Basic Electrical Technology

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Lecture - 26
DC Generators Part – II

Hello everybody, in the last session we were discussing about the DC generator and looked at how one could excite the DC generator with various forms of excitation methods that is the permanent magnet method, the separately excited excitation method, shunt excitation method and one more method the compound excitation method which we have still not discussed.

Of course we will revisit the excitation concept after discussion on the equivalent circuit of the generator. So we first discuss on the equivalent circuit of the generator and then we will follow it up again with the different types of excitation methods, its pluses and minuses, benefits and disadvantages and how they can be corrected.

So, coming back again to the DC generator the generation of the field that is the flux or the excitation is a function of the field current that is provided, the field current in the electromagnetic poles that we saw in the last session that the electromagnetic poles can obtain the field current either from a separate source then it is called a separately excited machine or it can be taken from the generated emf then it is called the shunt or self-excited machine.

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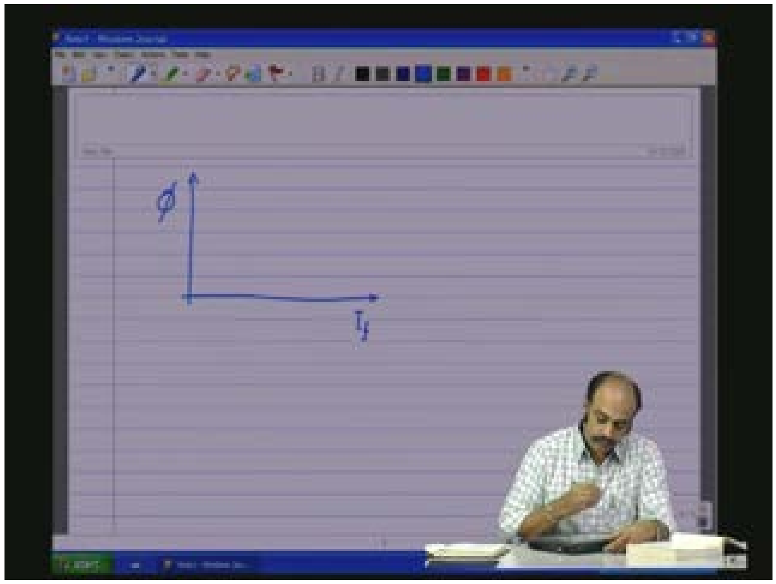

Now if we look at the graph of the I f versus the flux, as the I f increases……. so this I f is actually trying to provide the mmf the ampere turns by which we are trying to get a flux curve which is like this. After sometime if you further give more field current (Refer Slide Time: 3:57) the flux tends to saturate. So the flux the per unit values can vary from zero to let us say this is one per unit or 100 percent let us say and this could be somewhere around 1.25 per unit or 125 percent. now to reach 100 percent let us say you need 1 amp of current and if you further increase the currents the flux that is provided that is produced is not proportional as it was in the…… it is not having the same, for the same change in current you will not get the same change in the flux at the output. So as you still further increase the current somewhere here to produce some change in the flux here you need to have a very large change in the current here because the slope here is very small so you need to produce a very large change in current to produce even a small change in flux here then we say that these are the saturation zones.

One should operate the machine just up to the knee point. This is called the knee (Refer Slide Time: 5:50) just up to the knee point and it is not advisable to operate beyond the knee point because then the currents drawn will be much higher and therefore i square r losses will be higher.

Now this flux is used for obtaining the generated voltage across the brushes and which is given by p N phi Z by 60. So out of this for a given machine this is a constant, of course this is a constant value the number total number of conductors for a given machine is a constant and for a given speed of rotation E g is proportional to the flux. So now if we if we now plot the generator emf E g versus the feel current I f it will be more or less the same because E g is proportional to phi you will get a curve which is more or less looking like the phi versus I f curve. So your rated voltage should be somewhere around the knee point and this should be your E g rated and this would be the rated field current that you apply. So, beyond the rated field current the generated emf does not increase very much for changes in the field current. So this this is called the saturation curve, this is called the voltage saturation curve and this is called the flux saturation curve and this happens even at no load. so load this has the load has not much role to play in this, this is just obtain by the amount of the field current that flows through the field coils to obtain the flux phi the main primary flux phi.

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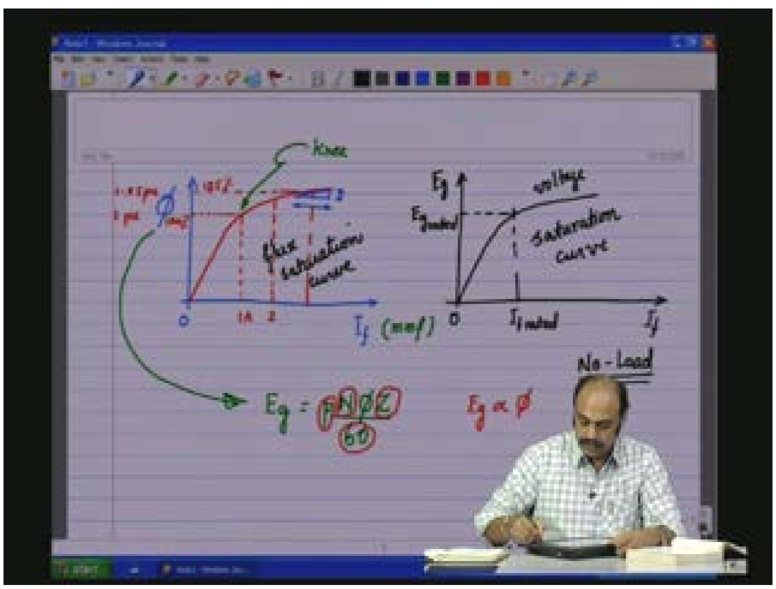

Now there is there are two non-idealities that will come into the come into play while we are talking of equivalence. We will represent the commutator and the brush like that and we will represent the shaft like this. Now this shaft is connected to a prime mover and from the brushes from the brushes the machine is connected to an external circuit which contains the electrical load. So this would be the electrical equivalent of this DC generator. So this is the DC generator (Refer Slide Time: 10:10) so the armature, the conductors in the armature, the poles all those things are contained within this circle and the commutator, there is the brushes which link the magnetic portion of the DC generator to the electrical portion of the circuit and there is a shaft which is coming out of the generator which is connected to the armature and that is linked to the prime mover and here is the mechanical source and you have a mechanical interface, goes into the magnetic domain and then you have the electrical load.

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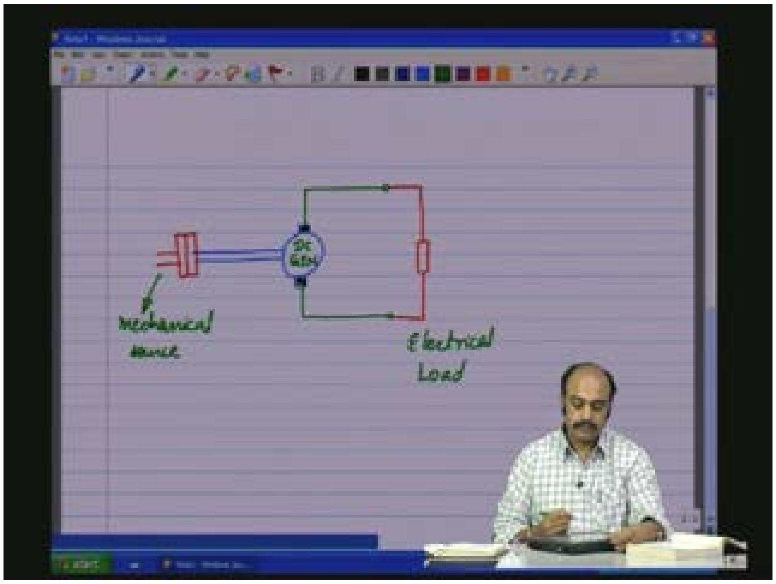

