Fundamentals of Electric Vehicles
Technology and Economics
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Lecture 16
Engineering Considerations - Part 2

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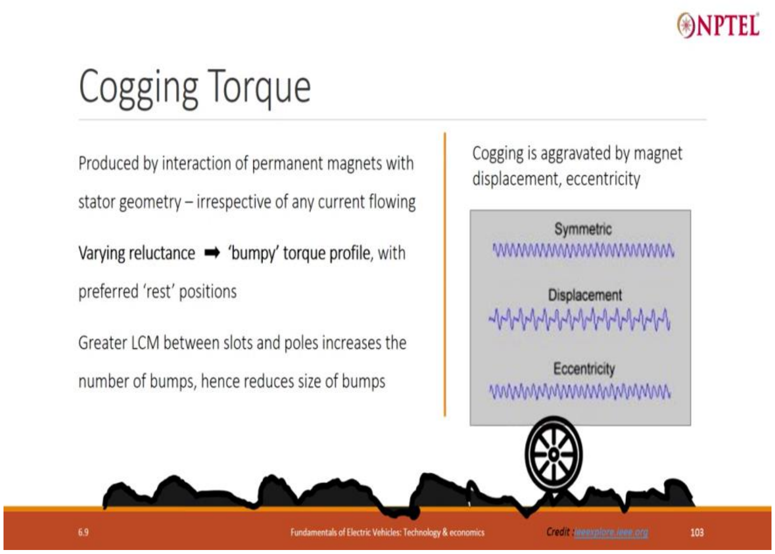

So, we have discussed a number of different practical engineering considerations that we need to bear in mind while designing motors. There are a few more interesting topics in that category which we will go on to cover. The first thing I want to talk about is what is called Cogging Torque and see the rotor has magnets and the magnetic field that is set up around the rotor is not exactly uniform, it will have some ups and downs and in turn it is coming into alignment with different teeth as it rotates.

So, particularly when the motor rotates slowly you will be able to easily feel it very often you may have picked up a motor which has permanent magnets inside it and if you just turn the shafts slowly by hand you will feel a certain graininess in the way it moves. It sort of moves in a jerky, jumpy way and that is called cogging torque and this is because of the varying reluctance profile around the rotor because of the intermittent teeth and slots that are there and in fast running we may not feel it so sensitively but it is never the less there and it gives a certain poor quality of ride in a electric vehicle it gives rise to some vibrations, not a very smooth experience.

In general, when we are designing a motor, if we want to minimize the graininess an easy way to do will be to increase the number of bumps. When we have more number of bumps the size of every bump reduces. You cannot make everything perfectly smooth, so this is the practical way in which we do it and the number of bumps that we get in our rotation is linked to the LCM, Least Common Multiple between the number of poles and number of slots.

Poles means the number of magnets and slots are the spaces between the teeth where the windings happens. So, in general we try to design the motor in such a way that the LCM is maximized and what makes the Cogging worst is that in practical manufacturing there is always some eccentricity between the stator and the rotor and the air gap between the stator and the rotor is typically half a mm to 1 mm, even 1 mm is too large.

So, within that, if I even have a point 1 mm eccentricity I am actually creating a 25 percent difference in the air gap around. So, that asymmetry will further aggravate the Cogging torque. Likewise, the magnets may not be exactly at the position I intended. They may be a little bit displaced in the angular way because of some small manufacturing clearances and these will further aggravate the cogging behavior. So, as you can see in the animation below you feel as if you are going on a bumpy road, although you are not travelling on a bumpy road. That is what cogging does.

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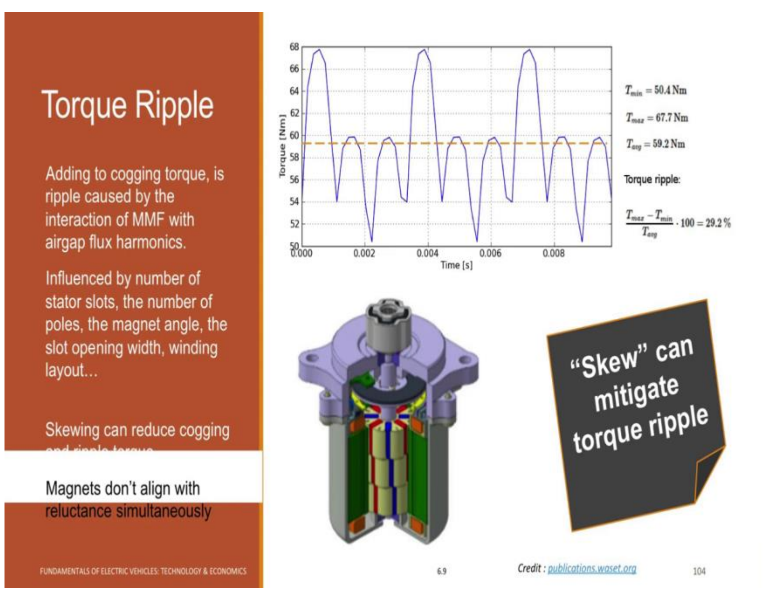

