Fundamentals of Electric Vehicles: Technology and Economics
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Lecture - 55
The d-q Equivalent Circuit - Part 2

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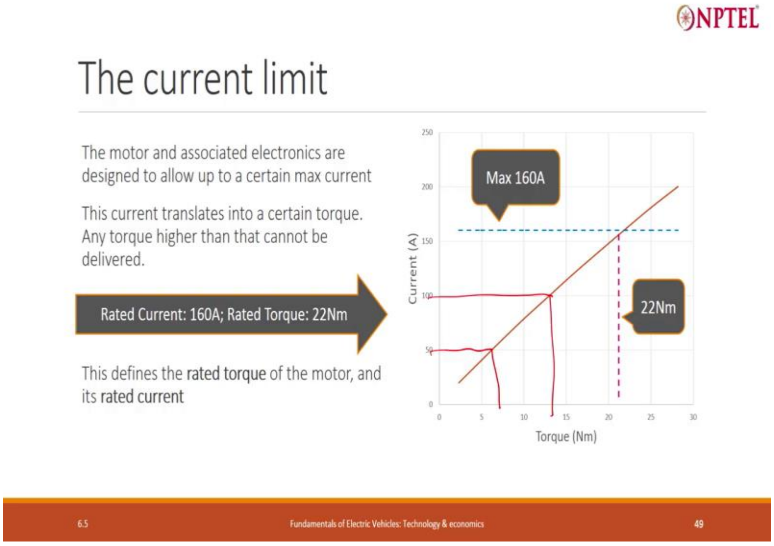

Now, we will come to a couple of very interesting things about the motor, its actual performance. First, just call the current limit, and the second no marks, no marks for guessing is called the voltage limit. And what these two limits do, defines actually the performance of the motor. Let us look at the current limit first. The electronic devices are rated to perform within a certain current limit, the controller.

Likewise, the motor is also rated to perform within a current limit, so that the heat generation is within limits. If the current drawn is more than that, it will cause temperature rise to unacceptable levels, which cannot be then handled. So based on primarily on thermal considerations, the current limit is fixed. Now, I have to operate within the current limit, which means I cannot allow the current to be greater than what that limit is.

If I operate at a very low current, I will get a very low torque. For example, if I apply only 50 amperes of current, I will get a torque like this. If I gradually start increasing the current, I will get more and more torque. I can keep on doing this till I hit the current limit, which is shown by the blue line. And at that time, whatever torque I get is the maximum torque that I can get on continuous basis.

If I increase the current any further, I will get more torque but the temperature will rise beyond acceptable limits. And it will damage both the electronics and the motor. So this is the maximum torque that I can get out of this motor. And that is called the rated torque. And this current limit is called the rated current. So in this example, the rated current is 160 amperes and when I apply 160 amperes, the torque I can get is 22 Newton meters.

And so, this is an important specification of any motor if you, if you are shopping for motors and you ask for datasheets, all the data sheets will give you specifications of the motor. One of the important specification will be this. What is the rated current, which means you cannot allow current more than this to pass. And when you supply that much current, which is allowable, what is the maximum torque that you can get that is called the rated torque. Is this clear? It’s a very important spec of the motor.

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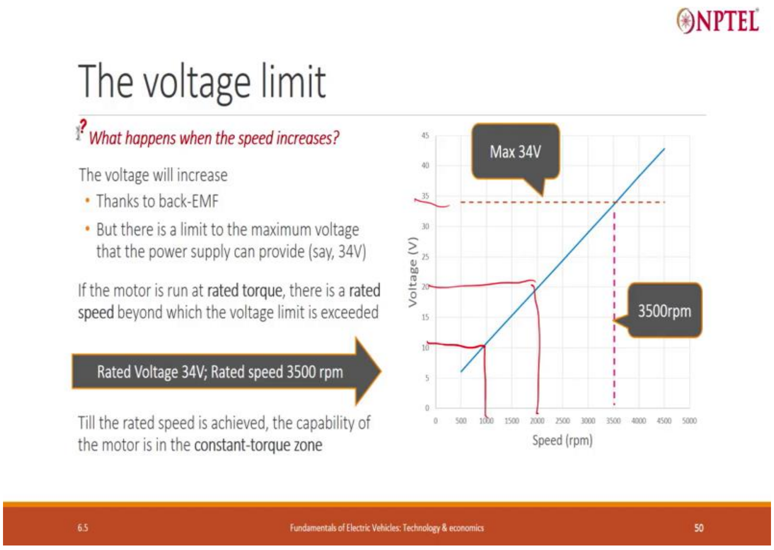

