Course Name: Design of Electric Motors

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Title: Design of Switched Reluctance Machine: Stator Design -1

Greetings to all. In the last lecture, we have discussed the sizing equations to find the volume of a machine. In this lecture, we will see the design equations for stator as well as for rotor of switched reluctance machine. Let us consider the switched reluctance machine having an outer diameter D naught s and inner diameter Di s and length of air gap is l g. Here, length of air gap is l g and pole height with respect to the stator is d s s. It should be s pole height with respect to the stator is d s s and pole height with respect to the rotor is d s r and inner diameter of the stator is d s s and pole width with respect to the stator is wsp and pole width with respect to the rotor is wsrp and back iron thickness of the stator is dcs and height of the coil is stator winding coil is hc and height of width of the stator coil is wc and angle with respect to the stator pole arc is nothing but beta s and rotor pole arc is nothing but beta r with respect to the rotor pole arc.

It will be beta r for stator pole. It will be beta s and inner diameter of the rotor is nothing but shaft diameter that is Dir and outer diameter of the rotor is nothing but D naught r. D naught r is equals to D i s minus 2 l g, 2 times the length of air gap. First, we will design the stator like how to find the slot height, this one or pole height and slot area, this region slot area to place the coils and back iron thickness and height of the coil and width of the coil and how to select the number of turns and what is the wire gauge.

All those things we will discuss with respect to the stator design. Then, rotor design also we will discuss. First, with respect to the winding, how many number of turns we have to select per phase. From the voltage equation with respect to the last lecture, V phase is equals to omega m that is angular speed into number of turns per phase flux density at the air gap peak value D i s that is inner diameter of the stator by 2 into l e into 1 minus 1 by the inductance ratio terms product. So, this is the equation we have derived already.

So, from this equation, N phase is equals to V phase divided by V phase peak value omega m into Bg D i s by 2, the same equation I am rewriting it here, sigma u into sigma s. So, here we know the voltage with respect to the peak value, phase voltage peak value and flux density with respect to the air gap and rotor speed, length of the core and outer inner diameter of the stator. This term, the inductance ratios product term that is k 2 also we know. So, based upon that thing, we can calculate the number of turns per phase. It is always directly related to the voltage applied.

So, number of turns we can calculate with respect to this equation. Here, k 2 we can select in the range of 0.75, 0.65 to 0.75. In other method, like from the electric loading, El is equals to ampere conductors per unit length, right. That is 2 m is nothing but number of phases conducting simultaneously into N phase, i phase peak divided by pi into Dis. From this equation also, we can find the number of turns, either this one or this one. With any equation, we can find the number of turns for a stator winding.

Next, how to calculate the i phase peak current with respect to the winding? That is nothing but from the input power equation divided by number of phases conducting simultaneously into voltage into duty cycle.

This equation will give the stator current. Once we know the stator phase current, we can calculate the cross sectional area of the conductors by utilizing the equation i phase rms divided by current density. So, we have to convert i phase peak to i phase rms, convert it and substitute in this equation. Then, we will get the cross sectional area of the wire. This is equation number 4.

Here, J is nothing but current density. Current density with respect to the copper or whatever, it may be the aluminum, whatever with respect to the winding type, we have to select the current density. So, it is in the range of 3 to 5, 10 power 6 ampere per meter square. Next, how to select the number of phases? We have discussed the equations related to the number of turns per phase and current flowing through the each phase and cross sectional area of the winding. Next, number of phases.

I am representing the number of phases. How to select the number of phases in a switched reluctance machine? We have to select the number of phases depends upon the power or torque density. If multiple phases are there, the power per phase or torque per phase will come down, but if the torque generated or torque developed by the machine is happening with respect to only one phase, one phase is conducting at a time and it is generating the torque means, the multi phase machine will not help and it will only reduce the torque ripple. Torque ripple will improve with respect to the higher number of phases, but if you are exciting each one phase simultaneously, then the torque per phase or power per phase will not come down and current flowing through the winding is same. For example, 4 phases are there in a machine or other machine having a 3 phases.

