Basic Electrical Technology
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Lecture - 24
DC Machine Part – 2

In the last class we were discussing about the DC machines and in particular the DC generator. We discussed about the structure of the DC generator how a DC voltage the unidirectional voltage is obtained. We saw that the DC machine is internally an AC machine with the currents in the voltages being an AC signal and as it comes out of the brushes through a commutator it becomes unidirectional and gets rectified this we saw in the last class. We will of course consolidate our understanding of the DC motor further in this class and just have a quick review.

We saw that last class if we have a north pole and a south pole and a coil has shown here in red (Refer Slide Time: 02:09) the conductors near the north and the south pole will have the current directions out of phase and these currents are going to be flowing through the external circuit through these brushes in black through these brushes in black. Now these brushes are in spring contact with the ring to which the coil the coil is soldered one end of the coil is soldered; the other end of the coil is soldered to another ring and that is in contact with this brush.

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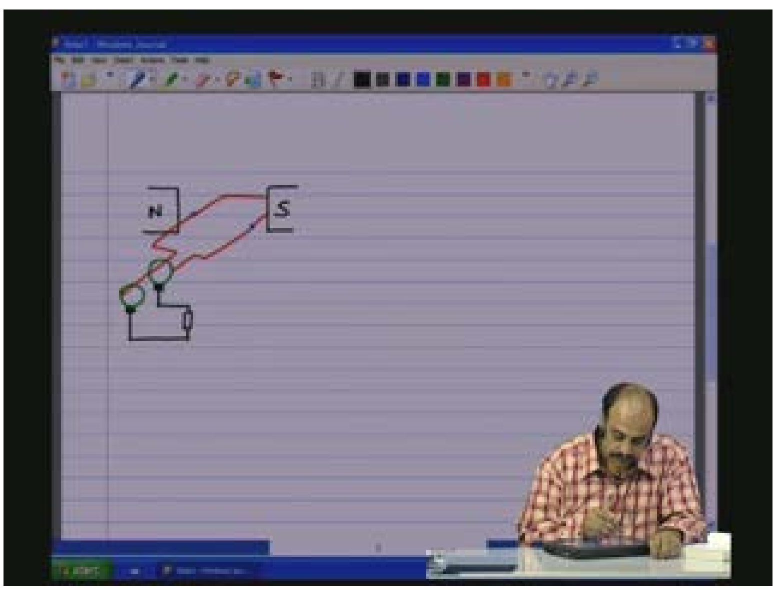

Now here as the coil rotates let us say this is the coil conductor a and this is coil conductor a dash the current through a is positive, let us say this direction is positive and as this comes into an orthogonal plane that is perpendicular to the north south axis then the current through a and a bar will become zero and then on further rotation the current through a starts going negative and the current flows in the opposite direction in the external load and as it keeps going in this manner it takes a sinusoidal wave shape pattern in the external circuit and the induced emf is given by the flux density B, the length of the conductor L and the velocity with which the conductor is rotating and is cutting across the fields. So that would be the induced emf that one would be obtaining for each every conductor and there are two conductors and therefore there will be wise as much.

And then we also saw that to rectify the waveform here one could use split rings, rings that are split as shown here. You see these rings are combined one single ring (Refer Slide Time: 4:23) but it is split in-between, there is no electrical contact between the a side and the a dash side of the ring. Of course the brushes are making contact, they are fixed and through spring contact they are going to take the current into the external circuit. So, as the as the coil rotates when it is at position north as shown here the current is flowing through the brushes in this direction and this is a and a dash and here in this the current is flowing in this direction also and as this rotates the ring is also rotating along with the coil and when this a portion of the conductor has come to the south pole side which means which means we have a on this side a dash a dash on this side likewise here also we have a dash on this side and a on this side which means it has rotated.

Therefore, in a dash the current direction is as shown and in the external circuit also the current direction is as shown through the brushes. Whereas here the current sorry here the once this has made a rotation this would have gone to this point that is the connection here (Refer Slide Time: 6:26) because a is connected to that slip ring and a is connected to this slip ring.

Now, on on on the position getting interchange now a is at the south pole like here the direction of current in the brushes has reversed. So here it is AC whereas here it is unidirectional always so here you get a waveform pattern which is like that and here you will get a waveform pattern which is about the zero line and this is about a zero line. Thus you get a unidirectional current as shown here. And this has been achieved due to this particular ring which we have put there and that is called the commutator. Even here this unidirectional waveform pattern can be achieved by using electronically a circuit called the full wave rectifier.

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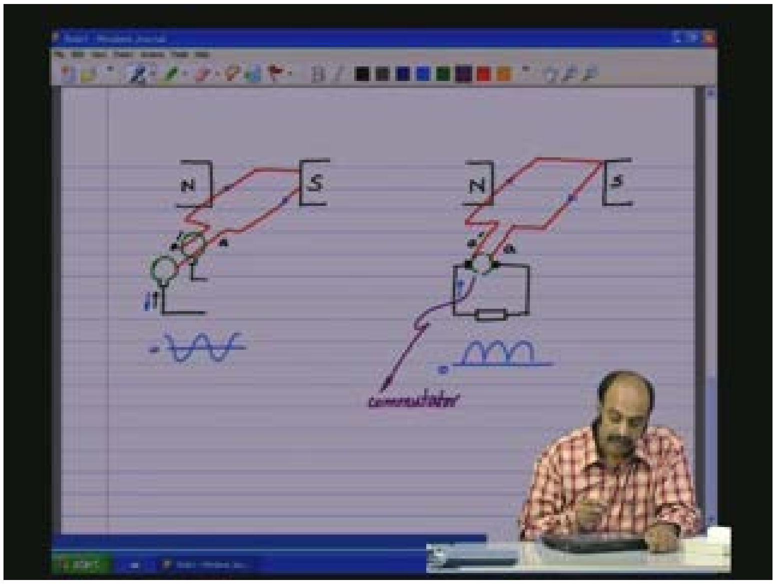

So let us say we have a full wave rectifier diodes like this, we connect the diodes in this fashion and connect the load here and this point is connected here and this point is connected here. So, when the current is flowing in this direction it will take this path, go through this load in this direction and continue continue to take this path out into the a dash. When the current is positive way that is when it has reversed the polarity whereby the a is towards the north side and a dash is on the south side we have a current which is flowing in this direction which means we have a direction of current which comes opposite, goes in this direction and comes like that which means through the load it is always the same polarity so you will have a waveform like this, unidirectional.