Now this wire through the brushes lead through into the coils of the armature. So therefore there are two non-idealities that can come into play: one is the armature the armature winding winding resistance and that is called R a. Now there is another second imperfection that can come or non-ideality that can come, one is the armature winding reactance; both these are coming in series and we call that one as L a the inductance L a. Note that the machine is DC but whereas the coils inside C AC. So therefore there is a reactance which comes into play in the motor. But these reactants come into play whenever there is a change on the electrical side. If on the electrical side the voltage is DC the current is DC there is no dynamics involved and the reactance component is not coming in to the picture because omega is zero omega L is equal to 0. But whenever there is any step change in the load, whenever there is a change in the excitation whenever there is a change in the generated emf any change is going to cause L di by dt and that counter emf or that L di by dt portion is going to lead to a dynamic situation and during those condition L a will come to play a role. So therefore the equivalent circuit will contain two components: one is the R a and the other is the L a the armature reactance the armature inductance. Of course armature inductance will come into play only during dynamics so this is going to come into play only during dynamics and when we are writing the dynamic model we will try to consider the L a and when we are talking of the steady-state model during steady-state omega L a is equal to 0 so we do not normally consider those L a effect the reactive effect.

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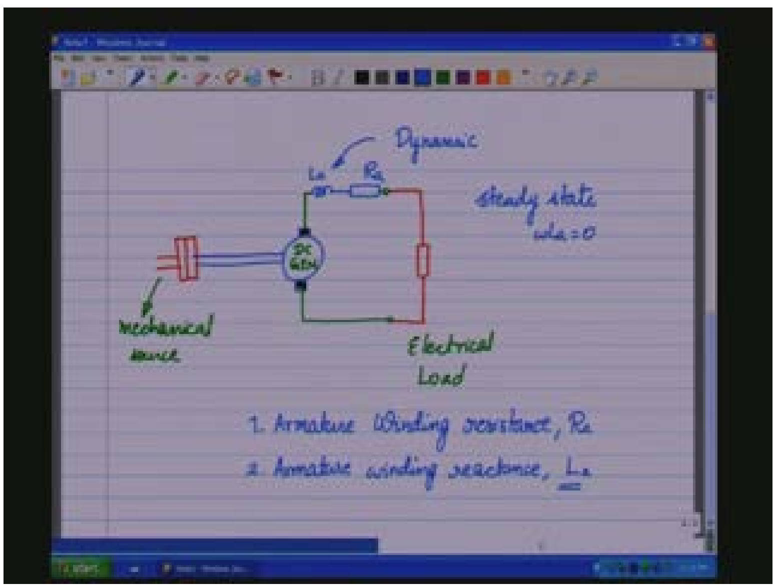

And therefore for the steady-state we just consider the DC machine in the following fashion. We have the brush. so always we show the brush like this, the machine itself is shown as a circle is the DC generator and then there is a shaft which is moved by a prime mover, the brushes are connected to the load but there is an imperfection which has to come in to the picture that is the R a for the steady-state and then the load is connected across the terminals of the generator. So this is E we will call this one as E E 0 and what is actually generated here we will call this one as E generated E g and this resistance is R a.

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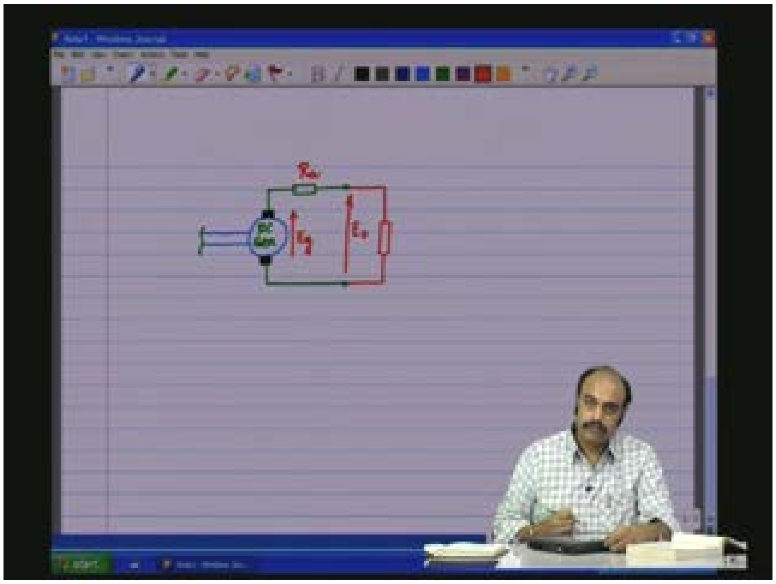

So there is going to be some current I which flows through this. So what is E 0? The actual voltage that is coming across the load will be E g minus I into R a and this is the equation which gives you the load regulation portion.

So, as the current here increases and why should the current here increase is if the load here increases; the load here increases the current here increases and as the current here decreases increases the I R a drop here increases thereby the effective voltage across the load across the terminals of the generator will be E g minus I R a which will be less than E g by the amount of the drop across the series resistance R a which is the armature winding resistance.

Now E g is the generated emf which is given by p N phi Z by 60 minus I R a that is E 0. So this equation gives a picture of how the actual terminal voltage along with the non-ideality R a is related with the fluxes and the speed of rotation N of the machine.

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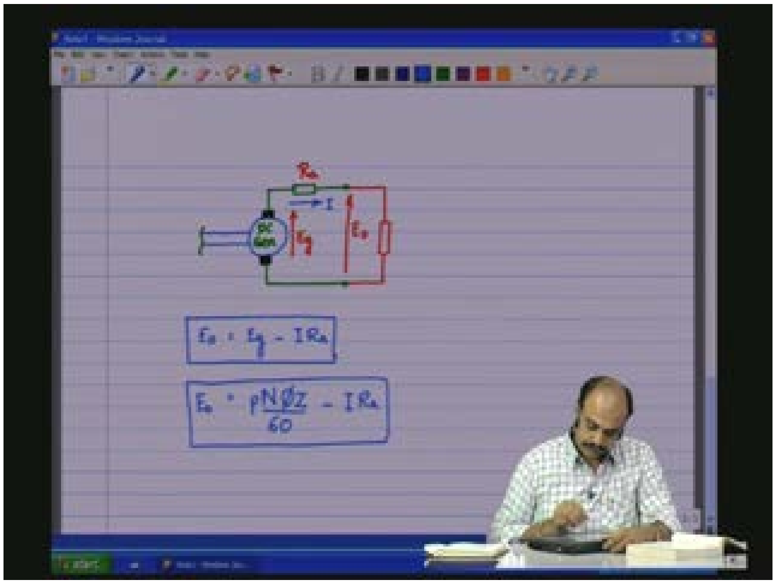

Now if you plot if you plot E 0 versus I f what would one obtain?

Now we saw in the previous graph here (Refer Slide Time: 18:12) E g and I f are given by this voltage saturation curve. So whatever a value of E 0 which you will get here is again basically given as something which looks like the E g curve so this would be the E g curve minus the load component and that load component is going to determine E 0 so this is going to be your E 0. So your actual E 0 curve across the terminals of the generator will be lesser than the E g curve.

