Course Name: Design of Electric Motors

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Title: Design of Induction Machine- Stator Design -3 (Stator Slot Geometry)

Greetings to all, in this lecture we will continue the discussion on stator core design. In the earlier lecture, we have discussed the number of slots and type of winding and how to select the copper wire SWG and resistance of the coil and copper weight and volume everything we have discussed. The remaining part with respect to the stator core design is how to select this or how to make the stator slot geometry. First in the stator slot geometry, we have to decide the shape, what kind of slot shape we have to select it. In the literature or in the most of the applications, the available slot shapes are with respect to the open type and semi-open type and closed type and other shapes. Open type and semi-open type and closed type are the three type of the slot shapes which are available and we are utilizing in all type of applications.

Some other shapes like double caged rotor and some customized slot shapes, we can design it depends upon the application aspect as well as designer aspect. Open type of slot is nothing, but the slot width as well as slot opening both are same. You can see here, this is the slot width that is W and slot opening is D0 both are same. In the semi-open type of slot, slot width and slot opening both are may not be same.

This is semi-open type of slot and closed type of slot there is no opening for inserting the coils. In other shape like different type of shape for example, double caged type of slot or example, one side circle, other side rectangle whatever it may be the shape depends upon the designer aspect as well as depends upon the application. These are the different type of slot shapes open, semi-open and closed. Generally, we will utilize the slot shapes in this manner. You can see the structure here, some type of slot shape semi-open type.

Stator lamination I am showing here, this is semi-open type of slot shape. Similarly, for DC machines and special machines, we will see the open type of slots in this manner. Semi-open type of slots, we will see the stator structure for induction machine as well as synchronous machine and closed type of slots for squirrel cage rotor and double cage rotor for induction machine, we will see in this kind of shapes. How to select the shape of the slot, we will discuss now. These are the basic shapes and if requires any other random shape also we can select it depends upon the requirements or depends upon the application.

What are the constraints to select this type of slot shapes means, first constraint is with respect to the cost. If we will design a random slot shape, the cost of the stamping will be high. If we will design a slot shape with respect to the available stampings, then cost of the lamination or cost of the stamping will come down. That is what with respect to the cost and similarly, with respect to the coil design and placement. For closed type of slots, we cannot place the windings that much easily and for open type of slot, we can easily insert the windings.

For semi-open type of slots, it is difficult to insert the like slightly difficult as compared to the open type of slots to insert the windings. We can see here in order to insert the windings into the slot, assume that here one conductor is there of thickness 10 mm. Here also some conductor is there, here also conductor is there. If you want to insert this conductor into the slot, in open slot it will be easy. In semi-open type of slots, slightly complex as compared to the open type of slot.

In the closed type of slot, it will be too complex. One by one, we have to make the things formed coils. We cannot insert it like formed coil is nothing but this one. We cannot insert this kind of coil directly. One end should go in from the other slot, it should come out.

First we have to insert one end, the same end should come out from the other slot like this design complexity will be there in the closed type of slots. Similarly, other type of slot shapes also, complexity will be there. First one is with respect to the cost, we have discussed and one more thing in the cost is the teeth flux density. The teeth flux density, we have to maintain less than the teeth saturation flux density as per the material, as per the standard or recommended flux density values. The saturation value should be higher than the peak value of the teeth flux density.

Second requirement is design complexity. The design complexity, the first foremost point with respect to the winding structures. I will show you one winding structure. We can see here stator laminations and rotor laminations for single lamination one, we can see here stator core and right side one is the rotor core. How it will both stator lamination as well as rotor laminations we can see.

These are the random coils and former coils. In the random wound coils, circular cross sectional conductor will be there and we will make the n type of n number of conductors in series and we will make one coil. In the formed wound coils, we have the rectangular based conductors. On top of one another, we will place the conductors and symmetrically we will form the windings. This is the random wound coils and these are the formed wound rectangular coils.