Therefore, a full wave rectifier diode bridge does the same job that the commutator was doing in the case of this machine. So in this machine we do not need an external diode bridge whereas in this machine to get a DC output you need a diode bridge. So this machine along with the commutator is called the DC generator is called the DC generator.

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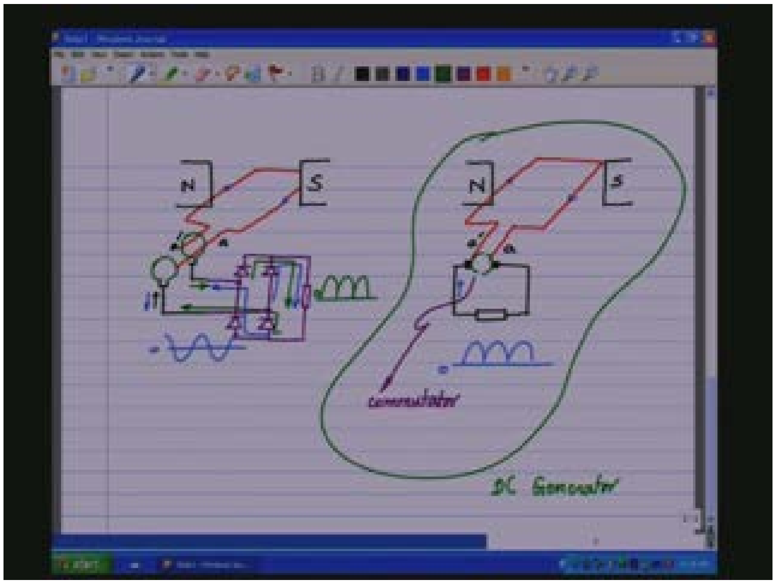

So now let us consider the machine at the commutator as shown here.

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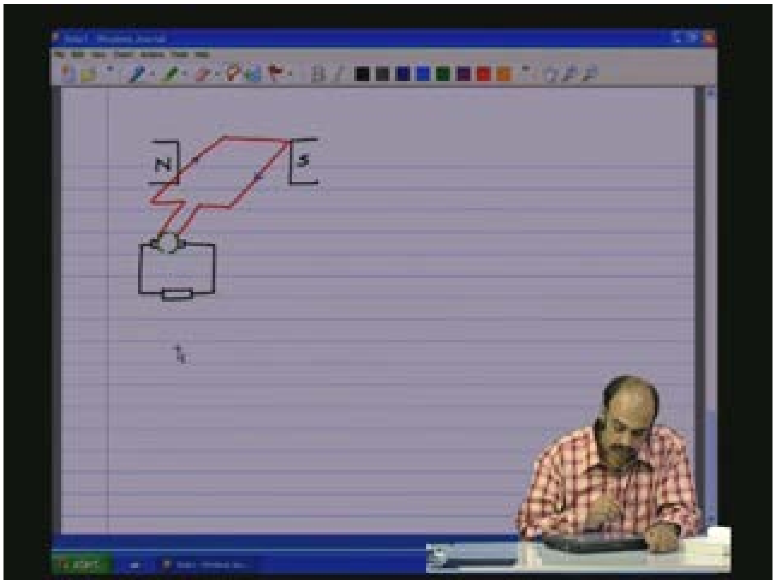

We would like to know represent it because this becomes very cumbersome to write or draw in 3D and trying to put it into a……………….. Let us now write a 2D a 2D picture of this DC machine so we have the north pole and the south pole. Now the conductor near the north pole there is one conductor in the north pole we show it in this fashion, there is another conductor in the south pole we take the cross section and show it in this fashion, the current flowing into the paper or into the board current coming out of the board is shown, this is shown in this fashion.

Now the conductor can't be just floating in free air it needs to be wound over the coil wound over a core and we represent the core, there is a slot in the core through which the conductor passes through and core is having a circular feature like this.

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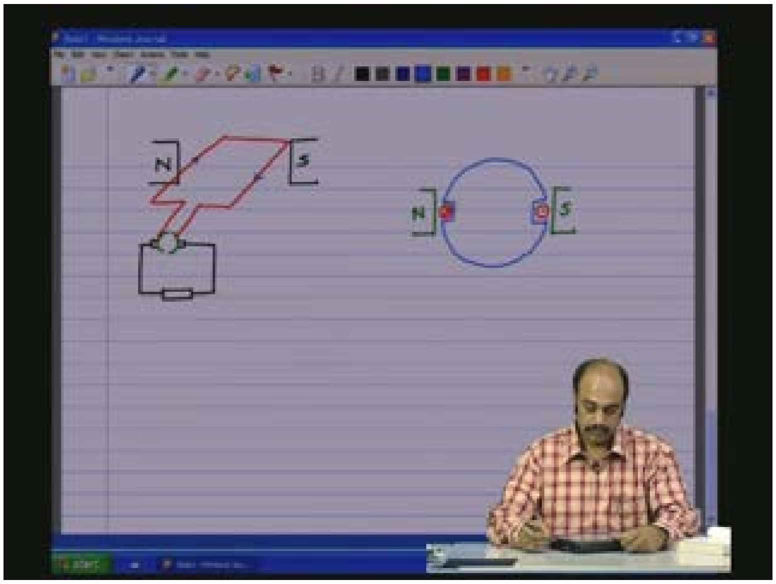

So this inner core is what is rotating. And along the shaft of the core will be this slip rings sorry will be these commutators so we shall put the commutator along the shaft of the core so this is the commutator. And then we have the brushes, so let us say the brushes are positioned like that and then out of brushes we take two leads which go to the external load. So there are two brushes: one for the positive and one for the negative; this is brushes and this is the commutator. Now we a draw line vertical line here indicating that this half of the commutator is not connected with the other portion of the commutator, it is insulated.

Now this winding this winding end let us say is a and this winding end or coil end which is a dash this will be connected here and this will be connected here (Refer Slide Time: 14:00). So this would be how a 2D picture of a DC machine will look like.

