Course Name: Design of Electric Motors

Professor Name: Dr. Prathap Reddy B

Department Name: Electronic Systems Engineering

Institute Name: Indian Institute of Science Bengaluru

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Title: Realization of Electrical Machines-1

Greetings to all, in the last few lectures we have discussed the magnetic circuits with respect to design analysis and force equations. In this lecture, we will discuss the realization of electrical machines from the principles of magnetic circuits and force equations. In the summary of last few lectures, we can see here, the study 1 is nothing but magnetic circuit with single excitation. Study 2 is nothing but magnetic circuit with multiple excitations. Study 3 is magnetic circuit with permanent magnet as well as electromagnet. Study 4, both side permanent magnets are there.

If we will see the study 1, one side we have the electromagnet, other side moving I bar. This is moving 1 and this is stationary. Based on the reluctance principle, it will work. Like simply, we can say that this is the magnet, north and south poles are induced based upon the magnetic principles and this is a simple iron piece.

So, iron piece will automatically attract towards the magnet and the induced poles in the iron piece are opposite. Based on the attraction principle, the force will be upward direction here. The force terms with respect to the equation, what we have seen in the last lecture, only reluctance term will be there in the force equation. If I talk about the rotating system, torque depends on the reluctance. There is no mutual nothing.

Only reluctance torque will be there in this kind of systems that is study 1. If we will take the study 2, we have 2 excitations, 2 windings, both sides based upon the magnetic principles, the induction of magnetic poles we can see here. Opposite poles will attract. Here also, force will be in upward direction. The I core is moving.

The force or torque depends upon the reluctance terms as well as mutual torque terms. We can see here reluctance with respect to the individual coils and mutual interaction of currents in both coils or fluxes to the both coils. Study 3, we can see here one side we have electromagnet, other side we have permanent magnet. In the electromagnet, the

poles will be in this manner. Then based on the attraction, again moving I core, this is the moving one.

It is moving upwards based upon the attraction of the magnetic poles. Opposite poles will attract based on that principle. It is moving upwards. Here the force or torque depends upon the two terms. One is reluctance with respect to the individual coil and mutual interaction of flux with respect to the permanent magnet and electromagnet.

This interaction will be there. In the study 4, only attraction and repulsions of the permanent magnet, this one will move upwards. In the torque equation, we can see the first two terms are reluctance terms and the third term is the mutual torque terms. We can relate it to all these four studies, the reluctance as well as mutual torques. In the study 1, there is no secondary current.

Then mutual torque is automatically 0 and I 2 square dL 2 by d theta term also 0. Only reluctance term will be there. Second study, the same equation will be valid. Third study, instead of I 2, we can consider the flux with respect to the permanent magnet. Now, how to realize the electrical machine with respect to these principles? In a rotating machines, there is an angular displacement.

Here we are seeing only linear displacement with respect to one direction. Here angular displacement will be there in a rotating machines. So, how to realize the simplest machine? The simplest machine we can realize with the permanent magnets, no need of windings, nothing. I am considering the study 4, stator side also a permanent magnet, rotor side also a permanent magnet. Based on the attractions and repulsions of the magnets, it will work.

Consider the machine will be in this manner, in a square or rectangular manner and circular stator surface is there that will be in this manner. Now, I will consider the case 1, where the rotor position is exactly aligned with the stator. This is the rotor, rotating one and this is the stator at the stationary part. We will see the case 1, where the rotor is aligned with the stator side. Both opposite poles will be in attraction, here also opposite poles in attraction, magnetic locking is happened.

So, how to make the rotation or how to break this magnetic locking in order to rotate the rotor? What we can do is just simply change the number of poles or increase the multiple poles. Before going to that one, we will see case 2, where the rotor position is aligned in this manner, vertical. Earlier, we have seen in a horizontal manner, now we are seeing in a vertical manner, 90 degree displacement is there. In this position, opposite poles will repel each other. In the other side, attraction is happening because of the opposite poles.

Here repulsion is happening because of the same poles. Now, rotor will rotate in this manner. We can see here, again magnetic locking is happening from this position to this

position, rotor is moved and magnetic locking is happened again. How to break this magnetic locking? That is possible with by utilizing the multiple magnets or poles at the stator side or rotor side, that is one option. Second option is change the poles or reverse the poles either at the stator side or at the rotor side.