The next limit is what is called the voltage limit. To understand why the voltage limit comes into play, let us try to imagine what happens when the speed increases? When the speed increases, if you recollect the voltage equation, the voltage will increase. Why does the voltage increase? Because when the speed increases, the back emf is proportional to the angular speed. So as I go faster, the back emf is increasing to compensate for it, for which I have to go on increasing the voltage.

But I am drawing the voltage from a battery. There is a certain limit up to which the battery can supply the voltage. Let us say, the battery can supply 100 volts. I can tap into the battery and draw any voltage less than 100. But I cannot draw a voltage greater than 100. So 100 volts becomes the limit that can be supplied by the battery. So in this particular example, the maximum power, maximum voltage that I can draw is kept at lets us say, 34 volts.

Why 34 volts? Why such an odd number? We will look at that later but in this, for now, we will take it that the limit of the maximum voltage that I can apply to the motor is 34 volts. As I keep increasing the speed, the back emf is going on increasing, and therefore, the applied voltage also goes on increasing. When I am running at only 1000 rpm, the voltage is 10 volts, when I am running at 2000 rpm it is 20 volts, and so on.

When I reach a speed like 3500, my voltage has become 34. Beyond this, I cannot increase the voltage, therefore, I cannot achieve a speed higher than this. All of these I am doing when I am supplying 160 amperes. And I am trying to get the full torque of 22 Newton meter, under that condition I am doing this experiment. At the rated torque when I start increasing the speed, there is a limit beyond which I cannot increase the speed.

And when I hit that 34-volt limit, I hit a speed of 3500 rpm. That speed is called the rated speed because that is the maximum speed at which I can also get rated torque. Remember, I am doing all of these experiment with that 22 Newton meter torque by supplying 160 amperes of current. At the rated torque, I cannot get to a speed greater than the rated speed which is 3500. Because the voltage will then hit the limit of 34 volts.

So we say that in this, for this motor, the next important spec I will put on my catalog is that its rated voltage is 34 volts and the rated speed is 3500 rpm. So is this clear? So we have discussed two very fundamental and important characteristics of any motor that we should look for if we shopping for motors. And if we are going to design a motor, these are the two important specs that we should keep in mind. The first spec is the pair defining the rated current and the rated torque. The second spec defines the rated voltage and the rated speed.

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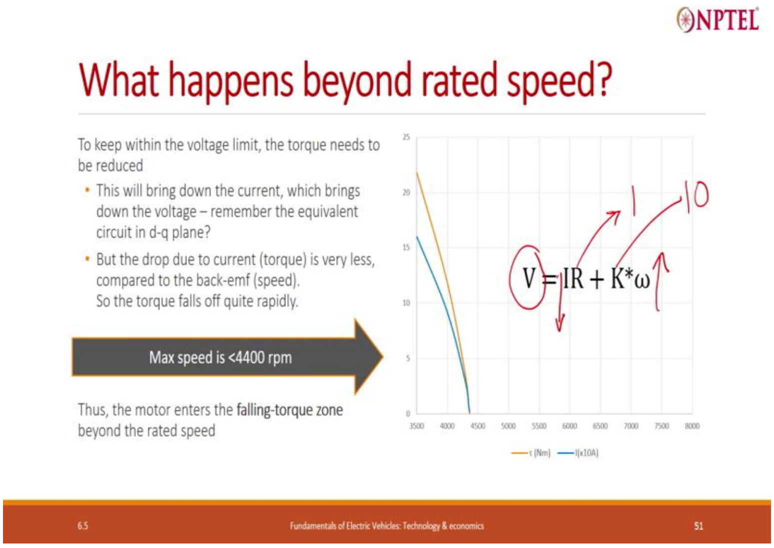

Now, the question is what will happen if I try to go beyond the rated speed. The battery is not going to give me more volts. The only way I can go at a higher speed, remember the voltage equation again. If I reduce the torque, the current will reduce, therefore, the ohmic drop will reduce. Therefore, I can gain some voltage there, I can save some volts by reducing the torque.