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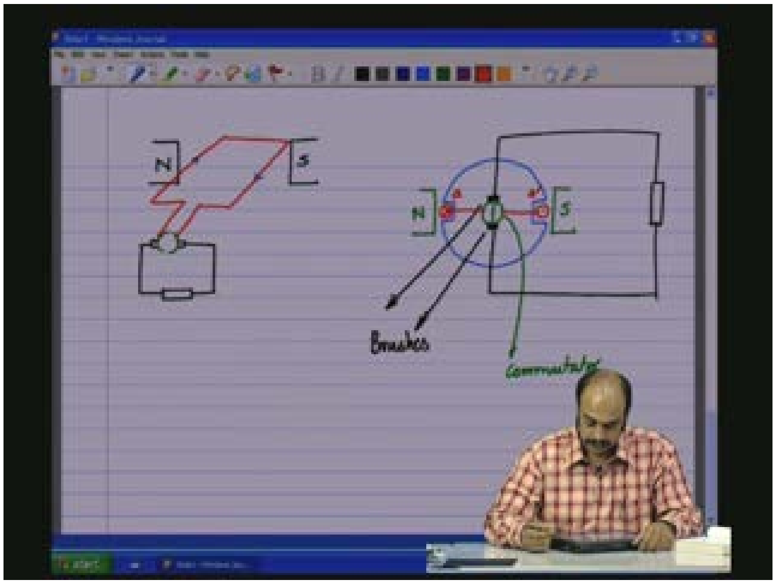

Let us consolidate this concept or this idea of this DC machine with more coils; also understand that a coil here meaning that there is one conductor, one wire which is being rooted through like this but it could have many wires, it could have like in a transformer many windings like this and the ends are brought out, so keep that in mind. So this is one coil with one set of conductors perfect ends of the diameter of the core diametrically opposite end of the core.

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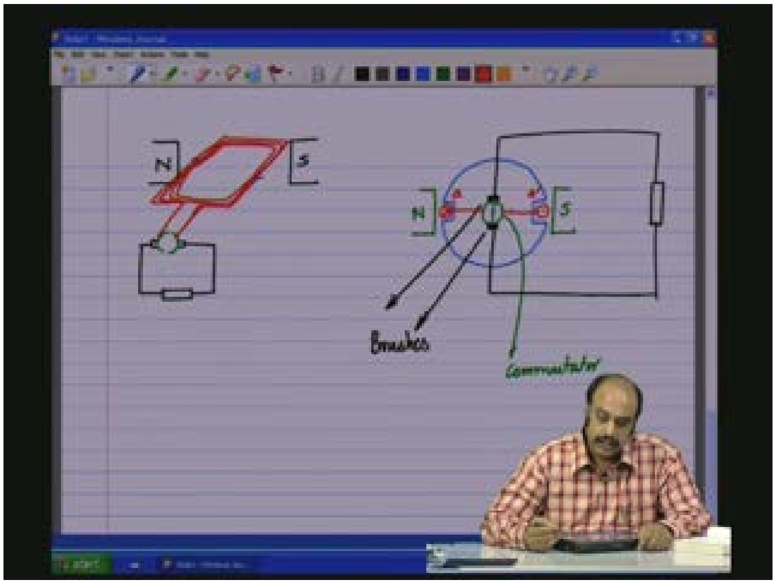

Now let us have a look at the machine which is having four coils. So let us have as usual the north pole and the south pole. Let us have a core with core slots. Let us first have a circular………. and to the circular core we shall have four slots as shown here like this. Now let us put in the coils.

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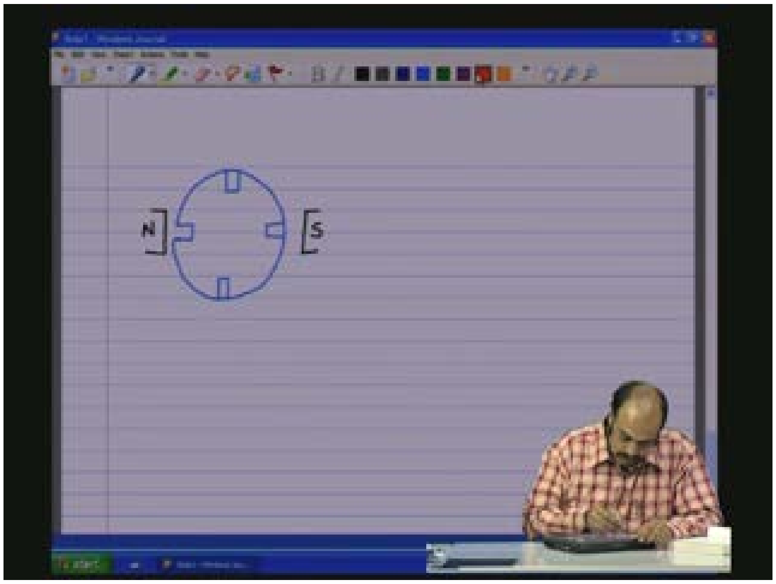

Let us have one coil here a a dash b b dash, let us have one more coil with opposite phase. Likewise, we have one coil here and one more coil with opposite phase. This means that if there is a coil let us say a a dash and then another coil here b b dash then i n one more set of coil let us say c c dash, d d dash which means a and c are wound on the same slot but having opposite direction of the coil winding, they are 180 degree out of phase which means that at this point both these coils are near the north coil conductors are at the north pole and the other part of the coil conductors are at the south pole which means that the a is having a direction of the current or an induced voltage in one direction the induced voltage would be in the other direction because of 180 degrees out of phase so the voltage between these two coils is going to be double and that is what is going to come across the brushes. And then in between in this fashion we have four segments so the commutator is having four segments as shown here. So now if the brushes are positioned in a manner like this and we make the connection a here a bar here (Refer Slide Time: 19:27) and make the connection b b bar and then you have c c bar then you have d d bar cyclically.

Now this is still difficult to understand this particular way of doing it but this is how it would like when you cut open the motor. But you redraw this slightly so that it becomes more understandable for us from the circuit point of view N S. Now let us have the commutator the commutator being split into four…………………..

Now let us start by placing the commutator always along the brushes always along the axis which is perpendicular to the north south axis because on this axis there is no voltage induced, the voltage induced on this would be zero so let us place the brush on this axis so between this and this would be the a coil let us say which means this is a and this is a dash coil and switch are connected, they are actually in………………..diametrically opposite but we are going to show this one as one single connection as such and then between this and this we connect the coil b let us say this is coil b with b b dash.

You see……………………………. coil share the same commutator segment then b dash then you have c c dash, b dash and c share the same commutator segment and then you have d d dash. But notice that but just be aware that d and d dash are two coil ends which are diametrically opposite on the core but you are bringing it and then interconnecting it in this fashion. This is much more easier to understand on that circuit point of view. so the starting of the coil you are starting at one commutator segment, the other it is connected to the immediate next commutator segment the other end of the coil, the starting of the other coil is starting from that commutator segment ends on the next commutator segment, the next one starts at that same commutator segment, goes to the next and so on and so forth. So this way the winding pattern for the four coils is shown. See that a and c coil will 180 degrees out of phase.