These are the two possible solutions to make the rotation in a symmetrical manner. The first solution with respect to the multiple magnets, we will see now. With respect to the multiple magnets, consider here, I am considering set 1 magnetic pole pair and set 2 magnetic pole pair at the stator side and rotor side, only one pole pair is there. Now, assume that we are placing only set 1 magnet, the situation will be in this manner, where the opposite poles are in an attraction state and repel similar poles are in a repulsion state. So, the magnetic locking is happened in this situation.

Consider this is case 1. Here magnetic locking is happened. Now, remove the set 1 of magnets and place the set 2 magnets. We are removing the set 1 magnets. Assume it just to realize the machine.

Once the mechanical arrangement is done, we cannot remove or we cannot place the magnets again back to the stator. For realization purpose, let us assume that set 2 magnets are only placed in the stator side. Then what happened? These similar poles will repel each other and opposite poles will attract each other. Here attraction is happening. So, the rotor rotation is happening in this direction, rotor rotation.

So, that we can see here, rotor is rotated in an anticlockwise direction. Now, again magnetic locking is happening between the stator poles as well as rotor poles. What to do? Remove the set 2 magnets and place the set 1 magnets at the stator side. This situation will come. In this case, if we will see the repulsion forces here also, the rotor will try to move in this manner.

Here clockwise direction, we are seeing the rotation, the rotor rotation. In the earlier case, we have seen the anticlockwise. That means, rotor is moving anticlockwise and then after 90 degrees clockwise direction, it will stall. Initially, it is in a anticlockwise and then clockwise. That means, rotor is not rotating symmetrically, it will stall.

So, how to avoid this situation? For that, replace the set 1 magnets, reverse it. We can see in this condition here, case 4. This is case 3 and case 2. In case 4, we can see here, we are just replacing the set 1 magnets.

We are reversing the poles. We can compare from this point as well as this point, case 1 and case 4. Next we are reversing the magnetic poles. Then what happens? Again, opposite poles will attract and same poles will repel. Based on that, rotor will move in this manner. Are you able to observe? In this manner, it is rotating.

That means, anticlockwise. It is rotating in a anticlockwise. So, from case 2 and case 4, we can see that rotor is rotating in a same direction. Then what will happen? In this situation, it will appear case 5. Here again, based on attractions and repulsion, it will rotate and it will attract towards that thing. Again, rotor rotation is in this manner.

Here poles are reversed, set 2 poles. If you will compare from case 2 to case 5, set 2 poles has been reversed. That is why symmetrical rotation in an anticlockwise direction, we are getting. But in a practical system or practical scenario, replacing the magnets and reversing the magnets is not possible. The demagnetization and magnetization of the permanent magnets is a challenging task and it is not possible and reversing of the magnets is also not possible once the mechanical design is done.

So, what to do? Before going to that solution, we will see if we will change the magnetic poles at the rotor side. Here we are changing the poles at the rotor side. Here locking is there, magnetic locking is there. So, to avoid that thing, the rotor poles have been reversed here. Then based on the repulsion here between the similar poles, it will rotate either upward direction or downward direction, depends upon the inertia or dynamics.

If both poles are at the same intensity, then we cannot find what is the direction with respect to the permanent magnetic poles. With respect to the electromagnets, we can find the force direction by utilizing the Fleming's left hand rule. Here based upon the dynamics, if the rotor is slightly in this manner, here north and here south and stator side north and south are there. In this situation, definitely rotor will move upward direction. If the rotor is inclined in this manner, slight disturbance is there, then rotor will move downward direction, here upward and here downward, depends upon the dynamics and depends upon the inertia.

Then rotor will move as per the repulsion, but the challenging with respect to the permanent magnets, we do not have any control and demagnetization and magnetization is a challenging task. We cannot reverse the permanent magnets spontaneously, once the mechanical design is done. What to do? We have to utilize the study 1 and study 2 and study 4, where the control is there with respect to the magnetic poles or magnetic fields. In these studies, we have a control on the magnetic fields. Based on that, we will realize the electrical machines with respect to the attractions and repulsions.

First, I will consider the study 2 to realize the machines. This is the stationary one and this is the rotating one. Consider this is a stator and this is a rotor in a circular manner or a rectangular core. Anything is fine.

Stator will be fixed and rotor is rotating. We will realize the machine from the basic principles. Here we can see at the stator side is this one. Here the field poles, windings are there. Based on that thing, we are generating the magnetic field poles or magnetic fields.

Here B is in this direction. We can see the B is in this direction and we are placing a current carrying conductor in a magnetic field. B field is in this direction and current is coming out. Then what about the force? It will be upward direction that we can see here. It is going upward direction.