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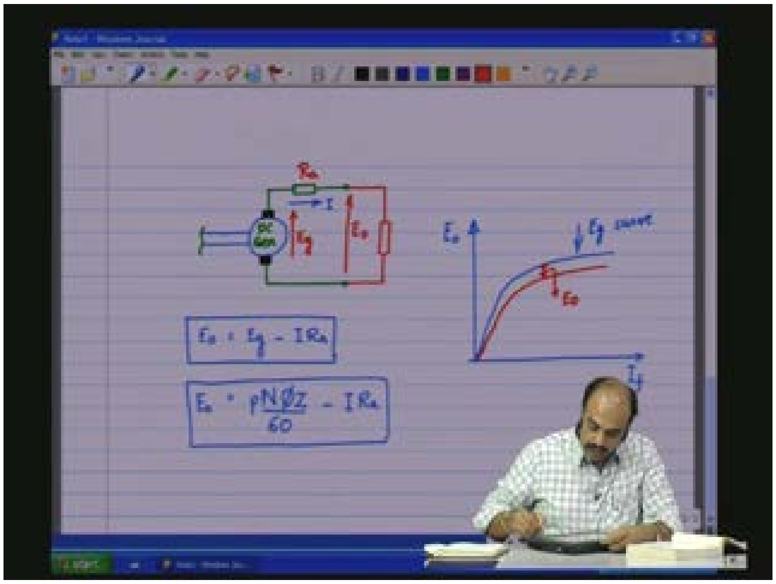

And with respect to I we have the voltage regulation curve, I is the load this is the load and you have E 0. So when the load is zero here no load resistance is connected, E 0 will be same as E g as it is evident from this equation here (Refer Slide Time: 19:52) when I is 0 it is……..

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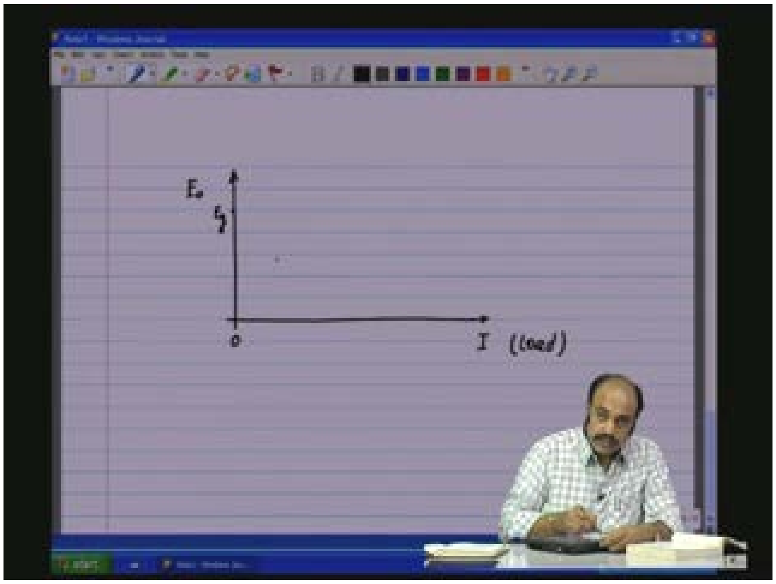

And then as the load increases………….so if this were E g let us say it is constant by some means and as the load increases E 0 starts dipping and that dip is I into R a drop. So it is not constant with different loads, what comes at the terminals of the generator is not constant with respect to the load because of the non-ideality R a; there is a I R a drop.

So now that we have is an understanding of the equivalence circuit non-ideal equivalent circuit. We will now revisit the excitation, the excitation issue.

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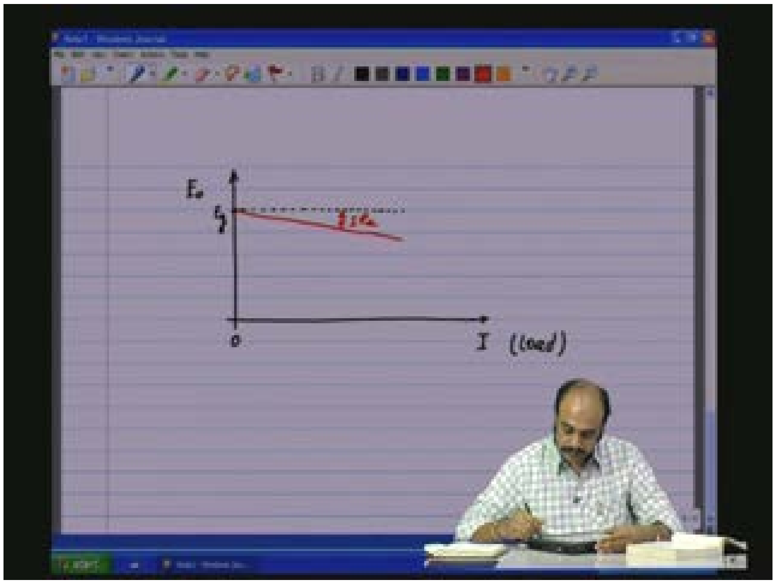

We have now here a motor the shaft. Now let us have let us have a small shaft and we have the brush and with the brush is connected to the external circuit, this is the terminals of the generator. now in between we need to add this non-ideality and that is R a the steady state non-ideality R a. So what you get here is E 0 and what you have here is E g and there is one more thing there is a field coil. Now this field coil is the coil that is wound on the field poles to generate the flux phi.

Now this field coil has to have a current to provide the excitation and it is has to have a field current I f. Now this field If can be obtained by a separate let us say source; it can be obtained by a separate source as shown here (Refer Slide Time: 22:51) so this is going to provide you I f. So at different I fs one obtains different possible voltage E g.

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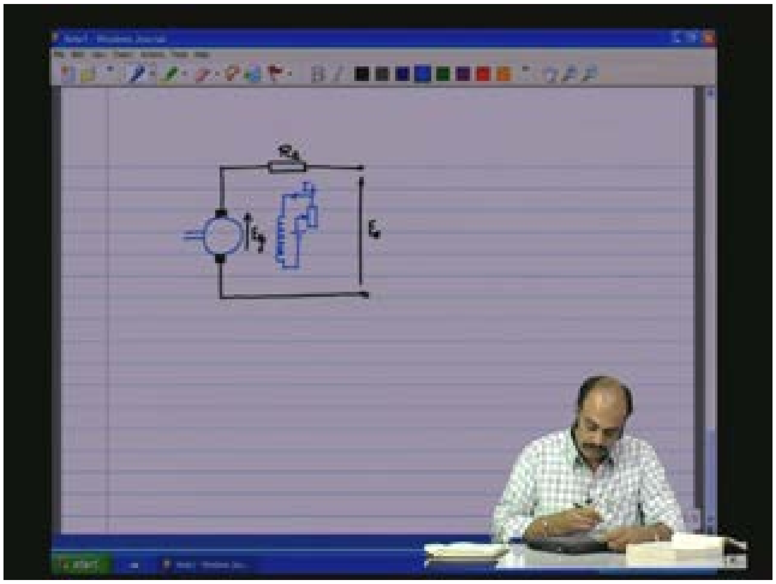

Now there is a rheostat here which can be used for adjusting the I f and based on that particular value of I f the amount of E g that is produced will be determined by this characteristic. Depending upon the If the amount of E g that is going to be obtainable will be determined. So, if we provide an I f which is let us say within the knee so let us say this is the I f that one provides I f the E g that one can get is this and for a given load the E 0 that one can get is this (Refer Slide Time: 24:05), remaining goes into the I a R a drop.

Now this is separately excited DC generator; the separately excited DC generator that we discussed in the previous class. The other generator that we were saying is the shunt generator.

