625 ohm therefore, the current I_a at 1000 R P M equal to E at 1000 R P M minus E_b divided by r_a plus R_L or I_a at 1000 R P M will be equal to 112.5 minus 2 divided by 0.665 ampere this comes to 166 ampere; however, in this problem we have neglected the armature reaction.

(Refer Slide Time: 47:40)

3.3 kW, 110 V, 1500 RPM, 4 pole

O.C.C.

I_f (A)	0	0.25	0.5	0.75	1	1.25	1.5	1.75	2.0
E (V)	5	40	65	82.5	95	103.5	110	113.5	117.5

& $\frac{2.3}{120}$

$r_a = 0.2 \Omega$, $N_f = 200$, $E_b = 2V$

$I_L = 20 A$, $20 \times 0.2 + 2 = 6V$

$V_t = 110 - 6 = 104 V$

Let us try to solve a problem incorporating armature reaction, for this let us say we have a DC machine which is rated power is 3.3 kilowatt and rated terminal voltage is 110 volts, rated rotational speed is 1500 R P M, 4 pole. The O C C of this generator is given by the following data, no field current the residual voltage is 5 volts, 0.25 ampere this 40 volts, 0.5 ampere 65 volts, 0.75 ampere 82.5 volts, 1 ampere 95 volts, 1.25 amperes and at 2.3 ampere the voltage is 120 volts. The armature circuit resistance is r_a equal to 0.2 ohm, number of field turns N_f equal to 200, E_b equal to 2 volts.

You can assume that the armature demagnetizing ampere turns is proportional to the armature current that is this line is a straight line and the effective demagnetizing ampere turns is equal to 1.5 times the armature current. So, you have to find out the terminal voltage of the machine at a given load current, when the machine is operated at constant speed. If we neglect armature reaction then let us say some load current I_L equal to 20 amperes, the total armature circuit drop would have been 20×0.2 plus brush contact drop 2 volts equal to 6 volts and if the field excitation field current is at just as. So, that at no load the terminal voltage is 110 volt then at 20 ampere I_L . V_t would have been $110 - 6$ equal to 104 volts, but when you take armature reaction into account then the voltage becomes different.

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The whiteboard contains the following handwritten calculations:

$$I_L = 20A, \quad AT/pole = 1.5 \times 20 = 30$$
$$N_f = 200, \quad i_{f,eq} = 30/200 = 0.15A$$
$$\begin{aligned} V_t |_{No\ load} = 110V &\rightarrow I_f = 1.5A \\ aR &\rightarrow I_f = -0.15A \\ I_f |_{Net} &= 1.35A \end{aligned}$$
$$E |_{1.35} \approx 107V,$$
$$I_a r_a + E_b = 20 \times 0.2 + 2 = 6V$$
$$V_t = 107 - 6 = 101V$$

Let us again say a load current of 20 amperes, it is mentioned that ampere turns demagnetizing ampere turns per pole is 1.5 times the armature current. So, demagnetizing ampere turns equal to 30. Number of field turns is N_f equal to 200 therefore, equivalent field amperes for the demagnetizing armature reaction ampere turns is 30 by 200 equal to 0.15 amperes. Now, in order to adjust V_t at no load equal to 110 volts we see from this table the corresponding field current should have been this corresponds to a field current of I_f equal to 1.5 amperes. The demagnetizing the armature reaction is equivalent to a demagnetizing field current a R armature reaction is I_f equal to minus 0.15 ampere.

So, the effective I_f net equal to 1.35 amperes, so the induced voltage with 1.35 ampere of field current will give you E at I_f equal to 1.35 this approximately from that data it is approximately 107 volts. And the armature circuit drop is $I_a r_a$ plus E_b that is equal to 20 into 0.2 plus 2 equal to 6 volts therefore, the terminal voltage V_t will be equal to 107 minus 6 equal to 101 volts. Therefore, we see without armature reaction, without considering armature reaction we are getting a terminal voltage of 104, but when armature reaction is included, the terminal voltage for the same field load current drops to 101 volt. This is the effect of armature reaction.

Thank you.