Electrical Machines
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Lecture 27
DC Machines: Commutation

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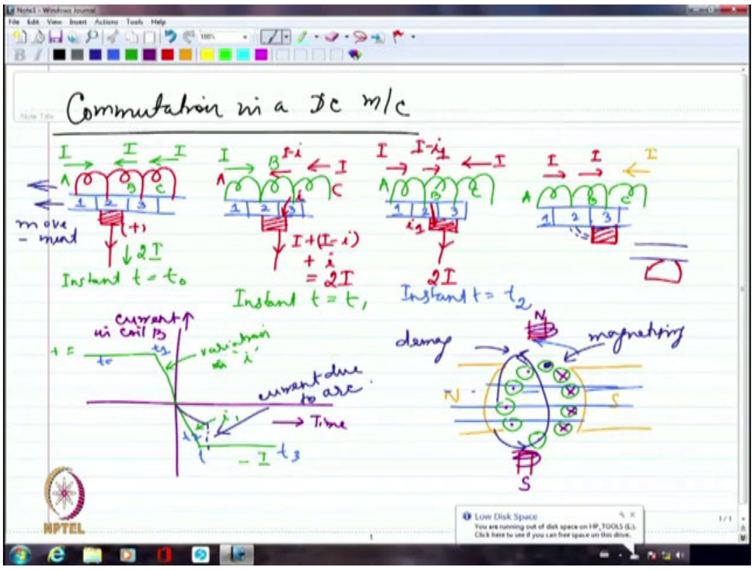

Let us try to look at commutation in a DC machine once again. So, what we said was every coil probably especially if it is a lap winding it is probably going to start off with the north pole it is going to end up in the south pole and then come and fold back that is what we said. So, I am going to represent the winding let us say these are commutator segments may be this is commutator segment number 1, this is 2 and this is 3 and I am showing one of the windings like this, another winding adjacent to it like this, the third winding adjacent to it like this.

So, we are going to have more and more windings like this continuously. Everywhere in the junction there is going to be a commutator segment. Now if I say that the brush is located somewhere here, this is where the brush is, and if I assume it is a generator, I should say the current should flow out of the positive brush so I should show as though the current is flowing like this and this will be the positive brush if it is the generator.

And I am going to have probably a current flowing in this direction like this which may be I, and I should have a current flowing like this in the opposite direction which is also I, there is nothing that is collecting the current form segment number 3. Let me name the coil this is A, this is B and this is C. Whatever is flowing in coil C should also flow through coil B, because they are essentially in series there is nothing that is dividing the current.

So, I should say this current what is flowing here will be 2I at this junction, so let me talk about this as instant $t = t_0$, this is the instant $t = t_0$ and we are having the brush to be stationery; there will be poles which are stationary but the movement is going to be actually in this direction. The movement of the coil as well as the commutator segment together, this is how the movement right.

Let me draw the commutator segment, so this is 1, this is 2 and this is 3 probably I am going to have the brush moving slightly like this. Please note that the brush has now come in contact with both 2 as well as 3, both of them are actually getting in contact because of which if I say that coil B is connected somewhere here, this is what we have shown as coil B. So coil B is being short circuited by one brush. What I have got that brush is going to short circuit coil B, because coil B is in touch with both segments 2 and 3, respectively and both of them are essentially short circuited together with help of a brush.

Now I have of course A here, B here and I am going to have C here. Now I would say maybe I have a current I here, and I am probably having a larger area here and smaller area here probably depending upon how much the movement has taken place. So, what is going to happen is, this is having a current of I. May be part of that current is going to flow like this. So that current is probably going to be *i*, so only $I - i$ will really go through B. Because this is the total current I which is flowing from the other direction and part of it has already gone into the brush because of which I am going to have a current here which is $I - i$.

Now if I look at the total current how much that is going here this is going to be essentially

I+(I-i)+i=2I, still that is not going to change, only thing is the distribution has somewhat changed among the 3 coils what I have. So, now if I look at it I am going to have this actually corresponding to may be instant $t = t_1$, after a little while, from t_0.