Conductor will move upward. Right side in this case, current is going in into the blackboard, where the magnetic fields are in a clockwise direction with respect to this one. Now, what will happen? Apply the Fleming's left hand thumb rule. Current is reversed. That means, what will happen? Force will be downward direction. Fields are in the same direction, but current is reversed.

Then force also will reverse. That force we can see here. It is coming down. Now, instead of a single current carrying conductor, we will consider a coil. Here a coil is there and it is carrying a current. So, current is going in and coming out in this manner.

Here it is cross clockwise magnetic fields. We can see here it is dot anticlockwise magnetic fields. We can see based upon the thumb rule. So, if current is coming out, we can see the anticlockwise and if current is going in, we can see the clockwise direction. So, based on that, these magnetic fields are induced. If we place this coil in the magnetic field, what will happen? We will see now that is in this manner.

We can see here with respect to the left side conductor that is this one. This conductor with respect to this conductor, force is going upwards. That is what we have seen here. Force is going upward with respect to this conductor. With respect to this conductor, force is coming downward direction or if you want to realize the force with respect to the magnetic poles formation, we can see.

So, with respect to the north opposite poles will be attraction and similar poles will be repulsion. Here both north and north will repel each other. Here north and south will attract each other. So, force is in a upward direction based upon the magnetic poles attraction and repulsion also we can find the force here.

That is explained in this figure. Just I replace the rotor with the magnetic poles. This is the coil carrying a current going coming outward and here current going into the blackboard. So, based on that this magnetic field poles are induced one side north and other side south. There is a repulsion and there is a attraction based upon these things it will work. So, force here upward and here downward if we will apply the Fleming's left hand thumb rule.

What will happen? Based upon this thing, the rotor will move in a clockwise direction in this manner and it will align to this position. After 90 degree rotation from this point to 90 degree rotation is happened at that particular condition rotor is aligned with same magnetic locking situation. We can see here opposite poles both sides then it is in a

magnetic locking situation motor will not rotate at that particular location what to do? We can see with respect to the magnetic plot lines also and force equations also with respect to the magnetic field lines north and south and north and south are in a magnetic locking situation. So, we will apply the Fleming's left hand thumb rule here dot right force is upward. There is no mutual interaction of fluxes as well as current carrying conductor then there is no force.

Torque equation we can see here f equals to b i l x sin theta right this is torque.There is no interaction between the current as well as the field lines that is why the torque is 0 at 90 degree position. At 0 degree position here it is 0 degree position right maximum interaction between the current carrying conductor and field lines is happening. We can observe in the earlier slide here field lines are going in this manner and current carrying conductor is there maximum interaction is happening that is why we are seeing the force or torque. We can see here at 0 degree we are seeing the maximum torque at 90 degree torque is 0 and magnetic locking is happening because of that reason torque is 0 or we can say with respect to the Lorentz force law there is no interaction between the b and current.

Because of that reason the torque equals to 0 how to avoid this magnetic locking situation. We can change the current in a coil after reaching this point. After reaching this point we will change the current direction then again attractions and repulsion it will work right. Second condition is change the excitation with respect to the field poles either we can change the excitation at the stator side or we can change the excitation at the rotor side. These are the two possibilities one possibility at the rotor side other possibility at the stator side.

First we will see the rotor side possibility this is the solution one after reaching 90 degrees we will change the current excitation. Here current we can see dot and here cross. So, fields are in this direction with respect to the rotor magnetic locking is happened at 90 degrees. If we will reverse the current direction in the conductors that is blue color one shown here apply a thumb rule and b fields are in this direction now. Based on attractions and repulsions here in between these two poles same poles right repulsion will happen.

Then the conductors at the rotor side will try to move in a same direction with respect to the previous state or we can apply the Fleming's left hand thumb rule and we can find the force. Then at an angle of pi what it is happening this is at this particular position current is not reversed and same current is there in the conductors and fluxes are in this direction and at the north side we can see current is coming out and field lines are going like this manner and force will be in what direction upward direction. Here force will be in upward direction or we can conclude based upon the attractions and repulsions also. Here repulsion is happening here attraction is there then rotor will move in this manner.

Then after 90 degrees what it is happening again torque becomes 0 magnetic locking is happening.

We can observe here between the opposite poles attraction is happened and torque equals to 0. In the other words we can say there is no interaction between the current carrying conductor and magnetic field lines. What to do again we have to reverse the current we can see here current is reversed now at this particular point 3 pi by 2. Then once the current is reversed then magnetic fields are in a opposite direction. Now instead of same poles we are opposite poles we are seeing the same poles here.