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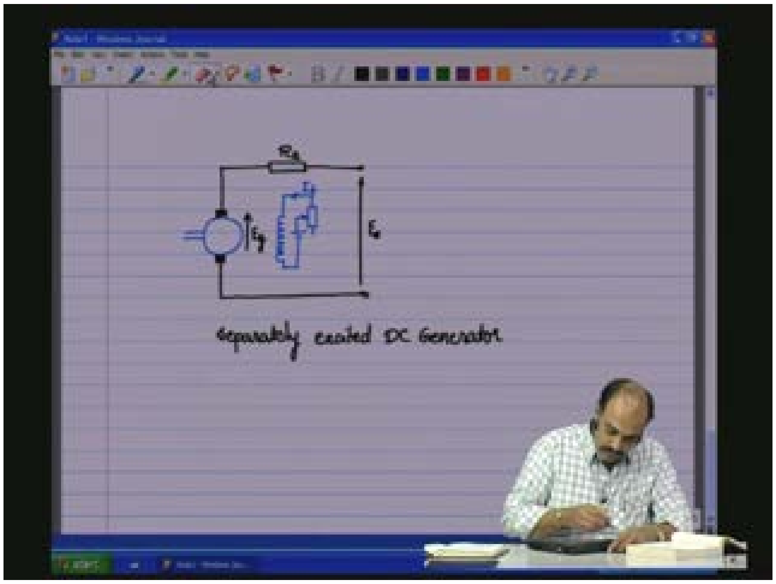

Now the shunt generator is obtained by connecting the field terminals to the terminals of the generator itself which means we select this, we copy that, go to the next page and paste it here (Refer Slide Time: 25:19). So what we do here is this we break, the source is no longer a separate excitation, we give it from the terminals of the generator like that which is from E 0. so E 0 by E 0 by whatever this R let us say this is R f will be I f. So, I f is equal to E 0 by R f which determines which determines the field current and therefore the flux. Now this is a shunt excited DC generator shunt excited DC generator.

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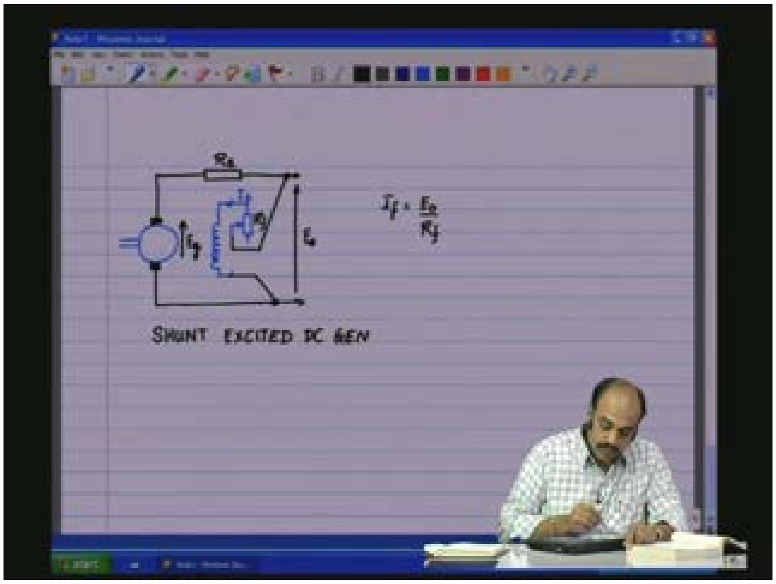

So under load what happens? So under load E 0 is equal to E g minus I R a. So then the I f the field current will be E g minus I R a by R f which is equal to E g by R f minus I into R a by R f. So the field current has two portions: one is a portion which is actually dependent on the generated emf emf and another is a portion which is basically the non-ideality. So in practice as R a is finite the field current is going to vary with the load. So the variation in the load is going to cause a variation in I f which means the flux here.

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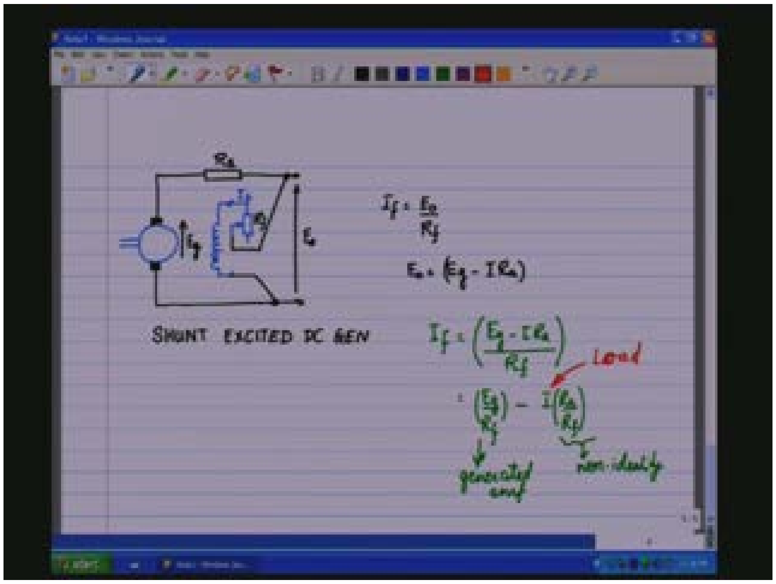

Now the flux is directly also going to affect E g which is going affect your regulation. Therefore the regulation in the shunt machine is going to be much poorer. So with load let us say you have 15 percent variation 15 to 20 percent variation in E 0 from no load to full load; from no load to full load in the case of a shunt excited DC generator and in the case of separately excited it will be less than 10 percent for the case of separately excited excited machine. This is because………. because in the separately excited machine the excitation voltage is constant and therefore I f is constant independent of the load and therefore that is not going to cause further fluctuation in E g whereas here there is a (( )) (29:30) effect change in change in the load I is going to affect I f which is going to affect E g which is going to affect E 0 and therefore I f. This will cause a much poorer regulation.

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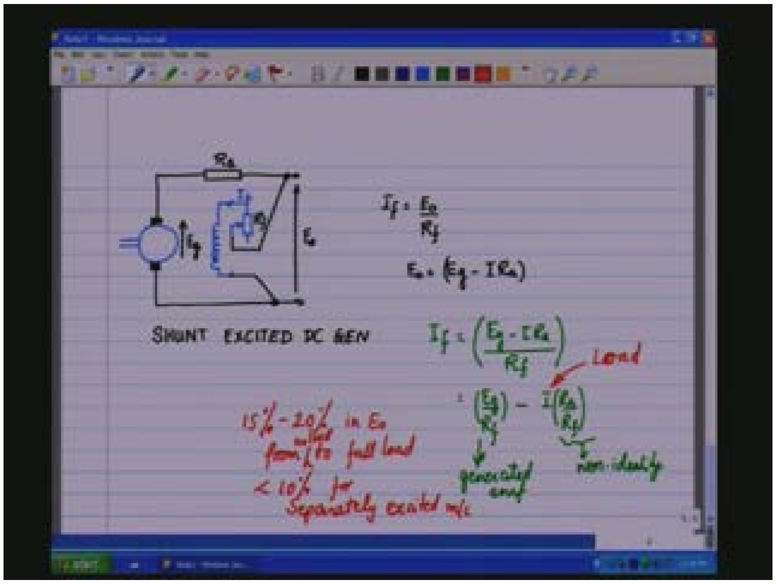

Now to take care of this to take care of this we use the compound excitation. So now let us paste this (Refer Slide Time: 30:03). So we use compound excitation to take care of the load fluctuation due to the shunt the self-excited. Now the shunt excitation is also called self-excited because the excitation is taken from the same mission rather than from a different source. So what do we do for a compound what do we do for a compound excitation ex ci ta tion?

So in this compound excitation we have the shunt field shunt field winding, we also have a series field winding a series field winding. The idea is very simple. That is we have this which is connected across the generated emf and there is also a series winding; let us introduce a series winding as shown.

Now this will have less number of turns because the current here is pretty high. This is the load current that is flowing through the series field winding. So this will be the series field winding and this will be the shunt field winding.