The total voltage is the sum of the ohmic drop and the back emf; I am ignoring the transient term. I going at a steady state. So there are two terms. As good designers, we always design the motor with the lowest possible resistance. Let us say, it is 1 in whatever units; 1 ohm, 1 milliohm, whatever; something 1. So that we keep the resistance low which means the losses are low, the heat generation is low, it is a small number.

At the same time, because we want to get good torque which comes from the back emf. We have designed with a significantly higher value of K, which is the back emf constant. Very broadly, I am just trying to give an intuition into this. Now, I have hit the voltage limit of 34 volts, I cannot increase voltage beyond what it is but I want to increase this, increase the omega. I want to go at higher speed what can I do? I can reduce the current.

When I reduce the current, the torque will come down but because this K is such a bigger number compare to R, if I reduce the current by 10, I will increase the omega by 1 that is all I will get. You understand? Because the two terms are weighted differently; R is the very small term compare to K. So for every little bit gain in the speed, I have to dramatically reduce the torque and that is what shown in the orange curve, torque versus speed.

When I try to go beyond 3500 rpm, for every little bit of increase in speed, the torque has to fall drastically. The blue line shows how much the current has to fall. And before I even hit something like 4400 rpm, the torque become 0. It means no further current I can supply. If it is completely frictionless and load is coupled to the motor. It is totally free and running in vacuum then it can run it 4400 with almost zero current.

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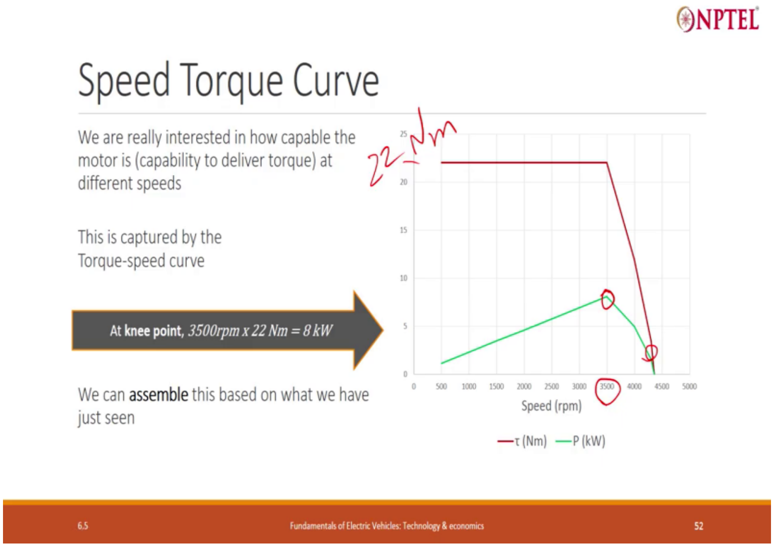

Anyway, we have understood what happens till the rated current and rated voltage limits are hit. And afterwards, if I tried to push the speed ahead, the current keeps falling, and therefore, torque keeps falling. Now, over the entire universe of operation, how does the motor perform? This is called the torque-speed curve. It means at different speeds how much torque can I get is the question.

From whatever just we have just now seen, we can actually assemble the torque-speed curve of the motor, it will look like this. Up to the rated speed of 3500, I can get 22 Newton meters. Why 22 Newton meters? Because that is the torque I get when the rated current, the maximum allowable continuous current is applied. But beyond 3500, the torque I get keeps falling and it becomes 0 even before I can touch 4400 rpm. This is the torque-speed curve of the motor. Very often you will find that motor manufacturers gives the torque-speed curve in their catalogs.

Now, the product of torque and speed is the power. So I can also draw using this the power-speed curve. When torque is constant but the speed increasing, the product of two will uniformly increase. So you see that the green line which is the power is uniformly increasing till the rated speed is reached.