Let me look at the next situation where here I have shown as though 2 is having a little higher contact area, 3 is having a smaller contact area instead if I have in the third situation again. Let me look at the commutator segment this is 1, this is 2, this is 3 and I am going to have the brush as though it is making a smaller contact with 2 and larger contact with 3. Then I am having the current still flowing out of this brush because it is a positive brush, that will not change.

Now let me draw the coils as well, so if I say that this is coil A, this is B and this is going to be C, these are the 3 coils. Now let me look at actually the current that is flowing, this is still I let us say right and this probably what came out of here is I. Let me write this current now what is flowing form commutator segment number 2 through the brush into the outside let me call that as some i_1 okay. The total current in coil A was I, some i_1 has already gone into the brush, so what will flow here will be now I-i_1, note the direction, it is in the opposite direction compare to what it was earlier.

So, now I am going to have again i_1 is flowing here, I-i_1 is flowing through commutator segment number 3 and I is again flowing from C into commutator segment number 3 back to the brush. So, this will be again 2I. Only thing is what happens originally was coil B was carrying a current in the direction which is going from right to left. Now the current is looking as though it is going from left to right that is all the difference.

Only thing you have to understand is, let us try to again look at the current variation so with respect to time let me plot current in coil B. Let me try to plot this. Initially at time $t = t_0$ when 2 was actually collecting the current no other contact was being made to 3, the brush was not making any contact 3 at that point in time I had the current as +I then it started slowly varying and then it will ultimately go to -I. If I may call this as +I and this as -I, I can say here is, actually the variation in coil B current.

So, initially may be it was originally I then it actually went to i_1 that is why i_1 looks like it is in the opposite direction anywhere in between I am talking about the complete slope which is actually changing from +I to 0 during that condition I am having *i*. So, *i* keeps on increasing slowly because of which then I am going to have this contact area exactly equal to each other that is the contact area of the brush to 2 as well as 3 they are exactly equal to each other, coil B will carry 0 current because *i* will become equal to capital I that is when it becomes 0 current.

So, coil B is essentially short circuited slowly the current changes and the current is slowly increasing in the opposite direction and as it increases in the opposite direction you are going to see that when it reaches a point the forward direction of current is equal to the reverse direction of current it is going to become 0 and eventually it will go into the other direction. So, it is defecting from one side to another side that is what we said initially maybe it was dot current then it will become a cross current and vice-versa that is what we were talking about.

Now if this kind of a linear commutation takes place actually it is related to the area of contact between the brush and the respective commutator segment, because of which no current has to flow through the air path. No current will go through the air path only. When the current flows through an air path you are going to see the ionization or sparking. Otherwise you will not see the sparking, but if I am going have the area of contact exactly being proportional to the current that is flowing through the segment into the brush.

Essentially the copper segment is going to pass the current into the brush and it is going out. So, there will not be any path for the current through air. But what happens now, I am going to talk about the next instant here when I look at the next instant here, so this is instant $t = t_2$, so this is actually $t = t_0$ this is the starting of t_1. This is what we are talking about t_2, these are the instances closed to t_2.

Now what I am going to talk about is instant t_3, where it has completely defected to the other side. So, I am going to have the commutator segments again, I am starting with 1, 2 and 3. So, I am going to have A, B and C now. Please note that the commutator segment is not going to make any more contact with 2, it has come exactly in contact with 3. Now because it has moved further, the armature has moved further because of which I am going to have the contact only with 3.

So, what I should have expected is, this should have defected completely in terms of this current direction, I should have this as *I*, there should not be any current going through commutator segment 2. Everything should have gone only through coil B and then segment 3 that is what I should have anticipated. So, this is again A, B and C. Now I should also expect that this current will be *I*, but what happens is, I normally anticipate that coil B is in the inter-polar region or in the border between north and south and south and north or whatever.

If I show it in the cross section of the machine I should show it as though I have the north pole here, the south pole here. I am not drawing the yoke and I am going to have actually my conductors here. I am showing big conductors and maybe I have one here and one here something like this and what I am showing here is probably B. If I try to assume that the direction of rotation had been in this direction please take your right hand rule, you would get that these are dot and this will be cross that is how the currents will be.