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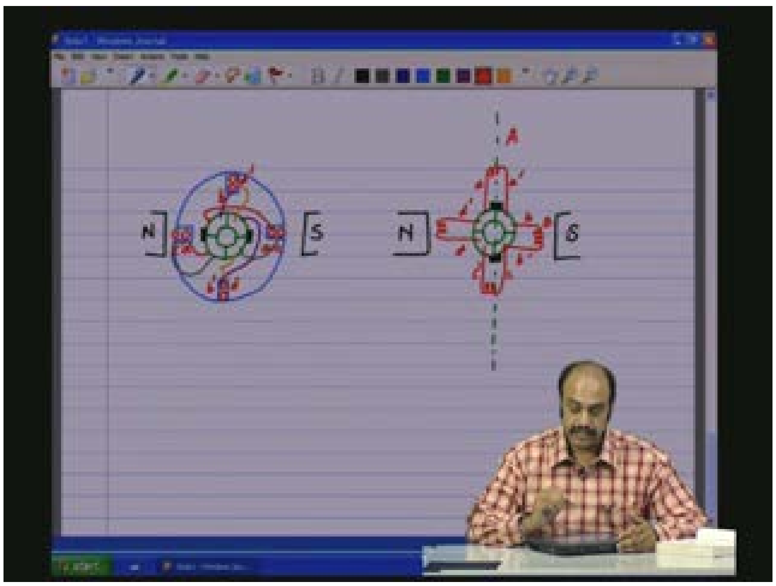

The reason we want to connect the brush here where there is no induced voltage in this line. at an instant when the position of the coils are like this where a is in the orthogonal plane to the north south plane there is no induced voltage here nor here, there will be maximum induced voltage on the b and the d that is let us say on b you have 10 volts and d also you have 10 volts so the voltage across the brushes would be because these two are connected so the voltage the induced voltage would be 10 volts would be 10 volts because this is connected here this brush is in contact with this commutator segment ,this brush is in contact with this commutator segment which is at b therefore it is 10 volts. The voltage across c b is 0 at this point the brush is shorting this coil c and as the voltage is zero there is no circulating current. Likewise, as this brush is shorting the coil a is on both sides of this commutator segment and as the coil voltage a is 0 there is no circulating current in the coil.

If suppose the brush were placed at any other position then there will be some finite voltage across the coil which are across the brush and that would fall that would form a circulating current and the circulating currents can be ((cooperative huge and)) (25:43) the i square loss could be very high. Therefore, it is advisable to place the brushes on the axis where the induced voltage will be zero and this is called the neutral zone; the axis where there is no voltage which is going to be induced on the coils or the conductors is called the neutral zone and they are always midpoint between the poles. So, if I am circumference between the north and south poles any two north and south poles consecutive north and south poles the midpoint is where the induced voltage will be zero and that is a neutral zone and the brushes should be positioned where the induced voltage will be zero that is the brushes should be positioned in the neutral zone.

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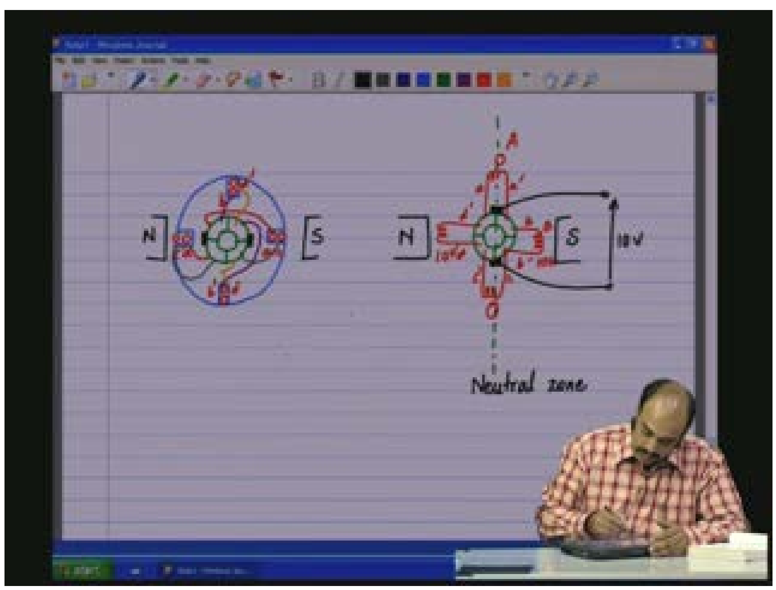

Now this here would give us that is to say this is e versus time. Now let us say that the position is as such here as shown here. So d is having maximum ten volts let us say the coil d the coil b is also having ten volts what is appearing across the brush is ten volts and let us just mark that as ten volts at this position.

Now as now let the motor rotate anti-clockwise in the positive direction; direction of rotation now as the shaft is rotated coil b comes to this position that is the top position and coil c would come to the position where the south pole is which means coil c coil coil c will now get 10 volts maximum. Now what is happening to the voltage across the brush? As it is moving as it is moving the voltage across the coil b and coil d is decreasing and voltage across coil c and coil a are increasing. So at some point in between even before it has come to zero the voltage across coil c would have increased beyond and the brush would take some of the voltages of the coils which comes between these two due to the commutator segments and it will have a wave shape like that in the case of the two segment commutator.

But in the four segment commutator where you are having four coils the coil voltages are like that and because the coil segments are rotating and the brush is coming in contact with the various coils segments it takes the maximum of the voltages which comes like this and we see a lesser ripple. More the number of coil segments lesser is going to be the ripple. If you have a twelve twelve segment commutator which means you have twelve coils then the ripple is going to be still further reduced.