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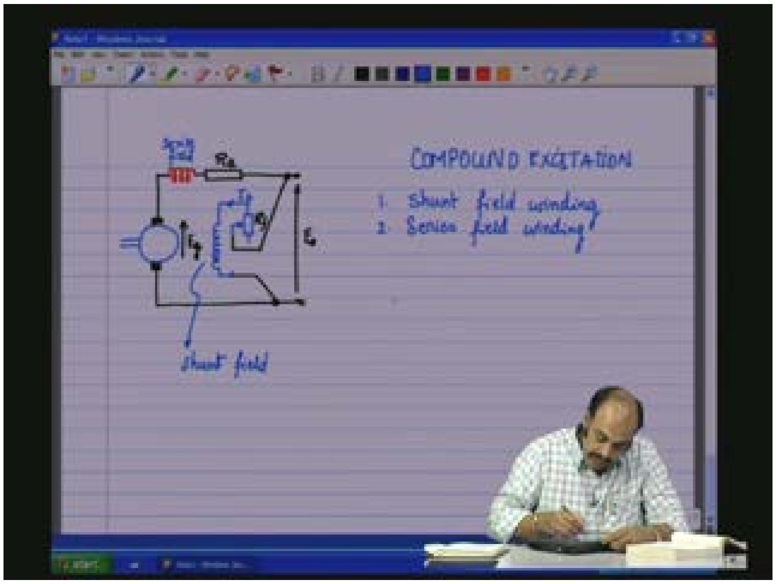

Now in the case of the shunt field winding the flux is proportional to I f which is given by E g by R f minus I R a by R f so this flux is going to vary with the load. Now there is going to be also another flux provided within the machine due to the series field and that is proportional to the armature current I itself. So the series field this is the shunt field and let us say the series field will be proportional to the load current itself.

Thus, if we make the effective flux will be phi shunt plus phi series vectorially which would be E g by R f minus I R a by R f plus phi series which is a function of the load current. So, if the number of windings on the series field is so designed such that the series field cancels out the load component of the shunt field then this will become zero then your actual field will be just equal to E g by R f like in the case of a separately excited DC machine. So that is the function of the series field. So because we are having the series in the shunt field together it is called the compound it is called the compound excitation or the compound generator compound generator.

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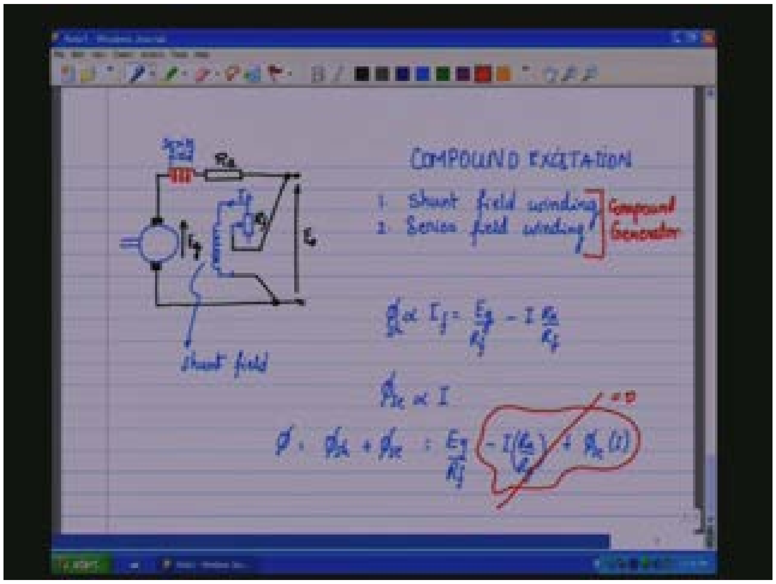

Therefore, internally the connection will look something like this so let us say we have we have the two poles let us have the armature, commutator all represented within in that circle and let us have this we have the brush as shown here, we have actually E g generated between the brushes. Now now from this brush, we are taking because there is internally R a from this brush let us have first the shunt field winding so the shunt field winding goes like (Refer Slide Time: 35:48) that, like that so on, then it goes to the other poll and let us wind it, we take it and connect it to the other brush so we have this connection here.

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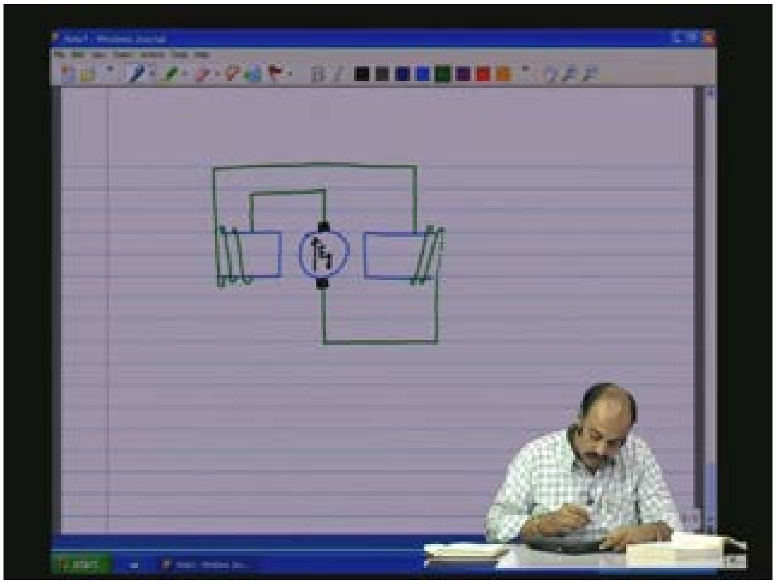

So through this is flowing I f. of course we need to provide a rheostat here, so let me provide a rheostat there. So we have R f which can set the value of the field current to the required amount. So through these you have the I f which is flowing I f flows through this direction, flows like that, flows in these directions and then flows here, (Refer Slide Time: 37:17) flows in this direction note the direction of I f so they all are yielding field. Now we connect……… so this is the this is the shunt field.

We also need to connect the series field which means through the load. So let us have the load component taken from again from the brush. So before the before it is given to the load actual load terminal let us make some windings on that let us make some windings on that, let it go to the load and then from here it will go here and goes to the negative portion of the brush.

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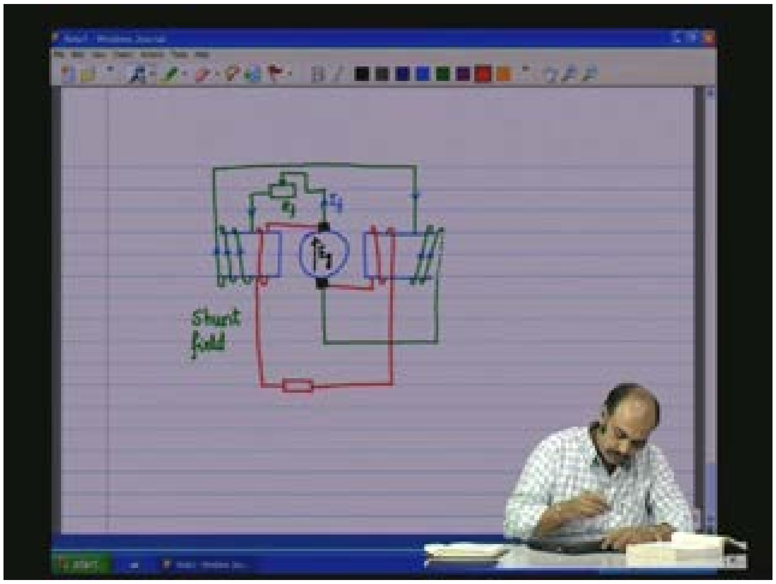

So again here the direction we see the current direction flowing in here it comes in like that, goes like that here, goes into in this fashion so these are aiding fluxes which will try to cancel out the load component of the shunt shunt this one due to the armature winding resistance. So this is how the series field is put into the picture, this is R load and this is current I whereas that was I f.