Current flowing through the winding is same. In that situation, the losses will be same under the condition where the winding resistance is same. If the number of phases are increasing with respect to the power rating, then losses for a given current and the resistance of the winding is not changing, then losses with respect to the multi phases machine will increase and efficiency will come down. If the winding resistance and current is not same, then the losses may come down and efficiency will increase. So, with respect to the losses also, we have to select the number of phases.

The next thing is fault tolerant capability. So, if one or two phases becoming faulty, if requires higher fault tolerant capability, we have to go with higher number of phases. With 2 phase machine or 3 phase machine, if one or two phases becoming faulty, the machine will be unable to start or unable to rotate. So, in order to make higher fault tolerant, we have to select the higher number of phases. Next thing will be starting capability.

This is the important parameters like if we will consider only single phase SRM, where only one pole at the stator side pole pair at the stator side is there. If once the rotor will come and aligned with respect to this pole means, then it is unable to rotate. It will be in the magnetic locking. So, in order to make the symmetrical rotation, we have to select the higher number of phases like 2 phases or 3 phase in this fashion. So, with respect to the starting capability also, we have to select the number of phases and then cost with respect to the inverter or power converter.

The number of switches and drivers will increase under the condition that where the current and voltage of the switch is same. Let us say one machine is designed with 3 phase and other machine is designed with 4 phase. The voltage rating and current ratings are same and power rating is also same means in that condition, the cost may increase, but the voltage and current ratings of the switches are coming down and the number of switches are going up means the slight compromise between the two systems will be there. For example, here 100 volts and 50 amperes which we are utilizing here 100 volts and 100 amperes which we are utilizing means even though here, the number of switches are increased by 2, the cost will be compromised in between. So, we have to select the number of phases depends upon the cost also.

After selecting the number of phases with respect to all these aspects, next we have to select the number of poles with respect to the stator. The number of poles with respect to the stator, we have to select as per the standards like stator and rotor and 6 by 4 combination and 8 by 6 and 12 by 8 and 12 by 10 or 16 by 12 or 16 by 10 etcetera. The stator side number of poles should be higher to make the symmetrical rotation, but lesser number of poles also can be possible. There the torque repel and other limitations we have to address accordingly. As per the standards, we can see the stator number of poles and rotor number of poles with respect to this thing.

We have to select the number of poles with respect to the stator and the stator poles depends upon the cost also. In order to select the number of poles, we have to consider the cost higher number of poles are there, higher cost will be there because winding placement and complexity will increase and terminal cost also will increase and higher number of semiconductor devices will come accordingly. So, we have to consider the appropriate number of poles to minimize the cost also and the always the stator poles to rotor poles that is n p s. We can say poles at the stator side, poles at the rotor side should be a non-integer fraction should come always. If it is integer, then we will see the magnetic locking kind of thing and the torque repel will be very high.

So, we have to select the pole ratio from stator to rotor as a non-integer. Next, we will discuss the how to find the slot or a pole height and pole depth. We will analyze the flux densities at the different parts of the iron. Let us say the flux density at the back iron part is nothing but Bcs. Flux density in the pole region is nothing but Bsp and flux density at the air gap region is nothing but B g.

Here, we can see Bsp and here Bcs. We will analyze, we will find these three flux densities at the various parts of the machine and we will find the height of the slot or pole that is dsr and width of the back iron that is dcs To find the width of the stator pole that is wsp, width of the stator pole is nothing but this one. We know the angle that is beta s. The angle with respect to the stator pole arc is nothing but beta s and this length is nothing but wsp and if we will create or if we will assume half section with respect to the right angle triangle here and sine beta s by 2 is equals to width of the stator pole divided by 2 divided by this diagonal is nothing but D i s by 2 that is inner diameter of the stator divided by 2 or radius I can say. This will give the width of the stator pole is equals to D i s into sine beta s by 2.