That is why we are drawing the two direction that is A coil is carrying current in one direction whereas C coil is carrying current in the opposite direction, that is what we have drawn. Now this coil what is in the middle is B and that coil is the one which is connected to the commutator segment number 2, which is eventually connected to the brush. So, I am collecting always the current from the brush which is in the inter-polar region.

The commutator segment which is lying in the inter-polar region is the one which is getting connected to the brush and then eventually going and supplying my load that is what happens normally during commutation. I expect that coil B, because it is in the inter-polar region, will have hardly any induced EMF. Because it does not have any induced EMF I should not have a big problem short circuiting it or the current reversal and so on should not be a major issue basically in a DC machine but that is not really true when I have armature reaction.

When I have armature reaction what is going to happen is, we said basically that the original lines of force was like this, this is how the main flux was. Whereas these are going to create the flux lines in such a way that it is in the opposite direction here, because of which I am going to have definitely a reduction in the flux here. We said this is de-magnetizing whereas in the opposite direction this is going to be magnetizing that is what we said. So, the armature reaction flux is going to cause de-magnetizing effect in some of the conductors or some of the geometrical region and magnetizing effect in some of the geometrical region.

Because of which I am not going to see that this particular conductor what I am talking about is in the neutral region, it is not in the magnetically neutral region any more. It is rather oriented more towards the south pole because that is the magnetizing effect that is taking place there. So that conductor even though it has geometrically, physically left the region of south pole, it is not going to feel as though it is in the neutral region. It is going to be under the influence of the south poles flux itself because of which although the current should have reversed completely the movement it has left contact with commutator segment number 2, the current is not going to leave its effect because the induced EMF is oriented towards south poles polarity.

So, the current is going to sustain itself for some more time even after commutator segment number 2 has lost contact with the brush. So, what happens is this B is kind of in a predicament. It does not have contact with 2 but it has to still supply some current which will go from 2 into the brush. So, there is some amount of current that is going to flow still from commutator segment number 2 towards the brush because of the induced EMF in the coil B which has kind of moved away from the neutral axis it is not its fault, the fault is of armature flux, armature reaction.

So, the armature reaction has created an effect such that the neutral axis gets shifted, if the neutral axis is shifted, coil B is not going to have 0 induced EMF. If it is not going to have 0 induced EMF and if it is going to be orienting itself towards the pole that was just left behind. South pole is the one which was left behind. So, it is going to continue to be favoring that current somewhat. So, because of which you are going to see that the path which is actually not a copper path which is existing between 2 and the brush that is going to get ionize, the air is going to get ionized.

And then it is going to actually show itself in the form of an arc, so that is what is known as sparking. So you call that as the sparking. There are actually more reasons I am not going into any of that because we are not even going to talk about how to reduce sparking and so on and so forth, I am leaving it at this basically. So, the sparking is essentially caused by the shift of the neutral axis, due to which there is an induce EMF in the inter-polar region. The coil occupied by the inter-polar region, in the inter-polar region that is going to have some induced EMF.

That induced EMF definitely is going to cause a delay in terms of the current not really reversing right away where it should have reversed even after commutator segment number 2 has not touched the brush. So you are going to have some kind of ionization taking place and arc is drawn out, a sparking occurs, and then the current is quickly going from whatever value may be i_2 it is going to +I eventually or -I if you may call it as -I.

So, actually speaking I am not going to have the current follow this path, it is going to get delayed slightly and then suddenly you will see due to sparking because arc resistance are generally larger. Arc will always have a little larger resistance compare to copper very clearly. So, it is going to probably wear out on its energy, stored energy or whatever and quickly it will just jump to this particular -I value from whatever value it was earlier. So, this particular dotted portion what I am showing is the current due to ionization or arc.

So, that portion is probably is going to jump from a particular value to -I very quickly and this is seen only when the armature reaction affect is pronounced otherwise it will not be seen. The armature reaction affect is pronounced only if I am going to have higher and higher load on the machine, whether it is a generator or a motor, it is immaterial. But I am going to see invariably that the effect of armature reaction is pronounced because of higher armature current.