So, if the number of turns here is so designed such that it cancels out the load component of the shunt field winding flux then the flux in the flux in the machine will be dependent only on E g like in the case of the separately excited machine. So this is a compound machine.

now we saw earlier that if we have a plot of E 0 versus I the load at zero load this is E g, as the load increases there is a droop there is a droop in E 0 and that is equivalent to I into R a that is equivalent to I into R a. Now if we if we give a field that is that much in excess; let us say for example; we take E g versus I f or we take E g versus flux E g versus flux in the machine so this has a curve which goes like that and then droops because there is no change in the flux, further it saturates. This is a function of I f. So E 0 is equal to E g minus I R a. Now if the flux let us say at this flux phi 1 we get some value of E g let us say E g 1 at a slightly higher flux we will get E g 2 and of this E g 2 compensates for I R a drop then the output voltage E 0 will be the value E g itself because the flux has not increased with the increased load which means E 0 equals p N phi Z by 60 minus I into R a.

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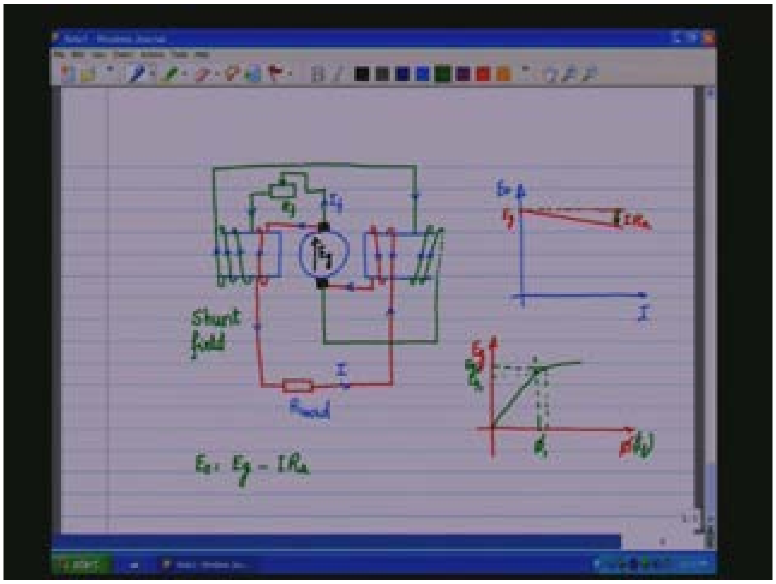

Now this will be equal to p N Z by 60 this is a constant, phi is proportional to I f so we can put it as a constant into I f minus I into R a. Or we can say p N Z by 60; phi in the case of a compound in the case of a compound winding or compound excitation is E g by R f minus I R a by R f plus series winding (Refer Slide Time: 43:27) the series flux which would be E g by R f minus I R a by R f plus flux series winding which is the function of the load current minus I R a which means now all these let me call this one as K.

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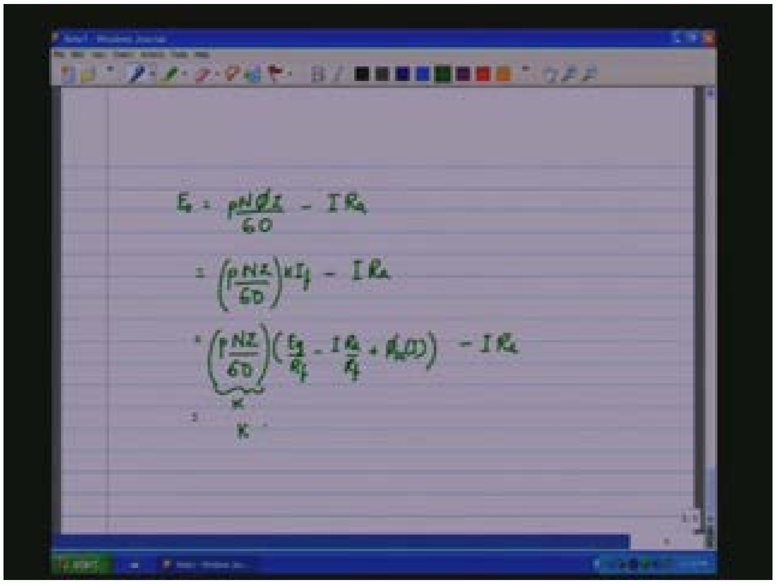

So we have K E g by R f or we will we will call we will call it as K 1 E g R f is also taken into the constant minus K 2 I plus phi se which is the function of load current with K 3 K 3 series field which is a function of load current minus I R e, this is going to be your E 0.

Now if we choose this if we choose this such that it can take care of both the load component of the flux shunt field flux and the load component of the drop then we have K 1 E g minus I K 2 plus R a plus K 3 series field which is the function of load. So, if K 3 and the number of terms is so designed such that it will cancel out this portion makes it equal to zero. So if the shunt field winding number of turns in K 3 is so designed such that the load component of the flux and the load component of the drop R a is equal to 0 then E 0 will be directly proportional to or equal to the E g Eg portions.

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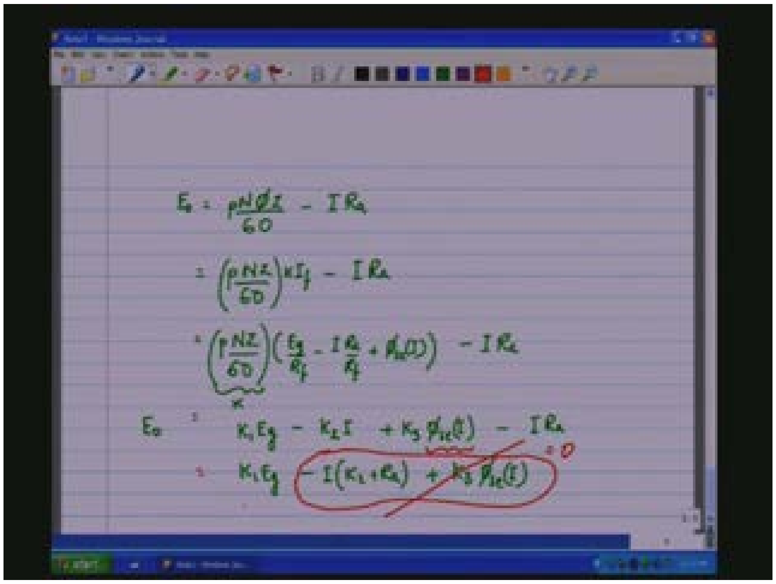

Hence, for such conditions we will have E 0 E 0 which is constant at E g whatever may be the load I. Now such compound generator is called a over compound that is a few more turns are added extra to compensate for the voltage drop of the armature winding resistance then it is called a over compound generator.

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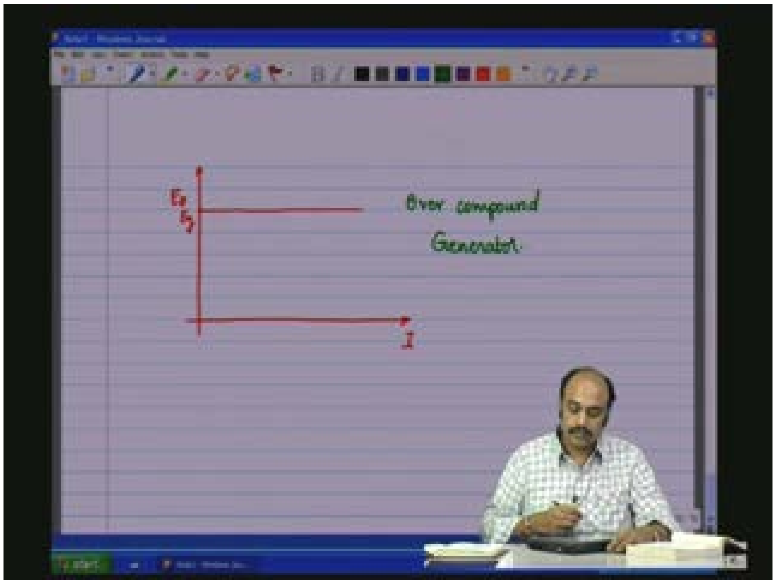

There is one more compounding effect which is the differential compound generator. In the case of the differential compound generator the series field winding is reversed so it has a sense which is reversed (Refer Slide Time: 47:50) so let me take this portion for explaining, copy, paste.