And in addition to cogging torque, cogging is a phenomenon which is entirely because of the magnetic reluctance. You can feel it even if you just turn the motor shaft by hand. No current is flowing but in addition when the current is flowing through the windings the windings cause a magneto motive force, which means they magnetize the teeth and we have seen that the profile of that magnetic field results in what is called the reluctance torque and that also is not very symmetric.

Therefore, when the motor is running under the influence of the current at different angular positions the torque that it delivers is sometimes high, sometimes low. So, what we normally refer when we talk about the torque is the average torque and that average torque is shown here. In this case it is 59.2 newton meter, which is indicated by this dotted line. But actually, the instantaneous torque as the motor rotates is sometimes high. It is as high as 68, 67.7. That is the maximum and sometimes it falls down to as low as 50.4 newton meter.

So normally we express the total Torque Ripple as it is called as a percentage of the average. So, in this particular case the torque ripple is 29.2 percent, which means comparing with the average torque, the ripple is plus or minus 15 percent approximately. So, this also leads to a very jerky and vibrating kind of ride experience. It is not comfortable, it could generate noise and it will also reduce the life of all the joints which are there in the vehicle.

And the behavior of this torque ripple on account of the current flowing is influenced by a large number of detailed factors which are there within the geometry of the motor design. Since we cannot completely avoid it, there is actually a cool trick to reduce it. As we can see here, the rotor is not like a straight cylinder in the sense that the there is one north pole and then there is a south pole going around the cylinder.

That is not the way it looks here. What happens is that here there is a pole which is then offset and then again offset. The entire rotor has been sliced and each successive slice, each successive slice is offset from the next one. As a result, what happens is that let us say as in this picture I have made 3 slices, then each slice is like a mini motor and 3 motors are connected in series, 3 rotors are connected in series and the torque ripple due to each becomes one third. Of course, average will also become one third, the peak and trough will also become one third.

The percentage of torque ripple on account of each slice of motor will not change because both the numerator and the denominator are getting reduced to one third of their original values. But the next slice will not hit the peak at the same time as the first slice. It will do it after a time lag. Likewise, the third one will hit a peak after a further time lag. So, at any given point of time the largest peak I get will be the sum of the peaks occurring at different times and so overall ripple will get suppressed.

Whereas the total average torque will be the sum of the average torque delivered by each of these and that will remain unchanged. So, this idea is called Skewing and by skewing I can reduce the cogging torque as well as the torque ripple due to the windings. And the idea is very simple, you ensure that all the magnets do not align with the reluctance at the same time. They do it with a time offset so this is a very neat and easy trick. It does not cost too much more to impart a skew but it will make the operation a lot smoother.

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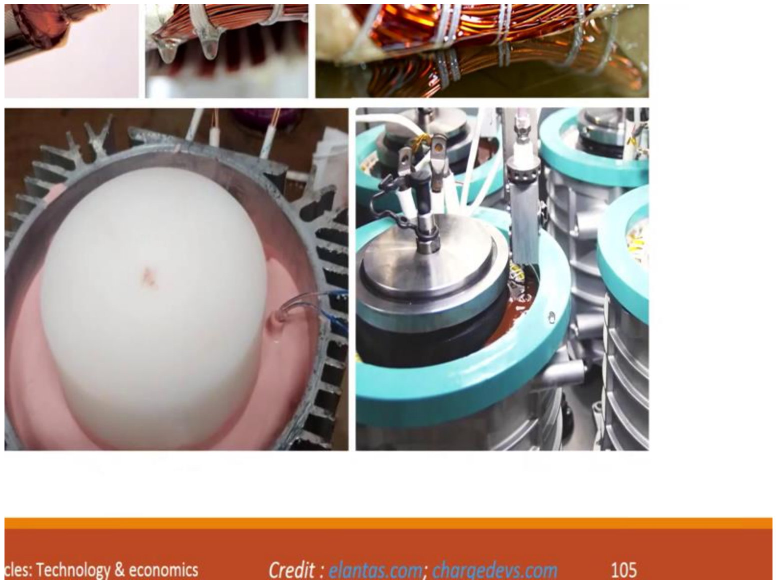

