Course Name: Design of Electric Motors

Professor Name: Dr. Prathap Reddy B

Department Name: Electronic Systems Engineering

Institute Name: Indian Institute of Science Bengaluru

Week: 10

Lecture: 54

Title: The Figure of Merits for SRM and Example Problem on Output Power Equation in terms of D^2L Product

Greetings to all. In this lecture, we will discuss the torque equation with respect to the switched reluctance machine sizing equation with respect to volume. Then, we will discuss some example to find the bore diameter as well as length of the core for a switched reluctance machine. Let us consider the power equation, what we have derived in the last lecture that is output power in terms of volume and magnetic loading and electric loading and speed of the rotor and some constant terms we can see. This is the final equation. The mechanical torque developed by the machine is nothing but T e.

T e is equal to in terms of output power P naught is equal to 2 pi N r into T e divided by 60. So, from these two equations, if we equate these two equations, then the torque developed by the machine is equal to pi by 4 into 1 minus 1 by sigma u and sigma s. This is inductance ratio, ratios product into efficiency duty cycle, then magnetic loading into electric loading into volume product. Here, rotor speed term will not come because speed in both equations will cancel each other and this is the final torque equation with respect to the volume product.

So, from this equation, we can analyze that or we can observe that torque is directly proportional to the magnetic loading as well as electric loading similar to the output power and also the volume product d square l e and efficiency and duty cycle. So, the torque developed by the machine is not only depending upon the with respect to the electrical quantity, torque is related to the torque is equals to I square by 2 into d l by d theta, right. The change in inductance with respect to the angular angle, change in inductance with respect to the rotor position and current. So, from the sizing equations, we can conclude that torque equation is also depending upon the flux density or magnetic loading with respect to the iron and electric loading with respect to the copper and volume product. So, we have to select these quantities appropriately to design the machine and we will see the range of the magnetic flux density and electric loading and the value of duty cycle.

We will select some suitable numbers and we will solve some examples at the end of this lecture. In order to compare in the earlier lectures, we have designed the induction machine. Now, we are designing the switched reluctance machine. In order to compare the different type of machines with respect to the output power, what are the figure of merits we have to consider means, first one is power density. Power density is nothing but power per unit volume.

This volume is with respect to the outer diameter D square into l e or if you are representing with respect to the inner diameter, we have to mention power density with respect to the bore volume. Generally, in most of the literatures and in the data sheets, we will see the power density with respect to the outer diameter of the stator, where volume is equals to D square into l e. Second parameter is torque density. First one is power density. Second one is torque density that is output torque t e divided by volume.

So, here also, volume is with respect to the outer diameter and length of the core. In terms of outer diameter and length, we have to represent. This is second parameter that is torque density. Third one is power to weight ratio or torque to weight ratio also, we have to consider. Power to weight ratio is nothing but output power with respect to the total weight of the machine.

That is nothing but another figure of merit parameter to compare the different machines, similar to the induction machine here also. Newton power is nothing but kilowatt per kg. Here weight is nothing but total weight including the copper, iron, frame, shaft, all parts of the machine, we have to consider. Complete machine weight, we have to represent here and then, we will get the power to weight ratio. That means, how much kilowatt we can generate for a kg or per kg weight.

Next one is torque to weight ratio. Torque to weight ratio is nothing but the developed torque by the machine with respect to the total weight of the machine. That is Newton meter per kg. It will represent the how much torque we are generating with respect to per kg weight.

The last parameter is shear stress, magnetic shear stress.

That is lambda m, magnetic shear stress, similar to the induction motor. It is flux density at the air gap, rms value and electric loading rms value. So, generally, we have, if you want to represent with respect to the peak, then it is Bg peak value into El peak value divided by 2. Whatever the power equation and torque equation we have derived, that equation, in that equation, this Bg value and El value are the peak values. These are the peak values.

So, if you will represent this equation in terms of magnetic shear stress, then efficiency into d duty cycle into the remaining constants will be as it is. Then 1 minus 1 by the inductance ratio times product into 2 into sigma m into volume product into speed. This is the power equation with respect to the magnetic shear stress. So, with respect to the magnetic shear stress, we can compare the different type of machines. So, this is equation number 18, 19, then it is 20, 21 and this is 22.

Finally, this is 23 and same way, we can write the torque equation in terms of shear stress, that is, pi by 4 into 1 minus 1 by the inductance ratio times product into efficiency into d into 2 sigma m D s square into l e. This is volume product. So, torque equation also, we have represented with respect to the magnetic shear stress. From these two equations, we can compare the different type of machines and top of these things, other four performance parameters like power density, torque density, power to weight ratio and torque to weight ratio also, we can consider to compare the different type of machines and other variable like cost also, we can consider. Cost depends upon the various aspects with respect to the performance parameters.

These five, we have to consider. The cost of the machine depends upon the application, depends upon the requirements. Next, in order to find the inner diameter of the stator or bore diameter and l e is nothing, but stator core length. At the end, power is equals to some number into volume product, we will get it, but how to decouple this volume product D square l e turns and then, we can find the inner diameter of the stator and length of the core. For this thing, we have to consider the aspect ratio similar to the induction machines length equal to diameter of the inner diameter of the stator that will give the aspect ratio.