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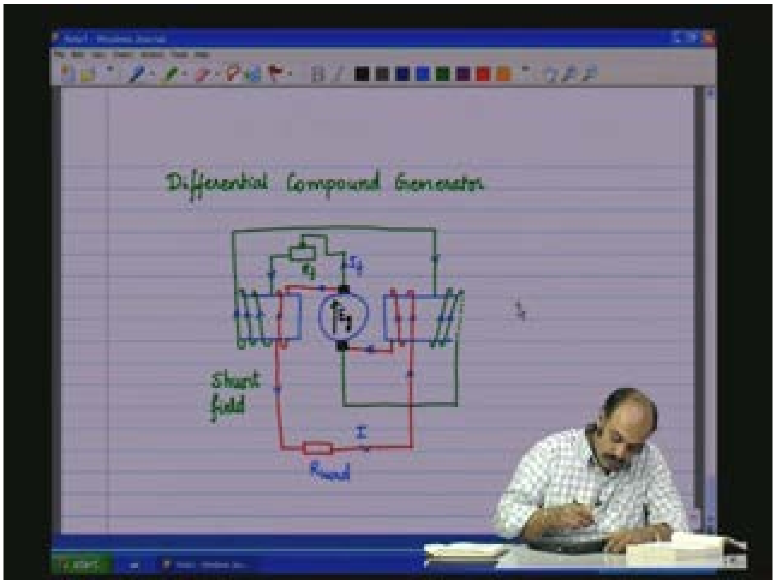

In the differential compound this winding of the series field is reversed in sense so what it means is that we try to we try to make the current flow in the reverse direction of the field so that it has a cancelling effect like that and so also here (Refer Slide Time: 48:43) it has a cancelling effect so that the current in the series field for the field is you see reversed with respect to the shunt field so therefore this is going to provide a cancelling mmf.

So what happens is that when we have with load E 0 as the load increases this equation that we wrote here as the load increases (Refer Slide Time: 49:37) the flux increases much faster with load. So this portion is not plus this portion here is minus so which means what you actually get in the compound differential compound is at the effective flux is equal to phi shunt minus phi series which is a function of load so which is E g which is proportional to E g which is proportional to E g by R f minus K I into R a by R f minus phi series which is a function of load.

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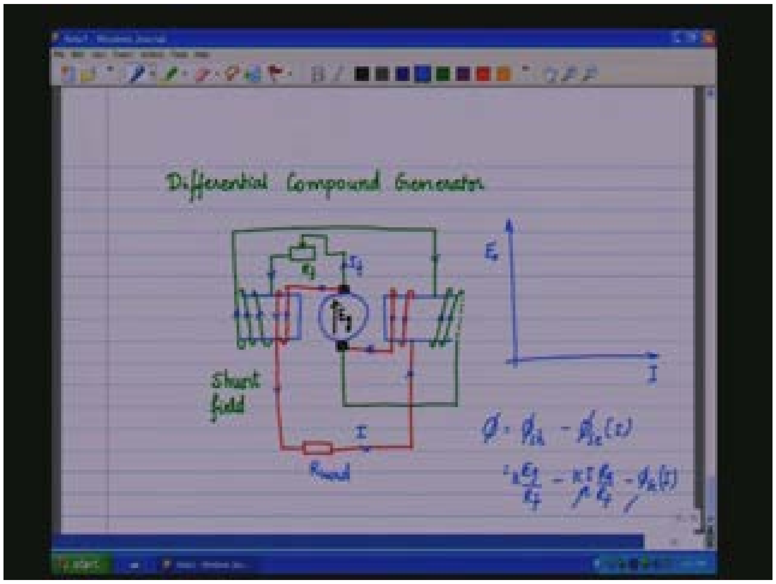

So, as a load increases this also reduces the flux the series also reduces the flux and it drops pretty drastically. So as the load drops the induced emf is as the flux drops the induced emf also drops drastically so the voltage with load drops quite drastically here. This is generally used in the applications where with load you want to limit the current such that the short circuit limit the short circuiting current if the load is very high like in the case of DC arc welding applications; there you use a generator which is differential compound so that as the load increases there is a short drop in the voltage to limit the short circuiting current. So this gives an idea of the different excitations that we have that we can use for a DC machine: the permanent magnet excitation, the separately excited excitation, the shunt excitation, then the compound excitation where you have the normal compound to take care of the loading effect, the shunt excitation, then you have the over compound to take care of the loading effect on the field plus also the loading effect of the armature winding resistance on the output terminal voltage and of course the differential compound so that you want bring down the output voltage drastically to limit the short circuit current in some of the applications like the DC arc welding.

So, if we look at a comparative graph of ……….versus the E 0 for different types of the excitations, at zero load we have let us say E g so in the case of a compound you see more or less constant voltage for as the load varies in the case of the compound that is one of the best in case of regulation and in the case of an over compound there will be a generation, let us plot let us plot in terms of E g so that which generates slightly higher with increase, that is with increasing load so that it compensates for the I R a drop and this is the over compound and then in the case of the separately excited machine E 0 with the load the E 0 value will dip let us say this is the separately excited excitation and if you have a shunt excitation it is slightly poorer than separate excitation this is the shunt excitation excitation and then the regulation is very bad in the case of differential excitation but we want to have a bad regulation in this case differential excitation.

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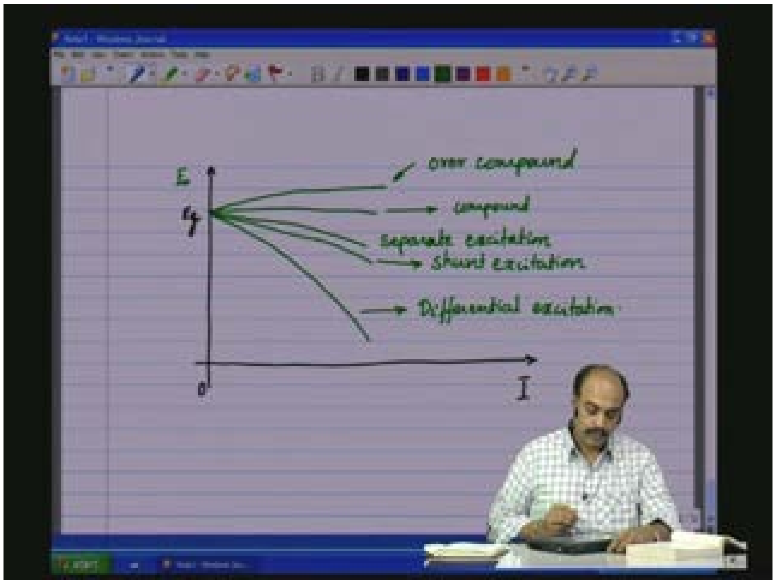

So these would give you a relative figure of comparison, relative picture of the comparison between the voltage regulation characteristics of the various excitation methods that has been used for the DC machine or the DC generator.

Now there is one final topic that we need to cover and that is the dynamic model of the DC generator. We saw that in the case of the DC machine we have the shaft which is of course linked to some prime mover, there is the brushes and these brushes are connected to the external circuit. But in the meantime there is two non-idealities that we need to improve: one is the armature winding resistance and the other is the armature winding reactance and then of course the final load.