This is equation number 5. If we know the angle with respect to the stator pole arc that is beta s, then we can find the width of the stator pole with respect to this equation. If you do not know the angle or if you want to find the width of the stator pole by utilizing the flux densities at the various parts of the iron, then we have to analyze the flux densities per pole. The flux density per pole with respect to the air gap phi g peak is equals to flux. It is the flux value and we are calculating the flux density value that is B g peak into A g and this is the rotor pole and here flux lines are flowing in this direction and we are calculating the area perpendicular to this thing that is A g. It is equals to Bg peak into Ag is nothing, but arc length that is beta s into D i s by 2 into y axis length is nothing, but le into ks.

So, this side length is nothing, but l e into k s is the stacking factor, steel stacking factor and this arc length we are calculating with respect to the beta s. Here also beta s requirement is there into Dis by 2. This is the angle into radius. Beta into r will give the arc length, right. So, arc length into y axis length with respect to the core will give the area.

So, this is phi g peak flux at the air gap. Next flux at the stator pole phi s p is equals to phi b s p peak flux density at the stator pole peak into area with respect to the stator pole. Here flux lines are coming in this direction. So, with respect to this thing, what is the area? So, this length we know that is wsp and y axis length is nothing, but le into k s. So, directly we can write the flux with respect to the stator pole peak value is equals to Bsp peak into wsp that is x axis length into y axis length le into ks.

This is equation number 6 and equation number 7. Finally, the flux with respect to the core flux at the back iron. Back iron, if we will see in this image, the flux whatever it is coming and it is splitting into two parts, right. This is the flux at the back iron and flux density at the back iron will be Bcs. So, flux whatever the flux is coming with respect to the one stator pole is dividing into two parts.

So, with respect to that thing, phi c s by 2 is equals to flux density at the back iron Bcs into the area is nothing, but dcs is the thickness of the back iron into le into ks is the y axis length stator core length. So, this will give the area Bcs into Acs. So, from this equation, we can find the flux at the back iron equation number 8.

So, from equation number 6 and equation number 7 and equation number 8, if we will assume flux value is same, that is phi g peak is equals to phi c s peak is equals to phi s p peak. With respect to this relation, here do not confuse here with respect to the flux flowing through the core.

I am considering as half, then that will be equals to phi c s is equals to 2 into Bcs into dcs into le ks. So, this phi c s I am considering here phi c s peak value. So, from equation number 6, 7 and 8, we can find the ratios like phi g peak divided by flux at the stator pole peak value, flux at the air gap peak value to flux at the stator pole peak value is nothing, but half Bg into beta s D i s. I am just substituting that equation 6 and 7 here, le into ks divided by the flux with respect to the stator pole is nothing, but Bsp into wsp width of the stator pole into length of the stator core. From this equation, we can get the value width of the stator pole is equals to this value is equals to 1, width of the stator pole is nothing, but half of the Bg peak value divided by Bs flux density at the stator pole peak value ratio into these two terms also will cancel beta s into Dis.

So, this is the final equation for stator pole width. So, the stator pole width we can calculate by this equation or by utilizing the equation number 5, either this one or equation number 9, we can calculate the stator pole width. Next, from equation number 6 and 8, take the ratio here also. Then ratio with respect to the flux at the air gap to the flux at the back iron is equals to 1 that is equals to half of the Bg flux density at the air gap peak value beta s into Dis into le into ks that is equation with respect to the equation number 6 and with respect to the equation number 8, 2 into dcs into depth or thickness of the back iron into length of the core and stacking factor. So, from this equation, we can get the final equation for finding thickness or width of the back iron dcs is equals to 1 by 4 Bg peak value divided by flux density at the back iron peak value into beta s into Dis So, from this equation, we can find the thickness or depth of the back iron.