If you will represent with k, then k value for low power applications and nano servo applications, it will be in the range of 0.25 to 0.7. These are the empirical relations and numbers with respect to the literature and different iterative procedures and k value for high power applications, it should be in the range of 1 to 3. So, by selecting different k value and we can try to analyze the power equation and decouple the inner diameter of the stator and length of the core.

In an iterative manner, we can change the D and l values. If the length of the core is long for let us say, for some applications like submersible pumps, length should be more and diameter should be less. At that time, the l by D ratio, we can select more and if length required small and diameter requires more with respect to the application requirement, then k value we have to select less than 1. If k is greater than 1 or higher value at that time, l e value will be higher. Here, l e value will be smaller.

Now, we will consider some example and then, we will decouple and we will realize the outer diameter and inner diameter of the stator as well as length of the stator core. Let us consider 6 by 4 pole SRM and it is a 3 phase structure and power rating is 1 HP. That means, 0.7457 kilowatt and speed N r is equals to 1000 rpm and find the inner diameter of the stator and length of the core. From inner diameter of the stator, if we know the slot or pole height that is dss and back iron thickness or back iron depth, then we can find the outer diameter also.

In this example, we will focus only on the inner diameter of the stator and length of the core. Now, consider the power equation, whatever we have derived that is this one. In this power equation, efficiency we have to assume that is 0.98 and duty cycle also we have to assume duty cycle is equals to 0.9. If it is equals to 1 duty cycle, then we will get the maximum output power and it is less than or equals to 1. So, I am considering 0.9. It is just iterative process. We have to consider the different parameters as assumed values and this is constant anyhow and this term 1 minus 1 by sigma u and sigma s, this inductance ratio terms I am representing with k 2, one more parameter.

This k 2 should be in the range of 0.65 to 0.75. These numbers I am considering with respect to the literatures and iterative process. Empirically, we are selecting the range of these quantities.I am considering here k 2 is equals to 0.65. Then, flux density at the air gap, consider 0.8 tesla. It should be in the range of 0.7 to 1.2 tesla. So, I am considering 0.8 tesla and electric loading E l should be 25000 to 90000 ampere turns per meter. So, for this example, consider 50000 ampere turns per meter.

So, this term we have to calculate and speed of the rotor, we know that is 1000 rpm. So, all quantities we know from here. Some assumptions are there. First assumption is efficiency. The second assumption is duty cycle and inductance ratio product terms and flux density at the air gap and electric loading.

All these values we are selecting as an assumption for first iteration. At the end of the design, if it is matching with respect to the requirement, then we can go ahead with these assumptions. At the end of design, we are unable to get 98 percent efficiency. Then, we have to change the efficiency and we have to change the numbers with respect to the volume accordingly. So, from this equation and the assumed values, the power with respect to the given value 0.7457 kilowatt is equals to D square D i square into le volume product into 2.0945 into 10 power 6. We will get and volume product is equals to 3.5604 into 10 power minus 4 meter cube.

This is a volume term. That is why meter cube will come and power in that I considered here into 10 power 3. I mentioned 0.7457 kilowatt means into 10 power 3 and remaining terms we can see here. Now, assume or consider the aspect ratio l e by D i s is equals to 0.6. That means, length of the core is equals to 0.6 times the inner diameter of the stator. Substitute this aspect ratio in the above equation. Then, inner diameter of the stator cube is equals to 3.56 by 0.6 into 10 power minus 4 meter cube. Take the cube root and we can find the inner diameter of the stator is equals to cube root of 5.934 into 10 power minus 4. This will give 0.084 meter. That means, inner diameter of the stator is equals to 84 mm millimeter.

From here, length of the stator core is equals to 0.6 times the inner diameter of the stator. This will give 50.4 mm. We can see here le is less than the D i s, inner diameter of the stator. Here, the diameter is more as compared to the length of the core. If requires, let us say for a given application, length should be more as compared to the inner diameter of the stator at that situation or at that condition, we have to change this aspect ratio l by D ratio to greater than 1. In that condition, we can get le is greater than the inner diameter of the stator. Like this way, we can decouple the D square l product and we can find the inner diameter of the stator as well as length of the core.

We can see the machine. This is the machine. The length we have calculated and inner diameter of the stator that is D i s. So, the total volume with respect to the bore diameter or air gap, we have calculated. If we will define or if we will assume the slot depth and back iron depth, then we can find the volume with respect to the outer diameter also with respect to this number. But in most of the applications and practical machines design, we will consider the volume product with respect to the D square into le, where D is nothing but inner diameter of the stator or bore diameter of the machine.

With this, I am concluding this lecture. In this lecture, we have discussed the figure of merit parameters like torque to weight ratio, torque to torque density, power to weight ratio and power density and shears magnetic shear stress and some example to decouple the D and l values like bore diameter how to calculate and length of the core how to calculate. Thank you.