But beyond the rated speed all though the speed is increasing, the torque is falling dramatically and the product of the two, which is the power, keeps falling until when I hit 4400 rpm multiplied by 0 torque the power is 0. So if you look at this, the maximum power is delivered when the current is at a maximum 160 amperes. And the voltage is at a maximum 34 volts. And at that point, the torque is 22 Newton meter and the speed is 3500 and that point is when I get maximum power.

And that maximum power will be the product of 22 Newton meter and 3500 rpm, and if you do the arithmetic you will find that is about 8 kilowatt. It is a very impressively powerful motor, which can deliver 8 kilowatt on a continuous basis. It is a strong motor but the moment I increase the speed by barely 10 percent, it becomes a very weak motor; just falls. Fine?

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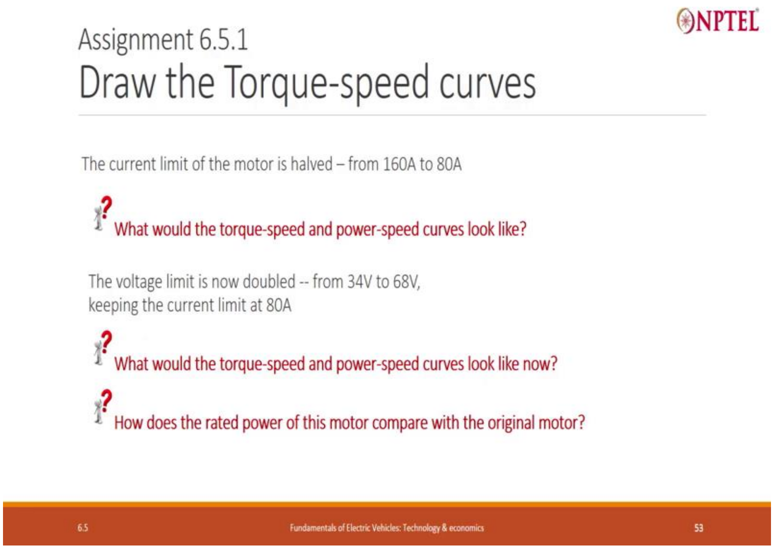

So before we proceed further, here is a assignment for you. I have built this motor and controller that we just now discussed and somebody comes along and says, hey, this controller, the controller you have built is very expensive, I want to use a less expensive controller with components of lower current rating. And he gives in my hand a different controller and says, now you drive the motor, same motor with this controller.

The only condition is that your earlier current limit was 160 amperes but now, the current limit is reduced to 80 amperes.

So now, what will the torque-speed curve look like? You have to figure this out and draw it. And I say, hey, you halve the current, I have got such a powerful motor but you are not feeding it enough current, it is a underutilization of the motor, it will give very little power. So to counter my objection that persons says, okay, I will give you 2 batteries in series, so will get double the voltage.

So he has halved the current limit of my motor but as a compensation, he has given me 2 batteries in series and doubled the voltage that I can apply. He is increased, he has doubled the voltage limit. Can I recover the old performance back or will it be any different, and what will be the rated power of this new motor? The motor is still the same, it is only the controller that is defining the limits but motor controller is a combination.

What will be the peak power of the new motor-controller combination compared to the old and what will be the torque-speed curve of the new motor-controller combination compared to the old? This is what you had to figure out.

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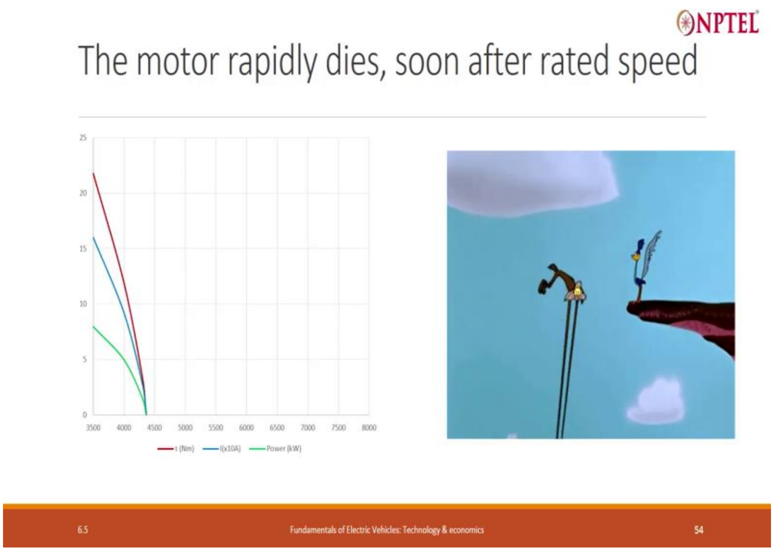