This value we can find that is dcs. So, this value we have calculated based upon the flux densities at the air gap and flux density at the back iron of the stator. Generally, the back iron width or back iron depth dcs is equals to 0.5 times the stator pole width and dcs less than 0.5 to 1. It is in the ratio with respect to the stator pole width.

We can define the back iron width that is dcs should be in the range of with respect to this equation empirical relation. Once after calculating the dcs with respect to this equation, we can verify with respect to the empirical relation, but this equation will give the exact width with respect to the stator back iron or directly also we can consider with respect to this empirical relation. In most of the cases, the dcs will lie in this range 0.5 to 1 ratio of stator pole width. The flux densities at the different parts of the iron, we have to consider Bg peak value is in the range of 0.7 to 1.2 tesla and with respect to the stator poles depends upon the magnetic material. It will vary 1 to 2 tesla and back iron Bcs peak value 1 to 1.8 tesla because the area with respect to the stator pole is less because of that reason. We can see here flux density peak value with respect to the stator value is more as compared to the flux density at the back iron. Next, we will analyze the slot area of the stator.

So, how much area is there to place the conductors? This is the stator pole height will be dss and back iron width or depth will be height will be dcs back iron width and this is the slot area to place the conductors. In order to find the area of this slot, assume this slot is in this fashion as a symmetrical trapezoid and this height will be dss and width will be w2s at the top side, w1s at the bottom side. Then, area of slot is equals to mean width of the trapezoid that is w1s and w2s divided by 2 into dss height of the slot. We can find by making rectangle and by subtracting this triangle portions also or directly we can consider the area of the slot in this fashion w1s plus w2 divided by 2 that is mean width with respect to the slot and height of the stator slot or pole height. This portion, the curvature portion I am neglecting this radius will be some r from here to here it will be d s s from here to here it is d c s.

So, directly I am considering d s s is the slot height and the perimeter equation with respect to the w 1 s. The perimeter equation with respect to the w 1 s is nothing but number of poles into w 1 s plus arc length of this one that is w arc length is equals to pi into d s s right. So, this is one circle we can see the inner circle here. So, with respect to this circle the perimeter will be pi into d s s. So, this pi d s is equals to number of poles into w 1 s plus arc length is this one will give the same perimeter and with respect to the w 2 s what is the perimeter of the stator circumference number of poles p s into w 2 s plus arc length is not changing right.

Assume the arc length is same in this region also here also I am considering w arc length and this is the width of the slot will be w 2 s I am considering here and here it is w 1 s. It should be equals to pi into d i s plus 2 into d s s this is the perimeter with respect by incorporating the slot height also. So, from these two equations we can find the depth of the or height of the stator slot. If we will consider this is equation number 12 and this is equation number 13 earlier equation is 11 slot area. So, equation 12 minus equation 13 if we will do subtract from these two equations 12 and 13 if you will do the subtraction the number of poles here I think here we have to consider the equation number 13 minus equation number 12.

Then w 2 s minus w 1 s is equals to pi into 2 into d s s this is the equation to find the slot or pole height. So, d s s is equals to p s by 2 into pi w 2 s minus w 1 s. So, w 2 s is nothing, but width of the stator slot at the top side that is this one and w 1 s is nothing, but width of the stator slot at the bottom side. So, d s s can be calculated with respect to this equation here w 1 s and w 2 s we have to calculate with respect to the equation number 12 and equation number 13. In general the slot height will be in the range of height of the coil and slot height to 1.4 times the height of the coil. So, if we know the height of the coil is h coil then the pole height should be in the range 1 to 1.4 times the height of the coil. Height of the coil is nothing, but here we can see this is the height of the coil this one h c represents the height of the coil. So, if we will know the height of the coil then we can find the w slot height also in the range in this range or we have to follow with respect to this equation.

Next with this I am concluding this lecture. In this lecture we have calculated the stator pole height and stator pole widths and flux densities at different parts of iron we have calculated. Thank you.