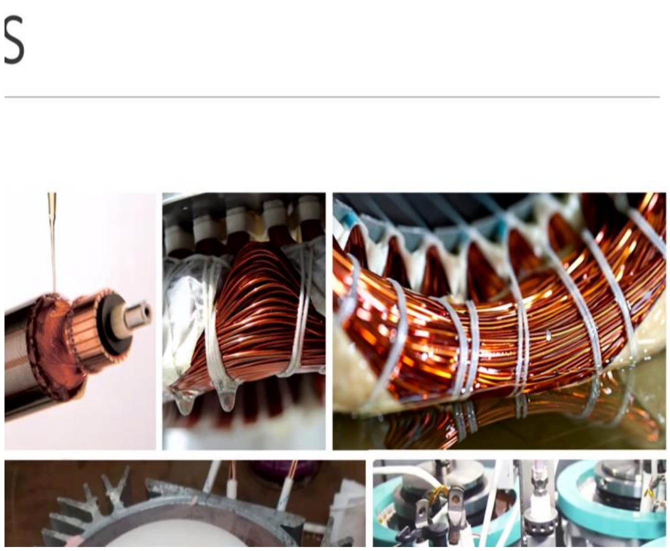

Now, in the motor there are number of places particularly the copper and the steel where heat is generated and this heat has to be evacuated and wherever there is air inside the heat will not be evacuated well because air is a poor conductor. So, we do a number of things to replace the air with some other material which is a better conductor. A conductor of heat but not a conductor of electricity because you must not have conducting materials which will lead to a short-circuit or a earthing problem.

The materials that we look for are those which are electrically insulating, thermally very stable up to fairly high temperatures but are good conductors of heat. So, the gap between the wires in a winding is often filled with what is called varnish which is impregnated. The picture that you see, let me zoom it and show you. This is a kind of equipment where the stator with the windings is soaked and through capillary action the varnish rises up and then when it is baked it sets and you get something like this.

So, the all the air has been replaced by the varnish and this helps in better heat evacuation. Another thing that one can do is what is called Resin potting which covers all the windings. What you see here. It encases all the windings including the overhang of the windings outside the stator in a thermally conducting but temperature-wise insulating enclosure and another advantage of this is that also substantially prevents any moisture that may seep in.

If the IP 67 protection is not very effective if it is worn out after some time and under some heavy submersions condition if some water trickles in, this will ensure that still that water does not get in contact with the wires and the other thing that we do is that at the interface between the stator which is made of steel and the housing which is made of aluminum.

The surface, the curved surface of contact, the stator is made up of laminations and the laminations are stacked. So, if I were to look at the outer surface it will not be very smooth. If this is the stator which is made of number of laminations then this surface will be like this. If I look at it through a lens and then when there is an aluminum housing inside which I insert it, there will be quite a bit of varying air gap, there will be a few points where the steel and the aluminum are in contact and other places where they are not in contact.

This is another place where I need to avoid the air because the air is an insulator. So, we apply what we call a thermal compound which is typically an Epoxy and then if I shrink fit the housing on to the stator after applying the Epoxy then all the air gaps are replaced by Epoxy and this significantly improves the heat evacuation. So, broadly no matter what method we use, the idea is air is a very poor conductor. It’s coefficient of conductivity is just point 03 watts pe meter Kelvin and something like Epoxy would be 100 times a better conductor.

Something like 3 watts which is a 100 times better that air and of course something like copper is close to 600. Steel will be in the order of 250 or 300. So, epoxy is not as good a conductor as metals but considering that the thickness is very little, the fact that it is 100 times better than air actually makes it a very good performer in those context.

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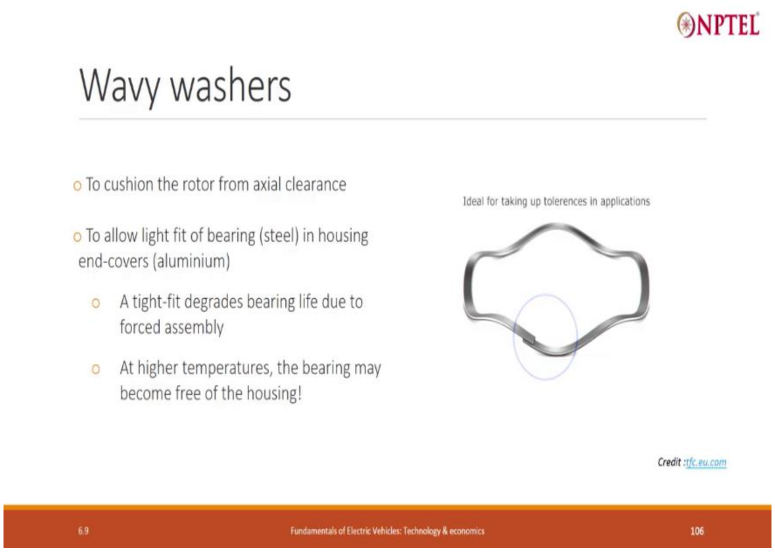