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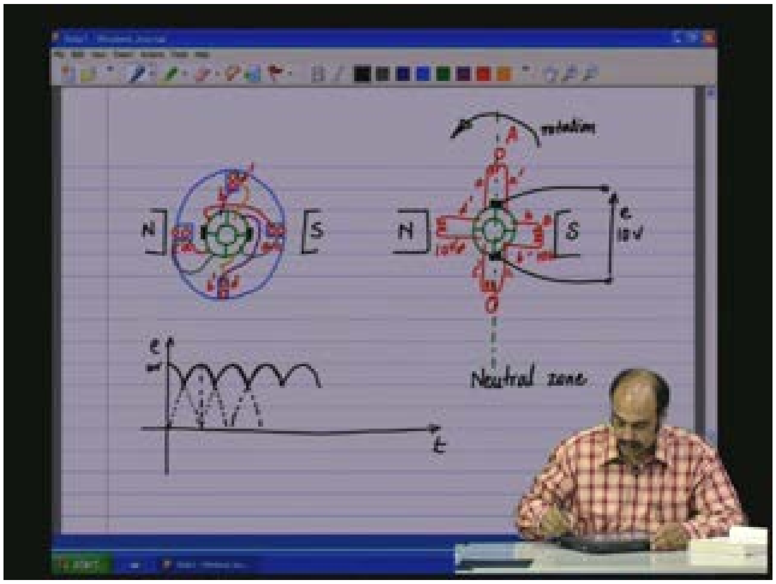

So let us have a look at how the schematic would be for twelve segment or twelve coil machine. So we continue to have the north and south pole the north and the south pole, let us have a reasonably bigger diameter circle here and we have the commutator which is now having twelve segment, the brushes mounted on the neutral zone we have 1 2 3 4 5 6 7 8 9 10 11 12 we have the commutator there should be twelve slots on the there should be twelve slots on the core the rotating shaft as shown here and these twelve slots you need to have two coils out of phase with each other. So you will have two coils out of face with each other so we will have twelve coils which are connected in the following manner.

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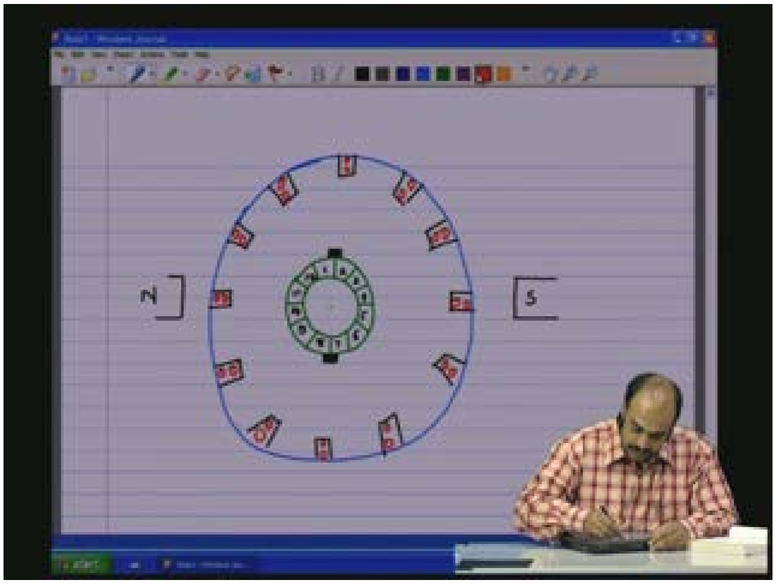

So let us put this schematic. So coil one coil side one and two. So each coil is having two sides which are there on diametrically opposite ends of the core. So let us say this is coil one coil then let us say a a dash and then another coil is connected in this fashion so like that you have twelve coils which are connected……..

Therefore, at the given at a given point of time the picture here let us see the voltage the voltage across this is going to be 0 volts because this is at an orthogonal axis with respect to the north south axis the voltage here is going to be 0 volts, the voltage here could be probably let us say 10, volts the voltage here is going to be 10 volts, let us say the voltage here is 8 volts and the voltage here is 5 volts, the voltage here is 8 volts 5 volts so you have 5 volts, 8 volts, 10 volts, 8 volts, 5 volts symmetrically. This is the voltage across the brush. The voltage across the brush let me bring out the brush leads outside here (Refer Slide Time: 35:47). The voltage across the brush let us say this is positive and the negative is you see that all these conductors all these segments are connected through the coils so between 2 and 3 you have 5 volts, 3 and 4 you have 8 volts, 4 and 5 you have 10 volts, 5 and 6 you have 8 volts, 6 and 7 you have 5 volts and then between 7 and 8 0 volts so across the brush it is summation of this 5 volt coil plus 8 volt coil 10 volt 8 volt 5 volts so that would lead to 16 plus 10 26 36 so that would be 36 volts up to this particular point. So you will see that the ripple here will be much lesser than in the case of the four coil DC machine.

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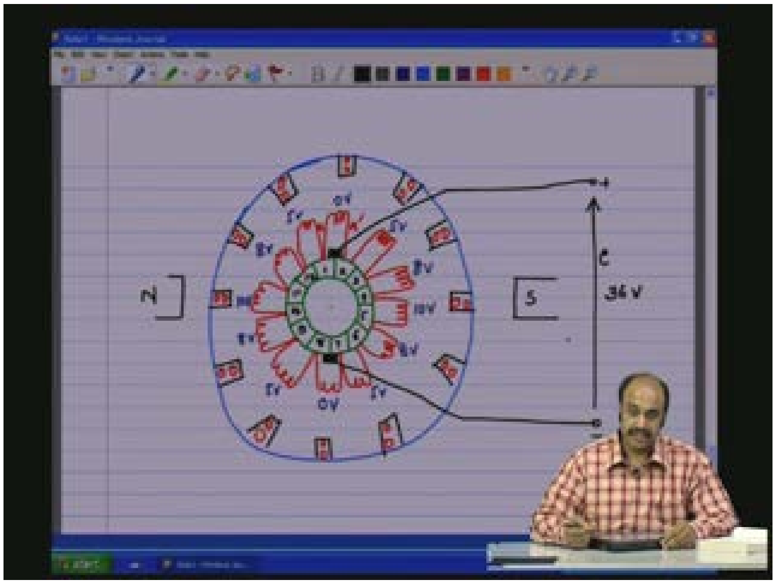

Now just imagine what would happen. The brushes are no longer here but instead the brushes are connected to these points. Now you see that the voltage across the brush now is between 3 and 4 you have 8 volts plus 10 volts plus 8 volts that is 26 volts plus another 5 volts which is now 31 volts for this brush position which means the voltage across the brushes is going to be is going to reduce and further the brushes are shorting the 5 volt 5 volts across the coil.