So now, let us go back to what we saw recently about what happens beyond the rated speed? Imagine that I am on a highway and I am going pretty fast. So I am going at the close to the maximum speed that is possible and there is one car ahead of me. I want to just overtake and get past him so that I can then continue to travel at my speed. For that short period, I have to increase my speed a little bit for a short period. There is truck coming in the opposite direction but it is quite far away, I have enough time.

But what I am not realizing is that I am actually close to the rated speed of the motor. So the moment I turn up the throttle on my bike, I am trying to accelerate but the torque capability just falls dramatically. And I am left struggling, the vehicle is gasping for breath not going forward. And meanwhile, the truck which was far away is no longer very far. This is a, an acceptable situation. So for a short period, I need to be able to push up the performance and how can I do it?

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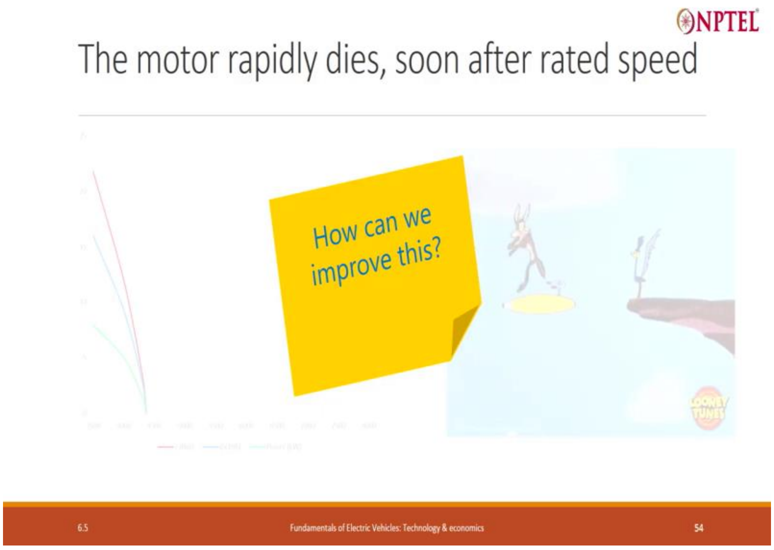

For this, we need to reflect a moment on why I am not able to go faster.

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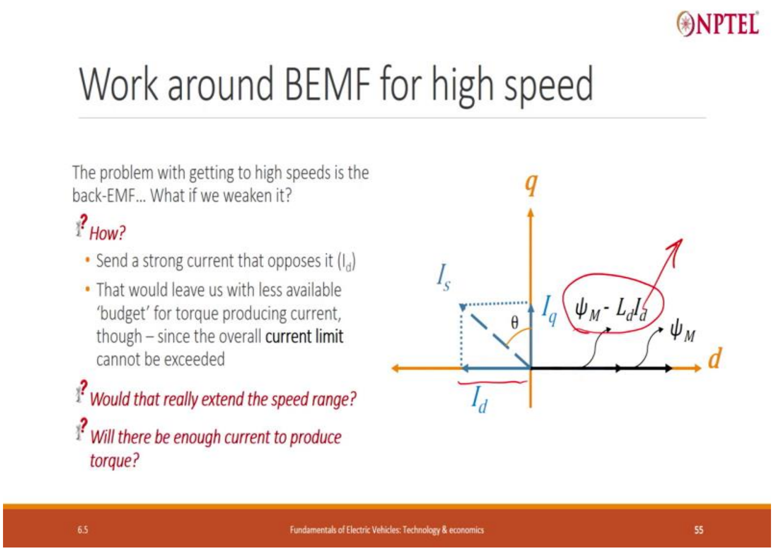

We all know, that is because of the back emf and we had kept a fairly high back emf because that will give us good torque. But the same back emf, which enabled us to get good torque in normal circumstances, when I hit pass the rated speed becomes my enemy and causes the torque to fall down. So in that regime where I am trying to operate beyond the rated speed, can I reduce the back emf? And if you recollect, the back emf comes from two components Vd and Vq. And they in turn come from change in flux.