Form wound coils easily we can insert in open type of slot as well as semi open type of slot and formed wound coils only preferable for open type of slots. Like this type of coils, we cannot insert in closed windings or closed slots. The slot is closed like this two slots are there. We cannot insert this type of coils here. For that we have to make the each and everywhere should go in here and should come out here.

Design complexity will come with respect to the different slots. The next thing will be we can see here the partially inserted stator core with random winding where the circular cross sectional conductors has been used and the stator core with respect to the form winding where the rectangular conductors are layered one another and placed in open type of slots. We can see here the slot opening is higher that means, open type of slots we can see in this manner. So, in this slot rectangular formed coils will placed one type of other whereas, in this case the slot opening will be like this and one another one conductor cross sectional conductor will be pushed into the slot. The bunch or a coil consist of n number of conductors one by one we have to insert it.

Conductor slot opening d naught will be 3 to 5 times the conductor diameter. So, this is the design complexity with respect to the random coils, random wound coils placement and form wound coils. In any type of winding with closed type of slot it is not at all possible and then insulation requirement with respect to the slot shapes that is also one design complex requirement and then coil connections with respect to the different type of winding. The mainly design complexity will come with respect to the type of winding and type of slot shapes. Next point we have to consider symmetrical air gap.

Symmetrical air gap is the key requirement for the induction machine. For example, for a switch reluctance machine there is no requirement of symmetrical air gap for induction machine and for synchronous machines the symmetrical air gap requirement will be there. Why symmetrical air gap requirement is there? We will discuss now with respect to some equations. First equation with respect to the reluctance, reluctance is nothing but l by mu A. If we are increasing the length of the air gap or different air gaps are there for example, here one slot is there and here one more slot is there.

The rotor structure is in this manner. So, here air gap length will be smaller and here air gap length will be different and here air gap length will be something else. That means, reluctance is keep on changing from one slot to other slot. Then automatically the flux will change. If the reluctance is changing, flux is nothing but MMF by reluctance from the magnetic prinicples we have discussed.

If the reluctance is varying, then automatically flux also will vary. If the large air gap is there in order to establish the same flux density at the air gap, we require the more current. I magnetizing current also will be very high if the length of air gap is higher to establish the same flux density at the air gap. Similarly, leakage fluxes we can see here. This is the open type of slot.

Let us take some closed type of slot. Here if we will place the conductor, n number of conductors are there for easy analysis. I am considering one conductor and we will see the flux lines here. The flux lines will be in this manner. So, most of the flux lines are passing through the air gap and linking with the rotor in this structure.

The air gap between the slot opening in this region, if we will see in this region, the reluctance will be very high. The flux lines may not flow in this manner. Most of the flux lines are linking and linking with respect to the rotor and it is flowing through the air gap. In the other case, with respect to the closed slot, in this portion reluctance will be very small. That means, resistance will be magnetic resistance will be very small.

Then the magnetic flux lines, most of the magnetic flux lines will flow in this region. The rotor structure is here. This is the air gap. We can see here in the pink highlighted region, the reluctance will be very small or we can say magnetic resistance will be very small. Most of the magnetic flux lines will flow in this region also. The leakage flux here more in this condition. Here leakage flux is less. Slot leakage flux we can represent it. The leakage flux in this condition is very high and leakage flux here is very less. If the air gap is uniform, then this leakage fluxes can be minimized.

The slot shape will be depending upon the air gap symmetry also. If the leakage fluxes are varying, automatically leakage reactance also will vary and overload capability with respect to the torque also will vary as per the air gap length. If we are selecting certain slot shape, depends upon the type of machine, we have to establish the uniform air gap length. The next thing will be slot harmonics or tooth harmonics. Slot harmonics are nothing but as we have discussed now, if the reluctance is varying with respect to the rotor structure.