In the earlier position when it was 0 volts when it was kept at an orthogonal position in the neutral zone at that position any coil at that position would have 0 volts and therefore it will not brush will not short the coil and even if it is short there is no circulating current. Here because the brush is not in the neutral zone, at the point where the commutator segments change over the coils are shorted so the coil around at that point……. at that point the induced voltage across the coil is around 5 volts which means the 5 volts gets shorted through the two commutator segments because of the brush so it gets shorted through the brush here which means there can be huge circulating currents in the coil winding which could result in lot of i square r losses.

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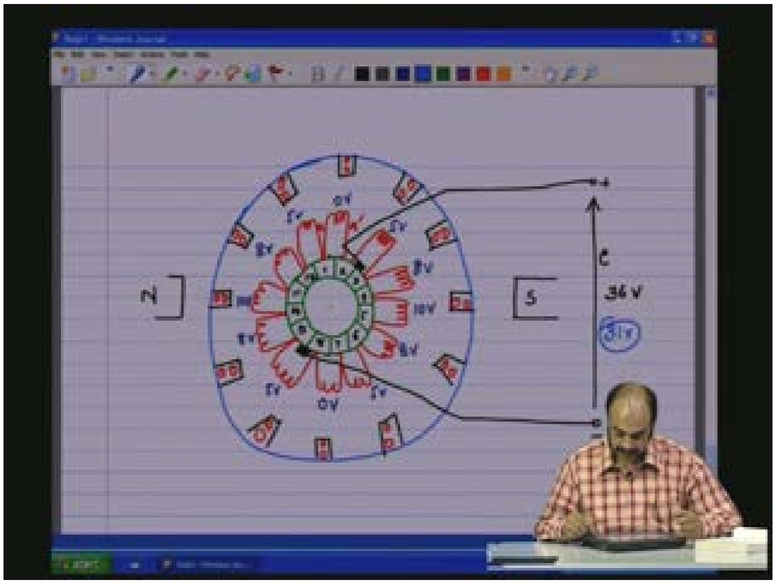

This is how the DC machine will look will look like and the structure of the DC machine is in this fashion. At this point it may be a good idea to have a look at how a real motor the core of a real motor the shaft of a real motor will be. So let us have a look at the shaft.

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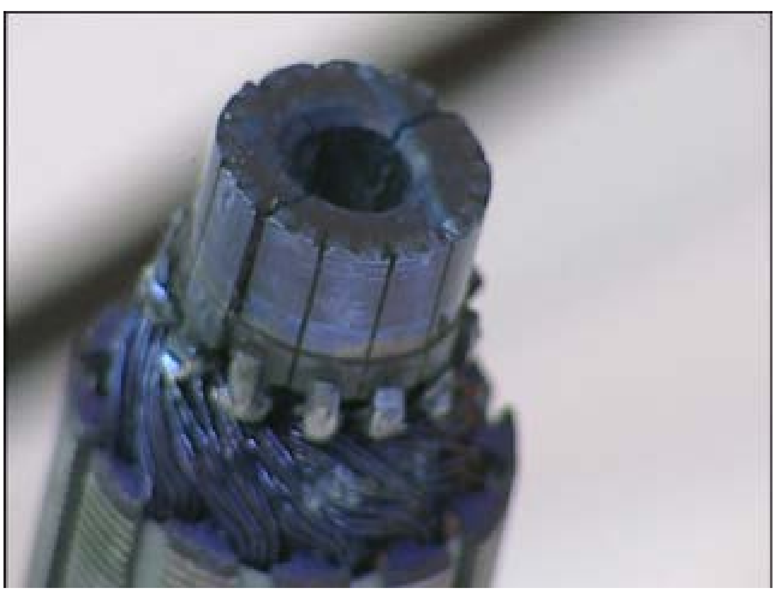

Before that I would like to ………… put inside………… these are called the poles, these as you know the commutator the commutator segment, these are brushes. Now these are the coils and it is called the armature coils armature coils this whole thing is the rotor the whole thing is the rotor which is rotating about a central axis.

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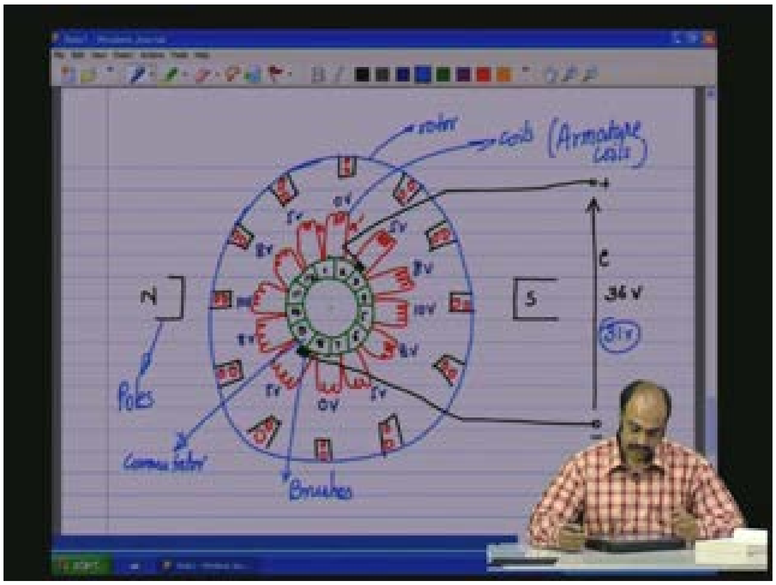

Now let us see the real motor or real rotor how it looks like.

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Let us have a look at this rotor. This is the rotor of a DC machine. This portion what you are seeing is the commutator segment. This is again a twelve segment commutator you have twelve slots and the rotor these are the rotor slots through which the coil are warm and there are twelve coils. So the coils here are coming from the slots from the twelve slots on the rotor and you have the commutator segments, the coils are soldered on to the commutator segments here if you notice (Refer Slide Time: 41:25) the coils are soldered on to the in the winding fashion that we just saw, discussed. This type of winding fashion is called the lap winding.

Now this whole rotor will be mounted onto a central shaft and then above that one will be another enclosure called the stator which will have the poles the north and the south poles it could have more than one set of poles and that would make the complete machine. This whole set together is called the armature. So the armature consists of the core and that is also laminated here again because as we were explaining during the time of the transformers the laminations are used to reduce the eddy current losses, this portion (Refer Slide Time: 42:32) is the coil ends which are joined to the commutator segment, the brushes will come in contact at this copper surface of the commutator segments so the brushes will come and in contact like that it will spring loaded you will have a look at that in a different machine.