And the change in flux is very strong in the d direction. Because a permanent magnets are very strong. The flux in the q direction is coming only from the q-axis current. But in the d-axis, you have a very strong permanent magnet. We like a very strong permanent magnet because it contributes B, I, A, and all that we have gone through.

It is giving us a very good torque but here, the problem is it is giving me very high back emf. So I want to temporarily weaken the magnets so that back emf comes down. And if you recollect our discussion earlier about phase angle and empty P A and all that, the d-axis current is creating a flux which is opposite to that of the magnet. You can say that it, d-axis is pointing on the leftward direction. So the net flux along the d-axis is Psi M minus Ld Id.

So one way in which I can reduce this will be by increasing this. If I increase the Id the, d-axis current, then this overall term will decrease. And that is why you see that the d component is much larger, and therefore, the angle theta is also very large.

This idea of supplying a large extra component of Id to weaken the magnetic field so that I gain the voltage needed to go faster, this idea behind what is called flux weakening. We will look at it in little bit more detail, but what I want you to appreciate before that is that there is also a current limit operating. I am not trying to operate close to the current limit because when I am going very fast, I am not trying overcome some load or go uphill or things like that. So I do not require the full current. I have a lot of surplus current left with me I can afford to spend it on the Id.

But the more I spend on the Id, the less current I will be left with to spend on Iq which is what is mainly creating the torque. So it is a tricky situation. I am reducing the available Iq by spending more on Id so that I remain within the current limit but I think that will help me get more torque. So will this, how will this really work out? So the tricky question and we have to explore it.

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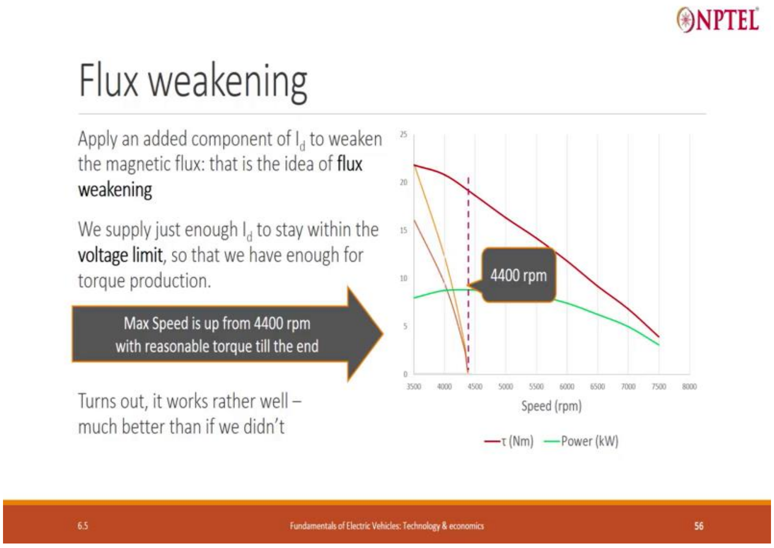

But this is the idea behind what is called flux weakening. That we apply an added component of Id over and above what empty P A algorithm tells us and use that extra Id to further weaken the magnet so that the back emf comes down we gain enough headroom on the voltage to be able to increase the speed further. So we do not want to waste the total current that is available. We have apply just enough extra Id that is required to sufficiently weaken the magnet so that I still have as much Iq available within the current limit.

And we plug this, this how it is. What you see on the left is the graph that we earlier saw without flux weakening. And after we do flux weakening, we find that the torque is falling of much more gradually, and therefore, the power also drooping off much more gradually. And instead of falling to 0 torque at 4400 rpm, we can actually go up to 7500 rpm and beyond and still have some torque left. So there is a tremendous improvement in performance.

Is this fine? So just we have starting with two very simple concepts. There is a current limit and there is a voltage limit. We were able to find what is the rated torque, what is the rated speed, and then, if we want to push the boundary beyond the rated speed, how do you achieve it? Through this trick called flux weakening? Is there any question so far? Let me know.