These are the number of slots and consider here rotor surface is in this manner. One pole pitch you can consider it. Here length of the air gap is different. Here length of the air gap is different. lg 1 and lg 2. lg1 is less than the lg 2 because of this change in air gap. The reluctance is changing. Since we are applying the MMF is not sinusoidal, whatever the MMF we are applying is not sinusoidal. It consists of fundamental third harmonic, fifth harmonic, seventh harmonic, all type of odd harmonics it will be there and third harmonic will not exist in a three phase system. So, the dominant harmonics will come fifth, seventh and other harmonics also will come into the picture and because of this reluctance variation in the air gap flux density waveform, this slot harmonics also will reflect.

If we observe here, this is the fundamental because of the slot harmonics. So, the resultant flux density waveform with respect to the air gap length variation will come in this manner, wherever the air gap length is smaller, where the reluctance will be smaller, then the B value will be higher and wherever the reluctance is more or length of the air gap is more, then the flux value will be less flux density values. So, we can draw the waveform in this way. So, these are the slot harmonics. The frequency of slot harmonics is equals to f into number of slots per pole pair.

The f is with respect to the fundamental and these are the frequencies with respect to slot harmonics. We can see this is one cycle, second, third, fourth, fifth. Here we can see 1, 2, 3, 4, 5 slots are there. So, slots per pole pitch is nothing but then frequency with respect to the slot harmonics. The order of slot harmonics is equals to 2 into Qs by P plus or minus 1.

This is the order of slot harmonics, n slot harmonics. Based on this equation, we can find what is the dominant slot harmonic. So, while selecting the slot shape, we should consider all these constraints with respect to the cost, type of winding and design complexity and uniform air gap, uniform air gap length and then slot harmonics. These are the constraints we have to select and the summary with respect to different type of slots, we will see now. This is the open type of slot and semi-open type of slot and closed type of slot.

This is the air gap length. Place a single conductor and analyze the flux lines with respect to the thumb rule and here also apply thumb rule and analyze the flux lines loop. For a cross, it will be clockwise direction as per the thumb rule. We can see here, the leakage flux or slot leakage is less here and here moderate slightly higher as compared to the open type of slot and here because of the less reluctance value type of slot in this portion, the reluctance will be very small and then magnetic flux lines, most of the magnetic flux lines will flow here. Because of that reason, the leakage flux will be higher here, slot leakage flux. The next thing will be with respect to the winding aspect.

Placing the winding will be easy here either it may be random wound coils or form wound coils. Both type of winding it is easy, slightly difficult as compared to the open type of slots and here not possible this random and form wound coils one by one, we have to insert it very difficult here. Next thing is with respect to the reluctance variation. Here reluctance variation will be very high and slot harmonics also will be there, will be higher and here moderate and here less because the reluctance will be very small here, variation will be less and symmetrical air gap is there and slot harmonics also will be very less because of the symmetrical air gap. The next point with respect to the leakage flux and leakage reactance.

Since the leakage flux is less, the leakage reactance also will be less. Here leakage flux will be less, but slightly more than the open type of slot. XL open type of slot is less than XL semi open is less than XL closed type of slot. The leakage reactance with respect to the closed type of slot will be very high.

Here XL is very high. The next parameter we will see the magnetizing current. In order to establish the current at the in order to establish the same flux at the air gap, the magnetizing current requirement will be very high because of the unsymmetrical air gaps in the open type of slots and here slightly less and here it will be very less. If the magnetizing current is less, the power factor also will vary according to that particular aspect. Power factor will be very high in the closed type of slots and low for the open type of slots and in between will be there for semi open type of slots. These are the few factors and summary to select the shape of the slot as well as the to select the number of slots also, but mostly the shape of the slot will be reflected with respect to these parameters.