So, only under loaded condition you will see this more and more, if the wear and tear in the machine is quite large then also you may see, because normally we expect that the brush has to make a good contact here. By chance due to wear and tear I am going to have the brushes' edges are rounded like this, it is not making a proper contact. Then also the contact area decreases because of which may be some portion of the current has to flow through the surrounding air.

So, you might see sparking in machines which have gone through years and years of life. This is one of the major reasons why DC machines are hardly ever used in inflammable environments like petrochemical industry, mines, it is not really a good idea to use DC machines where you might see some combustible gases coming out or petrochemical industry where you will see all over the place some inflammable substances. So, one of the major problems with DC machine is this commutator and brush arrangement which causes continuously sparking, especially when you load the machine.

And you would never run a machine without loading obviously. So, this is one of the major topics in the DC machine which makes it disadvantageous although it is advantageous in so many other ways. Last one mention we said that this conductor is going to get affiliated more and more towards south pole. It is favoring the south pole so just to nullify the effect of armature reaction we will put some pole called inter-pole, small poles.

The structure is in the stator, but the current carried by the conductors which are wound around the inter-pole is same as that of armature current. Because the armature reaction effect is perceivable I want the inter-pole to come into picture otherwise I do not want the inter-pole act at all.

So, the winding around the inter-pole will carry the current which is same as that of armature current. So, if this inter-pole is rather creating a flux corresponding to north pole and if this inter-pole is creating a flux corresponding to south pole in all probability I would nullify the effect of this de-magnetizing and magnetizing armature reaction.

Student: Do we decide the orientation (N or S) of the interpole?

Professor: See this is de-magnetizing effect which is actually making near the inter-polar region, this is opposing whatever is the direction of the flux lines here. The field lines are from this north pole to south pole whereas this line is in the opposite sense but if I have a north pole here this will strengthen the magnetic field here which will try to orient itself towards the north more.

Previously this conductor was orienting itself towards south pole because essentially the neutral axis itself has shifted, now what you are trying to do is to nullify the effect of the armature reaction flux which is in the inter-polar region alone. We already talked about compensating windings which will be put on, the pole shoes. The compensating windings are meant for nullifying the cross magnetization, the inter-poles are meant for nullifying the de-magnetizing and magnetizing effect of armature reaction.

So, we are essentially looking at two specific purposes of inter-pole and compensating winding. The inter-pole always intervenes with de-magnetizing effect and magnetizing effect of armature reaction which will aid commutation, whereas if I am going to have the compensating winding, the compensating winding is always going to nullify the effect of cross magnetization which is definitely kind of tilting the direction which will be not tilted ones I have the compensating winding in place.

But both compensating winding and the inter-pole windings will carry armature current as far as the magnitude of the current is concerned. So much so for commutation. So, we are concluding the topic of DC machines with this particular explanation for commutation.

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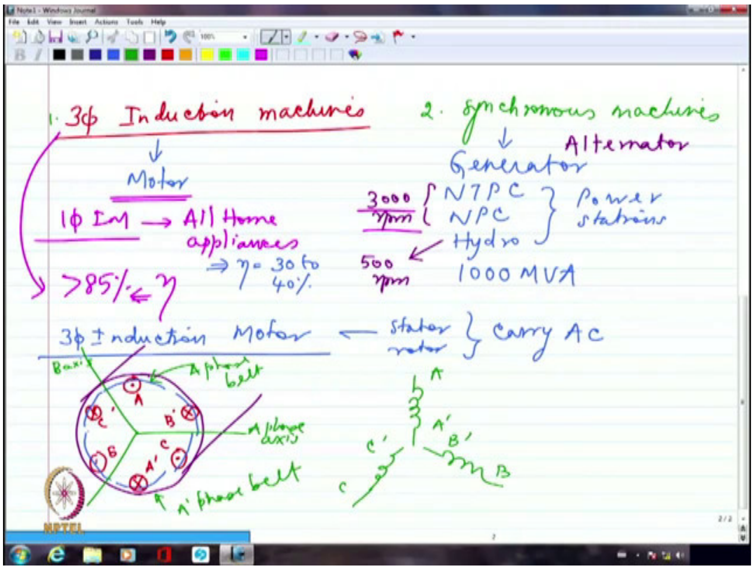

So, the next one that we are going to take up is one of the most important topics in the machine that is 3-phase induction machines. So, we are going to talk about two AC machines in this entire course, one will be induction machine, the second one that we will be talking about will be synchronous machines. The induction machine generally by and large is used as motor whereas the synchronous machine by and large is used as a generator. Definitely there are other applications as well that is induction machine used as a generator and synchronous machine used as a motor as well.