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You see that this is the armature which is fully mounted onto a yoke and this is a complete motor which you would which you see here, the shaft is the shaft is capable of rotating here, so the shaft rotates the commutator segments here which are the coppery portions may contact with the brushes; there are two brushes here on these two sides and the commutator segments may contact with the copper coils by virtue of being soldered.

Now at these end (Refer Slide Time: 43:39) there are very fine soldered joints which make connection with the coils inside on the rotor and this is this is thirty-eight slot motor and therefore you have much less ripple as compared to a two pole as compared to a two slot or a four slot motor that we just saw; four slot meaning you have four slots on the rotor with four coils, twelve slots means twelve coils, thirty-eight slots means you have thirty-eight coils in this area.

So, coming back onto the board we now saw the structure of the DC machine and in the case of the DC generator the power comes from the shaft, this is the shaft the mechanical shaft which is in the mechanical domain enters the DC machine, this is the DC machine, goes through the magnetic domain and through the brushes through the brushes the power is fed to the external electrical circuit through which to which the terminals of which is the load could be some load or it could be a load impedance, we will come to that.

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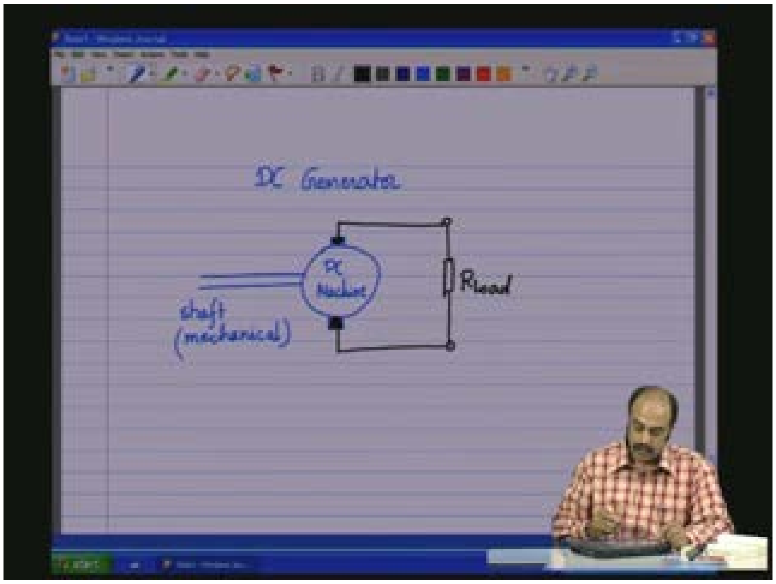

Hence, this is the schematic of the whole DC machine and we were looking at the internals of the DC machine how it is structured and how a mechanical rotation can give rise to a voltage and that too a unidirectional voltage or a DC voltage. So if we have many slots many coils per pole then the voltage across the load the induced voltage across the load will be almost ripple free, it will have negligible ripple across the load.

And now let us look at how much voltage is induced across the brushes. the induced voltage we will call this one as E generated E generated is given by N phi Z by 60 where N N is the rpm of the shaft rotation or the rotor rotation and rpm means revolution per minute revolution per minute and phi is the flux per pole this is in Webers; notice that we have always one pole set one north pole one south pole in all our discussions till now but it is not necessary that it should be just one pole set there could be many pole sets. So the flux phi is the flux per pole and Z is the total number of conductors on the armature is total number of conductors in the armature. So the total number of conductors in the armature, the flux per pole and the speed at which the rotor is rotating they are linked to the value of the induced voltage or the generated voltage.

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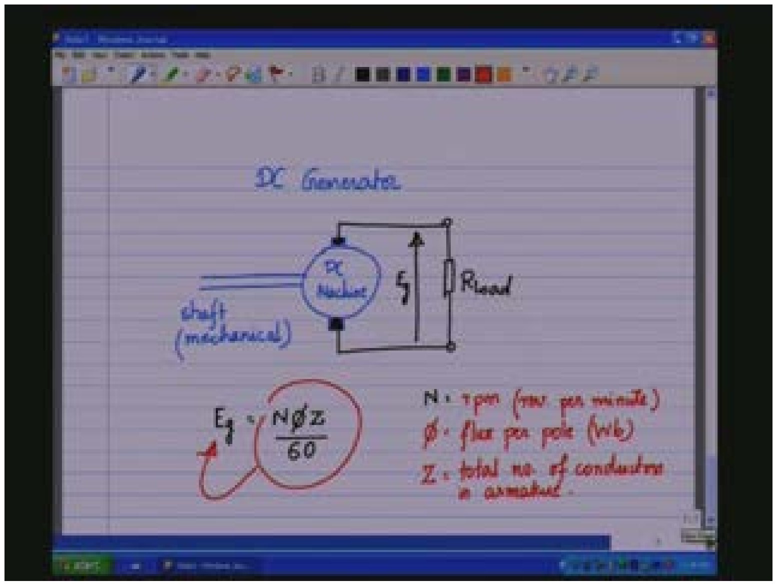

Therefore, the generated voltage E g is actually derivable from the alternate Faraday's Law of electromagnetics the equation which we have been using in the DC machines E which is equal to B L v where B here is the flux density flux density, this is the length of the conductor length of conductor and this is the speed at which the conductor is moving and this is given in meters per second and from this we have arrived at the induced or the generated emf E g which is N phi Z by 60.

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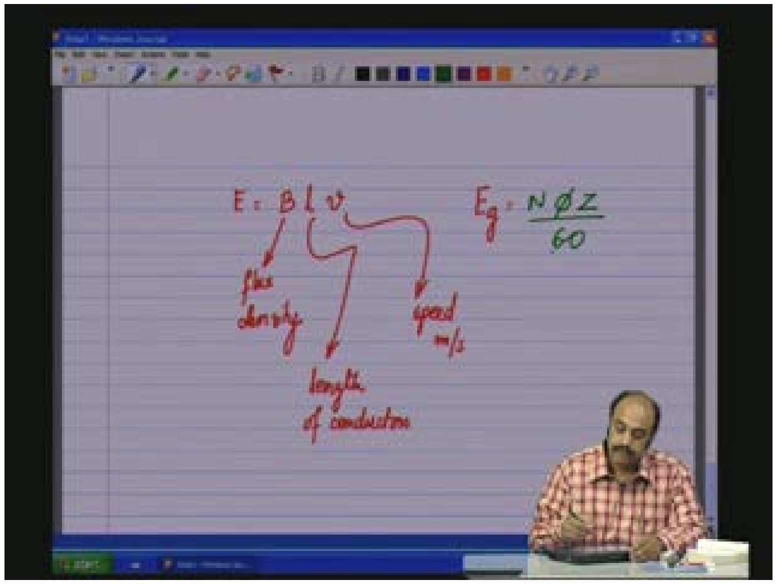

Now N is the rotation revolutions per minute rotation of the rotor so rotation speed of rotation of the conductors so this is related to the V velocity there. The number of conductors is related to the length of the conductors and the number of number of turns in the coil and then the flux of course is related to the B. So, starting from this equation E is equal to B L v the Faraday's equation from the law of electromagnetics one can derive this equation.