Then what it will happen repulsions will happen or based upon the Fleming's left hand rule also we can find the force. Like this way we can see the rotation of the rotor in a symmetrical manner. At an angle of 2 pi it is equivalent of 0. This is the working principle with respect to the realization of a machine where we are exciting a rotor conductors with AC currents and torque is in this manner. Now how to give the this kind of currents or how to change the current exactly at 90 degree intervals how to change the current.

To do that thing we have to utilize the brushes or commutators otherwise by utilizing some power converters. Traditional way brushes and commutators will act as a rectifier it will take a DC and it will convert into AC manner. As of now whatever the machine or working principle we have discussed that is a similar to AC thing we are giving the AC current here. It is a type of AC motor if you will remove the brushes and everything and if you will visualize the DC machine working principle it is a kind of AC motor only. Once if you will place the brushes and commutators and if you will give the DC then it will say as a DC motor we can consider it as a DC motor.

Now we will see how brushes and commutators alignment. Here we can say that two brushes are considered these are the brushes along with the two commutators at exactly at 90 degrees we have to change the current. So, because of that reason at an angle of 90 degrees we have a gap here exactly. So, after rotating the 90 degrees we can see current is reversed here current is going out and here current is coming in. Earlier in this conductor current is coming in. Now, current is started coming in just rotate a few angle like 10 or 20 degrees then automatically it will rotate or automatically current will be reversed at this particular point based upon the brush arrangement.

Here one more problem is torque is discontinuous we can see here torque is coming down to 0 and then it is increasing and then it is coming down to 0. The discontinuous torque we are seeing here how to avoid this discontinuous torque we will see now. So, the brushes are arrangement here placed exactly to change the current direction at 90 degrees. At 0 position one side conductor is seeing the positive and other side conductor

consider negative current it is coming in and going out assume in this manner. After 90 degrees what it will happen is let us consider 100 degrees after crossing the 90 degrees.

Then this brush will come this side and other brush will be there here. So, this is commutator A and commutator B. Now, commutator B will contact this side and commutator A will be in this direction at this side. So, automatically current is reversed here that same picture is shown here, but just before crossing the 90 degrees. If you will cross the 90 degrees let us say 100 degrees then here current will be reversed in this arrangement.

Now, we will see how to get the continuous torque. In order to get the uniform torque or higher magnitude of torque we have to add the multiple coils at the rotor side that we will see now. So, this is coil one placed at the 0 degree reference here current is coming out and here current is going in cross and in the second coil exactly placed at 90 degrees. So, the alignment of the coils at the rotor side like this manner this is coil one and other one is the coil two. Now, we will excite the coil one and coil two with this kind of currents and how the machine will work we will see how to realize the machine we will see now. And commutator segment duration is 90 degrees now because 4 coils or 4 ends are there.

So, the 4 ends will connect to the 4 commutator segments with 90 degree span of the commutator. Now first situation I am considering where only A phase is excited there is no B phase current or coil two current this is coil two and this is coil one coil one is excited and there is no current in coil two. So, based upon the Fleming's left hand rule or induced magnetic fields we can find the force will be in upward direction that is shown in the left side image here force is going upward direction and this side with respect to the right side south pole side force is coming downward direction. The rotor will try to move in this manner upward thing.

Next at 90 degrees what it will happen earlier torque is becomes 0. Now because of the 4 commutator rings or 4 conductors after 45 degrees rotation we are de-energizing the current coil one and we are energizing the coil two or I can say that current in coil one is 0 and current in coil two is high that is what we can see here. Here the transition is happening current in the coil one becomes 0 and current in a coil two is equals to high based upon the commutators alignment. Now based upon the forces we can see here still rotor is rotating in this manner only up to what point it will rotate from this point to this point from this point to this point it will rotate in a same manner that is 90 degree span. From pi by 4 to next 90 degrees we are exciting only coil two that is red color one rotor is rotating in a same fashion at pi by 2 also we are seeing the positive current in a coil two that is a blue color line and it is rotating in a clockwise manner and the respective torque we can see here.

From this point we are changing the excitation to coil two. So the torque in this with respect to the coil two is this one red color one. Now I will start with the same pi by 2 at particular pi by 2 point we are seeing the maximum torque after rotating a 45 degree in this line. After rotating next 45 degrees we will change the excitation to the coil one we are exciting coil one and current in a coil one has to be reversed at this particular point that is what we have seen in the earlier slide. Here current in a coil has to be reversed in order to make the rotation in the same direction rotor has to rotate in a clockwise direction. We are changing the coil one current we can see here highlighted with yellow color coil one current is reversed such that again positive torque we are seeing here that is green color one.