In most of the cases you would see that induction machine is normally run as a motor and synchronous machine is normally run as a generator. Synchronous machine if you look at all the NTPC power stations, all the NPC power stations, all the hydro power stations, all of them use very clearly only synchronous generators. And the capacities are really-really large. The capacities can be as high as 1000 MVA easily. So we have normally if you look at older power plants like Ramagundam or some of the power station in Dadri, some of the units you might see that it is only 500 MVA or 300 MVA, 250 MVA and so on.

Sipat is actually which came up couple of years ago that has a 1000 MVA alternator, synchronous generator is also known as alternator. So, these are generally rotated either by a hydro turbine or it is rotated by a steam turbine. So, if you talk about NTPC power station or NPC nuclear power cooperation power station in Kalpakkam, Tarapur or whatever there, you are going to see that generally they are all rotated by steam turbines. So, they will normally run at 3000 rpm.

Invariably you will see that many of them run at 3000 rpm whereas hydro turbines are generally slow. They will run only around 500 or even less rpm. So, hydro turbines generally run at lower speeds whereas steam turbines normally run at 3000 rpm because of which you would see that correspondingly the number of poles are adjusted. So if you are looking at the generator configuration of a synchronous generator it will always be at constant speed, it can never be at any other speed other than this. It will run as a rule at 3000 rpm because only if it runs at 3000 rpm it will create 50 hertz.

Otherwise it will not be able to create 50 hertz and what we want is 50 hertz because which is connected to the grid and our grid frequency is 50 hertz so we do not want it to run at any other speed other than 3000 rpm. Whereas if you look at the induction motor, if you actually say that the total generating capacity may be of our country now is about 275GW almost 80 percent of the electricity generated is used by induction motors because if you look at any industry be it pumps, sands, compressors, cement mill, paper mill you name it textile mill all of them use 3-phase induction motor for their rotational purposes.

So, 3-phase induction motor are the most utilized machines in the industry. The name 3-phase is because you give a 3-phase supply there is also single phase induction motor clearly so let me at least make a passing mention about single phase induction motor if we do not have the time to deal with it in detail. The single phase induction motor is the most used in this drive at home. The home appliances if you look at many of them use single phase induction motor for example water pumping motors at home, fans except for mixer and hand drill.

If you look at hair dryer, you look at lawn mower, you name it anything for that matter many of them are single phase induction motor, so this is used in all almost all home appliances. But this single phase induction motor nobody cares about their design because they all actually work at fractional kilo watt maybe 20 watts, 30 watts, maybe at the most 300 watts. So, nobody really cares too much about their efficiency and design because even if it is working at 30 percent or 40 percent efficiency it is okay, that is what people think.

But we are wasting huge amount of power in that because every home uses at least 10 to 15 single phase induction motor. So, you can imagine we probably consume 40 watts in the fan but what we convert into the form of circulating air, it will be only corresponding to 20 watts or even less. So, we are really wasting a huge amount of power in single phase induction motor. But 3-phase induction motor we have really a very good efficiency in most of the cases it goes definitely greater than 85 percent if not more than 90 percent.

So, 3-phase induction motor generally the efficiencies are greater than 85 percent whereas in single phase induction motor the efficiency is as low as 30 to 40 percent nothing more than that and nobody cares to really improve it either because it is a very competitive market, you guys definitely know the aggressive advertisements that are taking place in refrigerator, washing machines and so on and so forth. Every little drop in the price will cost them heavily, the other person who is having a higher price.