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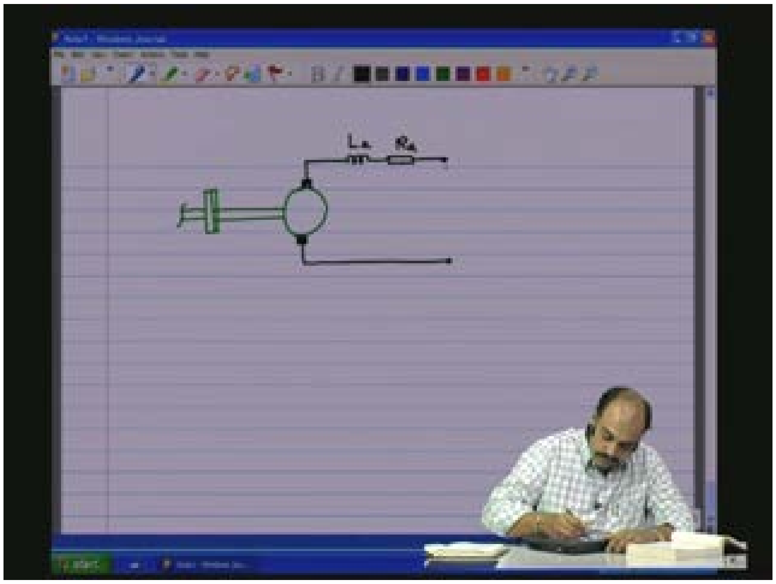

This would be your E g of course you have the load R L which is connected here R L and due to the R L there is a current I which is flowing in. So this is the DC generator. Now here on this side on the mechanical domain side on the mechanical domain side there is a prime mover which is providing the torque to rotate the shaft to produce the voltage generated emf which is being generated sorry we need to correct this this is not the generator this is the output E 0 this is the output E 0; E g is generated at this point, this is the terminal voltage and this is rotating at a speed omega and that is being passed into the DC gen and comes out as E 0 into I as the………….. so if there is absolutely no loss T into omega watts goes through the generator comes out here as E 0 into I.

Now E g is p N phi Z by 60. So, for a given machine this is fixed, this is let us say fixed for a given excitation, total number of currents conductors in the armature is fixed and of course this is a constant. So therefore E g is proportional to the speed of rotation N or E g is proportional to the omega in radians per second or E g is equal to some K into omega. So the generated emf is dependent on omega a proportional to omega here and the constant of proportionality K is dependent on the machine this is probably sometimes provided as a name plate value.

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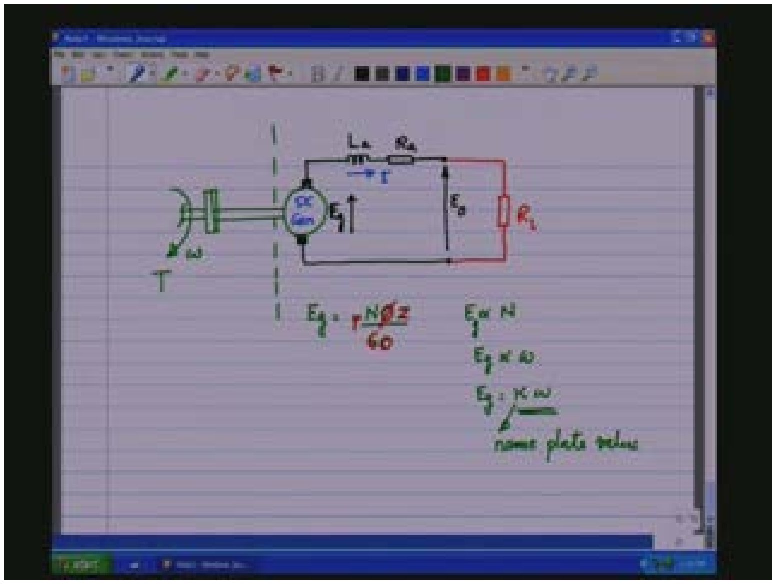

Now you see that the potential variable E g is now dependent on the flow variable or the kinetic variable of the mechanical side. So this is a gyrator so which means that T is proportional to the load I because we saw that the load I is going to give an opposing torque on the mechanical side by the Lorentz force because of the Lorentz force and the torque has to overcome that opposing torque which has to be proportional to I and T will be equal to the same K into I which is provided in the name plate. So these two are the connecting links between the mechanical and the electrical side.

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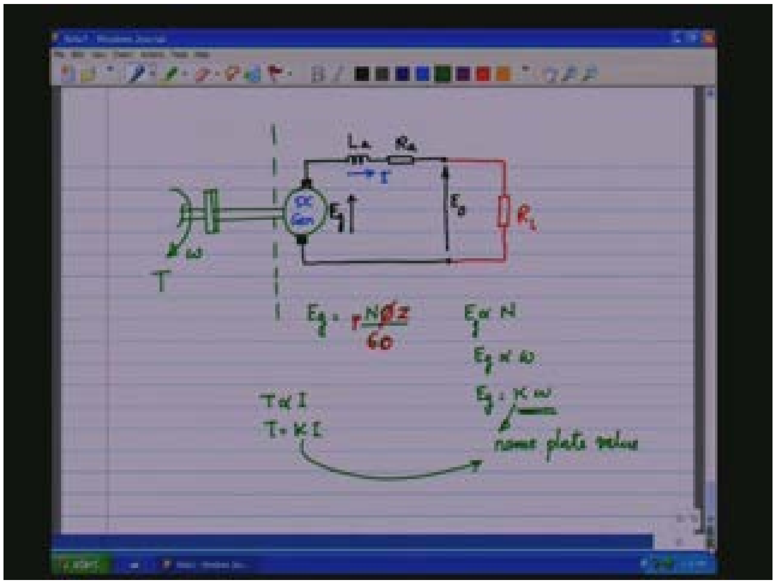

So based on this we have two dynamic elements: one is L a and the other is shaft whatever the reflected inertia j. There is an R a and there could also be the friction B the inertia. With these we can find the state equations for the DC machine.

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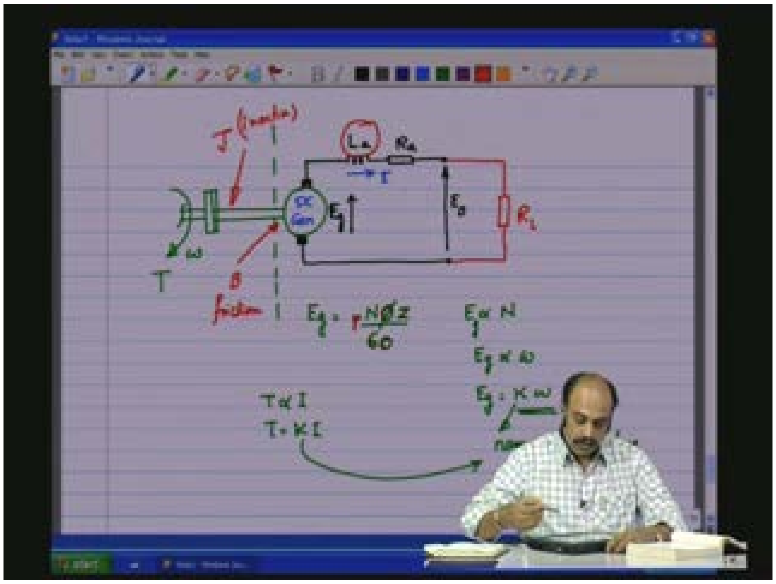

We will evolve the state equation for the DC machine DC generator in the next class and then continue with the DC motor.

Thank you for now.