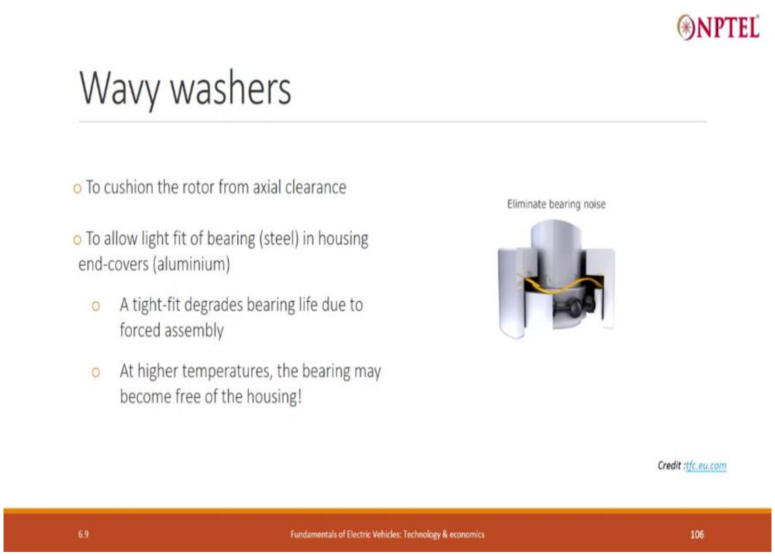

The other important useful thing that we use in our motor, the shaft is assembled onto what are called the end covers where there are bearings but these end covers go into the housing and inside the housing is the shrink-fitted stator so we have these 2 parts which are assembled together and every part that goes into this overall assembly is independently manufactured and anything that is manufactured will not be accurate, there will be some variations which is called tolerance and when a number of these parts are put together and assembled then the total deviation between one part and the other is negotiated in the form of adding up the tolerance of all the parts that makeup assembly resulting in this deviation and that is called stack-up of tolerance and this stack-up of tolerance can be quite high.

So finally, we may find that after we have assembled the motor, the shaft if I push it with my hand has a little bit of play inside the motor. It can move in by an mm. if I pull it, it will come out by an mm. So, this makes for a wobbly kind of motor. I do not want a shaft which is able to travel axially in a loose way without any control or governess.

At the same time if I try to reduce the tolerance on the one hand the manufacturing cost will become too high and on the other hand I may over-correct and then the shaft will simply not be able to move. It is jammed and that is a terrible situation because the motor will not perform at all and finally even if I achieve very perfect manufacturing and assemble everything, during operation when the motor's temperature rises, the housing will expand, the shaft of the rotor will expand but the shaft will expand less because it is made of steel compared to the housing which is made of aluminium.

So, a clearance will develop. So it is unavoidable that there is a clearance eventually. So, to take care of this small axial problem it is very small in magnitude but if we do not do something about it, it will cause rattling and very bad behavior of the motor. So it is small but subtle point and so to cushion the axial movement of the rotor we use something called a wavy washer and the other advantage of the wavy washers that I can have light fit of the bearing on the housing see what happens is when I am assembling the entire motor I will press fit means give a very tight fit between the bearing and the steel shaft of the rotor.

Then when I have to cover-up everything by putting the end covers, the end covers have what are called bearing seats into which the outer diameter of the bearing will sit. But if that fit is tight then I have to beat the whole thing or press it with some high pressure in a hydraulic press to assemble and that will damage the life of the bearing fact the life of the entire motor depends on only one thing.

When we talk about life, provided that we are not operating it out of thermal limits, we have already discussed it. If it becomes more hot than it is designed to then the magnets may get weak and that will be end of life. But if we do not operate outside of the specified designed boundary of a motor, there is only one thing that defines the life. In principle the motor can run forever. Infinite life, the only thing that will loose life and therefore cause the motor to loose it's life, is the bearing.

And the life of a bearing depends on how harshly it is treated during assembly. If I am going to beat it then there itself I have ensured that I have harmed the life of the motor. So, I do not want to give a very tight fit which causes beating of the bearing into the bearing seat. I will want to give a light fit. But when I give a light fit, when the temperature rises the bearing will expand because it is made of steel.