So, generally nobody cares about the design of single phase induction motor so much even if you say it has 5 star energy efficiency rating nobody is going to go and fall on it as long as the price is somewhat lower in the other case that is the reason. Now let us go on to 3-phase induction motors basic structure. Very clearly a 3-phase induction motor also should have a stator and rotor and because it is working on induction principle it has to be carrying AC, it cannot generally carry DC. So, both stator and rotor carry AC.

Please remember in DC machine the field carries normally DC, only the armature carries AC, that is why we have put commutator and so on and so forth. So, here both of them are going to carry AC and if I look at the structure basically, I am going to have I am showing the cross section ofcourse it is like a cylinder which is extending into the board. I am going to have 3-phase windings which are distributed in space and which are also distributed at 120 degrees from each other.

So, I may show probably the A phase windings somewhat like this, this is A, this is A’. So, one is carrying the current in forward direction, the other one is carrying the current in the return direction. And I may have B here and B’ here, so I call this is B, this is B’, this is A, this is A’ and I am going to have C and C’. I have shown as though it is only 1 winding definitely it is not only one turn there will be multiple number of turns. So, I should show as though may be the A is again spreading over the entire periphery of the stator, the inner periphery of the stator.

But generally, then I have A phase and B phase and C phase windings like this, it is not going to be easy even machine wise to actually wind the entire winding without getting confused, it is going to be very difficult. So, what people normally do is to allocate about 60 degrees for A, 60 degrees for A'. Another 60 degrees for B', 60 degrees for B, another 60 degrees for C' another 60 degrees for C. So, I have totally 360 degrees if I have totally let us say something like 36 slots, I am just arbitrarily saying 36 slots I am going to make 6 slots each for A positive, A negative, B positive, B negative, C positive, C negative.

So, this is generally known as A phase belt. This is also may be A' phase belt, every belt occupies about 60 degrees. So, we will generally put the windings corresponding to A phase. Please note that these 3 windings are completely independent. Each of them is going to be supplied by A phase current, B phase current and C phase current, respectively. So, I will have basically A phase winding shown like this, may be B phase winding shown like this, C phase winding shown like this.

So, I am showing that this is A, A' similarly B, B' and C, C'. I can connect them in star or delta according to my requirement. If I bring both the terminals out, I should be able to connect them in either star or delta not a problem. So, the stator basically has a distributed winding which will correspond to 3-phases but if I look at axis of A phase winding, may be this is the A phase axis. Similarly, if I try to look at B phase axis it will be 120 degree shifted, C phase axis that will be 120 degree shifted.

So, please note that I am going to have basically all the 3-phase axis shifted from each other by 120 degree. So, geometrically or physically I am going to place the windings in the stator in such a way that the axis of A phase I am looking at it this way, this is dot so the current is going like this, so I have taken it that way. So, in one sense this is the magnetic axis of A phase. Because dot is on the top I am talking about this as dot so the magnetic axis is pointing in this direction.

So, that is what I am talking about, so I can essentially talk about all the 3-phases having their axis shifted from each other by 120 degrees. This is the same case with synchronous machine stator as well. The synchronous machine stator is absolutely not different from the induction machine stator. The induction machine stator and the synchronous machine stator are one and the same there is hardly any difference between the two. Because I will not repeat this when we talk about synchronous machine that is the reason I am emphasizing this, the stator structure essentially the same in 3-phase induction machine and 3-phase synchronous machine.

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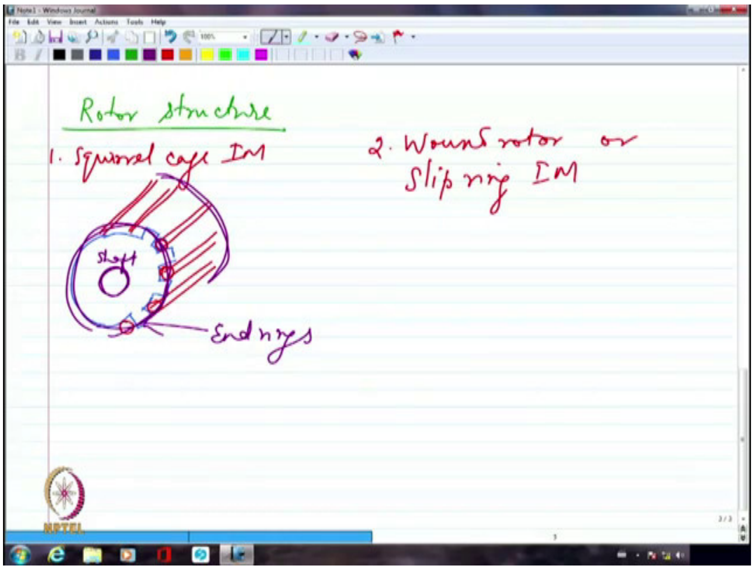