One more thing, if we will select the sharp edges of the stator slots in this manner, the flux lines are flowing in this manner and whether it is going out or coming in at this particular point sharp edges, there is a chance for saturation. We have to select the slot shape with respect to this particular aspect also. There is a chance for saturation at the sharp edges of the corners because most of the flux lines will merge or will be leaving from that particular point from the teeth. This is another point that has to be considered.

With this, the slot shape selection we can decide. The next thing will be slot geometry. We can see here as of now, we have discussed the stator winding and number of slots and how to select the stator slot shape also. Let us consider the slot shape will be in this manner. We are considering semi open type of slot and where the teeth width is t, teeth width is t and slot width at the bottom side will be w 1, slot width at the top side will be w 2 and back iron length will be w c and radius of this portion will be r 2 and this portion will be r 1 and the depth of the slot will be d s and slot opening width is b naught and d naught is the slot opening height. These are the parameters we have to calculate to complete the stator core geometry.

In order to calculate the stator slot geometry, we have to assume the following parameters the slot opening and the radius of the slot at the starting side are this one and the radius of the slot at the bottom side this one and this one we have to assume and then d naught slot opening height this portion also we have to assume. These are the four parameters we have to assume as per the designer initial data, but b naught value we have to consider greater than the 3 to 4 times the SWG wire data like cross sectional area of the conductor we know. Based on that thing 3 to 4 times the cross sectional area we have to consider for slot opening. We can see here in order to insert the 1 by 1 conductor here in the slots, this slot opening width should be 3 to 4 times the area of each conductor that is b naught and then teeth width. Teeth width we have already calculated while doing the D cube l product equation bg by bt here the maximum flux density with respect to the air gap maximum flux density with respect to the teeth into D is into pi divided by Q s into k s.

So, this is equation number 13 from this equation we can calculate the teeth width. The next is depth of the stator core or back iron length 2 into D is divided by k s into P number of poles Bg by Bc this equation also already we have derived this is equation number 14. If requires I can give the hints to calculate the this equations to derive this equations from this image we have to write the equations for Bg Bt and Bc. The flux per pole or average flux with respect to the machine flux average is equals to phi t average flux at the teeth average flux at the core average is equals to flux at the air gap average with respect to per pole. It will be same inside the machine from here flux at the air gap phi g is equals to average value 2 by pi into flux peak value.

So, here flux is nothing but B into A g. So, here area we have to calculate if we will see the slot diagram. Here the flux lines are entering in this manner in the air gaps and in the teeth also it is entering in the same manner. So, we have to calculate the area with respect to this portion perpendicular to this portion here also perpendicular to this magnetic flux lines and in the core the same flux lines are coming in both directions. This side phi by 2 and this side phi by 2 will be there. We have to calculate the cross sectional area with respect to this particular point.

First we will see with respect to the air gap flux per pole phi g average is equals to 2 by pi bg peak into here area of cross section with respect to this one perpendicular to this portion is nothing but here this one phi D Is by P into Le this is the area this is x axis length and this is y axis length from here we can calculate the Bg peak. And similarly phi t average is equals to 2 by pi Bt peak into what is the area with respect to this cross section x axis length will be t into Qs that is the x axis length and y axis length will be le into ks here ks is the stamping factor steel stacking factor or stamping factor we can select it steel stamping or steel stacking factor is nothing but this one. So, from this equation by P should come with respect to per pole t into Qs by P is the x axis length and le into ks is the y axis length.

And similarly to calculate the phi c average the average flux in this portion in this portion phi c average is equals to phi I will take this is phi c is equals to actual phi c average by 2 here in order to find the flux with respect to this portion this is the maximum flux density value with respect to the core right for that purpose here the flux lines whatever the flux lines are coming into the teeth or into the pole with respect to the magnetic poles it is distributed into two parts right phi by 2 in one direction other direction phi by 2. So, phi c average by 2 is nothing but B c peak into the area B c peak is nothing but maximum flux density during this core or back iron portion into area is nothing but d c is the back iron depth and le into ks is the y axis length.