The seat of the bearing will also expand. It is made of aluminum but the seat will expand more that the bearing. So suddenly the bearing will become free of the its seat. It will rotate together with the shaft and abread and that will be far more damaging to the life of the motor. So, the what I want is that I want to hold the outer raise of the bearing with some pressure so that even if the there is a clearance between the bearing seat and the bearing it should not be a free running outer race.

All of these are the roles that are played by the this very simple, humble component called a wavy washer. And so, we have discussed all of this. I will show you a very small animation on how the wavy washer works. So it is located in the axial clearance between the rotor and the stator at the place where the bearing is. On the outer race of the bearing. So, if there is a tendency for axial movement it provides a cushioning action and the restoring force.

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The next topic is something called a Shaft collar. I do not know how many of you have heard it, when I want to restraint something which is mounted on a shaft from moving axially, freely. For example the rotor stack made of laminations is assembled on to the shaft and I there again I do not want to keep a tight fit because the thin laminations. If I tried to beat it or press it they will get bent and damaged. I will keep a free sliding fit and there is a key and a key way to ensure that the shaft and the stack will rotate together.

But there is nothing if I do not do anything else there is a likelihood that the rotor stack made of laminations will slide axially along the shaft and move out of alignment with the stator. So that will lead to a degradation in the performance of the motor. So, to constraint anything axially conventionally what we use is something called a circlip, mechanical engineers in this classroom will be familiar with what the circlip is.

But the circlip comes with the number of advantages disadvantages and the shaft collar is what we prefer to use. The problem with a circlip is that the amount of axial restraining force it can provide is limited and it depends a lot on the fit between the circlip and the groove in which it is supposed to sit and therefore the groove has to be very precisely machined for a correct fit with the circlip.

If the fit becomes loose the circlip will just jump out and if the fit is too tight I cannot even assemble the circlip. It is a messy thing and the other problem is that the groove has to be machined at one location before the entire assembly of the motor starts I have to machine the groove of the shaft and then if there are any manufacturing deviations that groove may be imprecisely located. It would not be located where I want it to be. It may be located too far away from the stack or it may be going inside the stack itself. Then I do not even have access to it. These will come because of the tolerance stack-up.

So, the good thing about the shaft collar is that, since it is the last item to be assembled after all the assembly is over on the rotor, I can simply move it to whatever is the position of the face of the rotor, press it against it and tighten it and it provides a very firm grip.

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The other point I want to talk about is something often overlooked what is called Contact resistance. We design the motor very carefully so that we minimize the winding resistance, keep it of the order of a few milliohms. But what we do not realize is that outside of the winding there is a lot of copper and other conducting materials through which the electricity flows and if we do not pay as much attention to the impact they have we may inadvertently end-up increasing the overall resistance in the system and that will actually reduce the efficiency as well as cause unwanted thermal problems at different places.

So, one of the common areas which is overlooked is what is called the lug which is a metal which is used to hold all the wires together and if you look here there is a lot of air-gap between the wires and there is a lot of air-gap between the wires and the lug. The air-gaps indicate that the area of conduction is actually very much reduced at that place and when the area reduces we already know from what we learnt about resistance row l by a.

If area is very low then at that place the resistance is very high and likewise we in turn put bolts through the holes in the lug to fasten them onto other conducting surfaces in order to then lead them away. Now at all these places where we fasten the area of contact, supposing this plane this thing is not exactly plane, it is slightly concave, then we will make a line contact.

If the nut which I am using to tighten is not perfectly flat, well machined then it will dig-in at some place and have a clearance at some other place. All of these will lead to a significant increase in the resistance. So the bolt nut points are called terminals. Terminal resistance can be very high and then at the crimps and lug again the temperature can be very high and these could also become hotspots apart from reducing the efficiency because a large resistance acting on a very small region where there is very little thermal capacity will lead to a sharp rise in temperature.

And finally, the from the motor you have cables. The motor is normally located at some place under very severe space constraints of the vehicle and then the controller will be located somewhere else where there is space and the battery is positioned somewhere else and you have copper going from the motor to the controller, from the controller to the battery and that length can become very significant and will add to the overall resistance.

This is a kind of way things are often connected. So, you have wires crisscrossing all over the place and although copper is a good conductor when you have a significant length of it, it will all add-up and here we are talking about really milliohms of resistance. So, I may design a motor which gives only 12 milliohms but if I take into account all these other sources of resistance, the overall system resistance may be nearly double. So, we must pay attention to minimizing the resistance of the whole system not just the motor windings.

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