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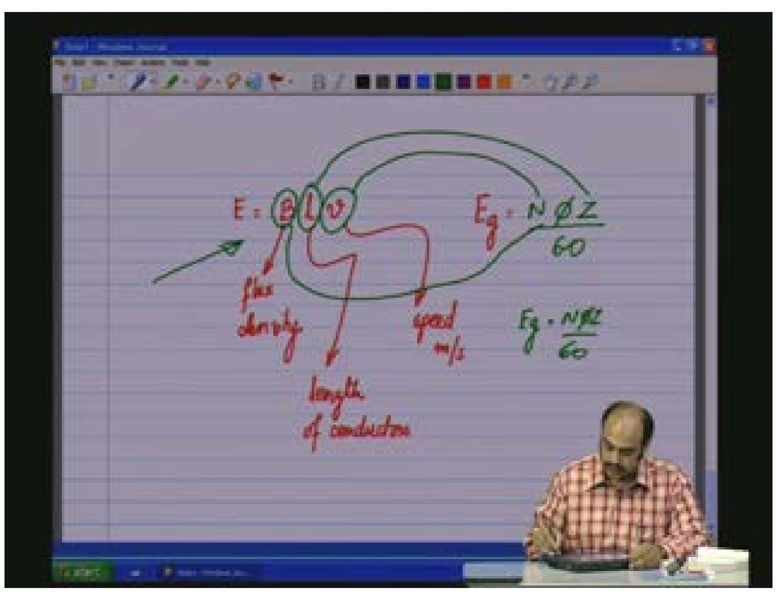

Now let us consolidate this understanding of this equation with a simple example which will give us a better idea of using the equation. So let us consider a DC machine whose armature has 6 poles and the speed at which the armature is going to rotate will be 600 revolutions per minute. Now this machine is designed to have 90 slots by slots means you see we were writing these slots you remember on the surface of the core on the surface of the circular core. So this was a four slot machine; like that let us say you have 90 slots and each coil the coil that is wound through the slots has four turns for coil. That is we used to always draw a coil with just one turn but there could be many more turns than one and in this case this particular generator is wound with four turns and the flux phi which is 0.04 Webers is the flux per pole.

So when given these information what is E g the generated voltage or the generated emf?
E g is N phi Z by 60. So let us first calculate Z. Total number of conductors in the armature. So there are 90 slots therefore there are 90 coils and there are 4 turns per coil and two conductors per turn. For every turn there is a there are two conductors which are diametrically opposite two coil ends basically. So this means this equals 90 into 4 into 2 which is 720 total number of conductors. The speed N is 600 rpm and therefore E g is 720 into 600 rpm into 0.04 Webers flux per pole divided by 60 which is equal to 288 volts. This will be the induced emf across the brushes of the generator of this particular DC machine which has its specification as given here (Refer Slide Time: 55:03).

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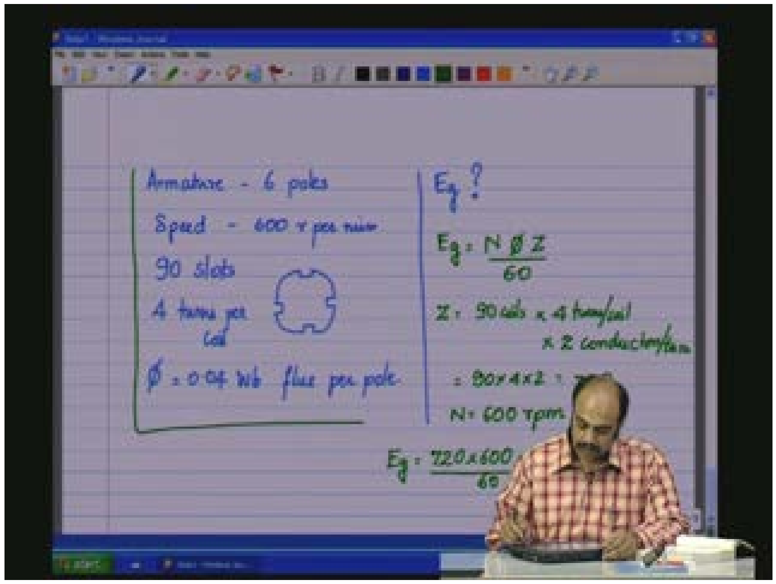

Now we know how to calculate the induced emf across generator, we need to look at the circuit of a generator and also the state equation that you would obtain for the following generator; the general state equation that is in the form X dot is equal to Ax plus Bu Y is equal to Cx plus Du so that you can do any analysis on any type of generator because all generators DC generators fall under the similar constructional principles and operational principles and thereby they can be mathematically modelled.

We will look at the mathematical model of the DC machine DC generator, we shall also look at the voltage regulation characteristics of the DC generator and the different types of excitation that is how the pole the flux is produced within the generator and another important issue and that is on the armature reaction a concept which we have still not discussed but we will discuss in the following session; the concept of armature reaction and how it is how it can be avoided. Now all these issues we will be discussing in the coming session.

In this session I would like to point out that the operational principle of the DC machine is quite simple actually and the number of coils the number of slots are increased so that you get a twofold advantage one is the increase in voltage across the brushes because each coil between the brushes there now there now going to be more number of coils and therefore the induced voltages of all these coils are going to add up and then come across the brush voltage as we saw in the discussion today; and the second one more important thing is that the voltage across the brush will have very less amount of the ripple as the number of coils and the slots increases. So, these two are the primary advantages in having large number of coils. Further if number of poles are also increased then the ripple content in the DC machine the in the output of the DC machine will be negligibly small.

So we shall continue in the next class trying to consolidate on the mathematical model of the DC machine and other aspects that I mentioned like the armature reaction and the voltage regulation curves and the output curves. Thank you.