So, this is the total area with respect to the back iron from here we can find the B c peak is equals to phi c average by 2 into 1 divided by d c into le into ks this is equation number 17. With this we can calculate the flux density peak value at the back iron portion from these three equations we can calculate the teeth value teeth width as well as back iron depth and then perimeter equation if we will do the equation with respect to this w 1 and t perimeter equation already we have derived with respect to w 1 and t Qs into w1 plus t is equals to phi into D is plus 2 into d naught plus 2 into r 1.

So, from here w 1 can be calculated here we know the value of t we know the value of Qs D is also known d naught and r naught also known value. To select d naught like 1 to 2 mm we can select depends upon the slot height this is the assumption value and r 1 also assumption value. Next with respect to the perimeter equation in terms of w 2 comma t w 2 and teeth width is nothing, but Qs into w 2 plus t is equals to phi into D naught s minus 2 d c r phi into D is inner diameter of the stator plus 2 into d naught plus r 1 plus d c.

So, from here we can calculate the value of w2. So, slot width at the top side also we can calculate it then the remaining thing is slot depth. Slot depth d s is nothing, but w 2 minus w 1 into 2 into number of slots by phi this equation also we have derived during D cube l discussion.

Finally, after knowing w1 w 2 t value and d naught d c d s r 1 r 2 we can find the slot area. Slot area is equals to w 1 plus w 2 by 2 into d s slot depth r 2 w 2 minus C 1 r 2 plus r 1 into w 1 minus C 1 into r 1 this is equation number 21. So, from this equation we can find the slot area here C is equals to 2 minus phi by 2.

If we will follow the D cube l equations from there also A s equals to pi into D naught s square by 4 into copper function f of lambda. From this equation also we can find the slot area.

The next thing is slot fill factor or copper fill factor. Copper fill factor K c u is equals to area of the copper divided by total area of the slot. If I will consider the slot in this manner here the inside liner will be there slot liner pink color one is the slot liner and blue color one are the conductors and red color one we can see here slot separators and slot closer again one insulating paper will be there the green color one is the closer and at the top there will be a wooden stick or wedges we used to say for closing the slot.

So, these are the different things which are placed inside the slot. So, in order to find the slot fill factor K slot fill factor is generally 0.6 to 0.8. If we will go for 0.8 the slot fill factor it is difficult to make the winding including all these wedges closers and slot liners and separators and conductors also.

Including all these components we have to find the slot fill factor A c u is the copper area and A other materials is nothing, but area of wedges closer slot liner separators and etcetera divided by total slot area this is equation number 23. So, from this equation we can find the slot fill factor. At the end after calculating the slot area and we know the slot fill factor slot area into slot fill factor should be greater than the cross sectional area of each conductor into total number of conductors in single slot that is nothing, but 2 into m into N phase divided by Q s. So, the copper area with respect to all conductors should be less than the slot area with respect to the copper slot fill factor.

This is the window check equation number 24. At the end of the stator core design this equation should be valid. The next we have to find the number of laminations. This we can do it at the end at the starting of the stator core also. Anywhere we can find it how many number of laminations required.

The lamination thickness will be 0.1 to 0.5 depends upon the material and flux density values. And number of laminations n laminations is equals to total length of the core with respect to the stacking factor divided by thickness of each lamination. This is the thickness of lamination.

This will give the total number of laminations. This is equation number 25. And at the end we have to verify the slot geometry where D naught s outer diameter of the stator should be greater than or equals to whatever the values we have calculated inner diameter of the stator plus 2 times the height of the slot opening and radius at the top side of the slot and depth of the slot and radius at the bottom side of the slot and d s is the depth of the slot and dc is the back iron length.

So, this equation should be valid at the end of the stator core design. So, with this I am concluding this lecture. In this lecture we have discussed the how to select the slot shape and how to calculate the slot geometry. In the next lecture we will discuss about the rotor geometry. Thank you.