At pi at an angle of pi what it will happen the coil one will reach to this point again it will see the maximum torque. Here the interaction between the current carrying conductor and magnetic field lines is more or high value because of that reason high torque is happening with respect to the magnetic poles attractions and repulsions we can see this side north pole and this side south pole. So, these two poles will repel each other and rotor will try to move in the same direction clockwise manner only. Next at 5 pi by 4 we have to change the excitation to coil two again at this particular point we are changing the excitation of the coil two to get the rotation in the same manner.

If it is if you are not changing what it will happen we will see now. So, this side dot is there this side cross is there as per this alignment as per this alignment this side dot and this side cross what it will happen if we will apply a thumb rule the flux lines are in this direction with respect to the current carrying conductor this side north and this side south poles are forming. So, these two opposite poles will attract each other these two opposite pole also will attract each other then what it will happen the rotation is in this direction opposite. So, this is not valid for us. So, we require the rotation of the rotor in this direction to make this thing we have to reverse the current in this manner I have highlighted here with yellow color. So, current at 5 pi by 4 we are reversing with respect to the coil two then rotor will be in this manner.

Next what it will happen? The same coil is carrying the same current we are not changing anything at 3 pi by 2 we will see the maximum torque that is happening here the force will be upward direction and torque will be maximum based upon the repulsions and attractions of the two fields. Next what it will happen at 3 pi by 2 at an angle of 3 pi by 2 it is same maximum torque we are seeing at this particular point at an angle of 7 pi by 4 torque reached to this point. So, here we have to excite the coil one with reverse current 7 pi by 4 we can see here. So, we are reversing the current here. Then the positive torque we can observe here as a green color one then the rotor will move in a same direction here also in the same direction it is rotating symmetrically in a clockwise direction.

This is the operation of the mission we have realized the mission with respect to the basic magnetic principles. In order to get the continuous torque if we want here still smoother torque what we can do we can add the multiple coils similar to the rectifier. If we have a single phase half wave rectifier what we will get it we will get the output voltage waveform in this manner with only one pulse. If we have a full wave rectifier we will get the two pulse in the output side.

If we have a multi pulse or three phase rectifier then we will see multiple number of pulses. If we will increase the number of phases in a rectifier automatically the output waveform we will see smoother. Same way here if we will increase the number of coils at the rotor side then this torque will be continuous or constant torque we can attain it. Now, solution two we will see this is the principle of DC motor where even though we are seeing the currents in this manner after the commutators this currents are after commutators. If we will see before the commutators like at the supply side DC supply side we are giving the constant current to all windings at the rotor side, but if we will see after the commutators then we can visualize the AC current waveforms that is in this fashion.

The brushes and commutators alignment is acting as a rectifier to get the continuous torque. And again at 5 by 4 duration also we can see how the torque is happening here also it is in a same direction in this manner. This is the working principle of a DC motor. Now, what is the solution two we can change the excitation at the stator side also right these are the stator poles and this is the rotor poles pair right. So, instead of changing the excitations or instead of adding the multiple windings at the rotor side we will change the excitations at the stator side these are the field poles right here also coils we have then we can change the excitation at this particular stator side also right. So, if we can change this thing also to avoid the magnetic locking then we can find the force in a same manner instead of south north here south is this side and north is this side now north south is reversed and this side also north south is there then based on the attractions and repulsion it will work.

So, these two poles will be repel each other and these two poles also will repel each other because of the similar poles. What the challenges here are to supply the rotor side winding or rotating winding we require again brushes arrangement and field windings side we require the variable supply which has to be changed exactly at 90 degrees in order to get the positive torque or the symmetrical rotation. We have to change the current in field winding side that is stator side in exactly at 90 degrees intervals and with respect to the field winding excitations getting continuous torque with multiple coils at the rotor side it is a slight complex task, but it is possible ok. If we will add the multiple windings at the stator side like this is one field pole same kind of field poles we can make the multiple field poles then we can get the smoother torque.

So, this is the working principle of DC machine. So, we have realized the machine from the basic principles of magnetic fields ok. Now, we will see how to avoid the brushes and commutators from the basic principle we have realized the DC machines right. Now, we will see how to avoid the brushes and commutators in the next lecture ok. In this lecture we have discussed the basic principles of a DC motor. In the next lecture we will discuss about the realization of other machines. Thank you.