Now let us try to take a look at the rotor, how the rotor is. So the rotor structure there are specifically two types of rotor in an induction motor. One of them is called as squirrel cage induction motor and the second type is known as wound rotor or slip ring induction motor. So, the name squirrel cage come because what I have is the rotor cross section let me show it like this. Maybe I have slots in the outer periphery like this. I am not drawing many slots other than this, this is all is the slot I am showing. There will be slots all over clearly.

Now what I am going to do is to put one rotor bar here, second rotor bar, rotor conductor, it is a conductor but very thick, so I am calling this as rotor bar. So, I am going to have several bars put along every slot, so I am going to have essentially this as the structure of the squirrel cage rotor. So, I am going to have imagine this is just going into the board, this is how it is. So, if you imagine you are going to have more and more conductors going around like this, it looks like a cage, if you just imagine without the core it is essentially so many bars and it is a cage like a parrot sits inside it, it is essentially like a cage, that is the reason why it is called a cage rotor, squirrel cage rotor.

Because on the top of the squirrel at the back side of the squirrel you see 3 lines or 2 lines whatever, so it is essentially similar to that structure so that is the reason why it is known as squirrel cage rotor. The major advantage of squirrel cage rotor is the rotor resistance is going to be really-really small because I am going to have thick copper conductors or thick aluminum conductors carrying these current so the resistance have to be small there is no other way, and one more major advantages ultimately what I do with this rotor bar is I am going to put one ring on this side another ring on the other side.

I short circuit all the rotor bars with two end rings these are called end rings, so the end rings are going to short circuit the two ends of the rotor so the current definitely can flow if there is some voltage induce is the short circuited path that is available. So, the current is going to flow no matter what because I have short circuited them already. There is no connection coming out of the rotor at all, I do not have any access to rotor current, the rotor is there it is carrying current it is going to produce flux, it is going to induce torque, but I will not have any access to rotor directly.

I will not be able to measure the rotor current if I do not even measure where is the question of controlling it, so control of induction motor becomes really-really difficult because of the fact that the rotor currents are not even accessible to me. So, what is going to happen is I will have actually a shaft here, the shaft will go through this, through the rotor rotation the shaft will also rotate because of which I will have an external mechanism rotating.

In a motor what I want is to rotate another mechanism that will be possible with the help of this rotor but this rotor does not have any connection with the external world. So, I have a problem of major control of this rotor but it is also having another disadvantage because there is no connection it is one rugged structure. I just mold the whole thing, I can just make copper bars, I can just make the end ring put everything together, weld it together whatever, put it in service forget about it for 50 years, nothing will happen.

Whereas if I have the brushes, if I have commutator, I have to every now and then check whether the brush is making proper contact, whether there is no sparking, whether I have everything properly holding, whether the spring is holding it all those things I had to check but I do not have to do anything in the case of squirrel cage rotor. Squirrel cage rotor is a really-really a very strong and rugged structure. In fact if you have to break a rotor bar we have done it once it was so difficult to break a rotor bar, because we wanted to check what kind of characteristic difference come when you break a rotor bar, when there is a crack.

It is not easy to break the rotor bar even if you want to break a rotor bar. So, it is a real rugged structure which runs your Rajdhani train and all the trains there you just put the motor, it is a 850 kW induction motor, 6 of them actually work in Rajdhani train. So, 850 kW induction motor you put it in service, forget about it for several decades. So that is one of the best motors you can think of for industrial applications, no wonder it is the king of industries as per today. So, this is cage rotor structure, will look at wound rotor structure in the next class.