Course Name: Design of Electric Motors

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Title: Design of Induction Machine- Stator Design -1 (Stator Core design)

Greetings to all of you, in this class we will discuss about the design of induction machine. With respect to the generalized procedural steps discussed in the last lectures, we will design the induction machine ok. The first step if we will see the initial design data, where we have to select the type of machine. For example, we are going to design the induction machine right. So, type of motor will be induction machine and type of rotor whether it is squirrel cage or slip ring ok. And then standards we have to follow the NEMA standards as well as IEEE or IEC standards.

And the basic specifications are data with respect to the output power and efficiency, torque and speed and number of phases whether it is 3 phase machine or 4 phase machine or N phase machine. And finally, is there any constraints with respect to the economic as well as volume boundaries ok. So, from the generalized principles with respect to the designer design procedure, step 1 is with respect to initial design data all these things we have to select. After this thing second step we have to decide the sizing equations or we have to decide the main dimensions ok.

We can see here this is a induction machine we are going to design. So, first we have to decide the which type of motor and which type of rotor and standards all those things covered in the step 1. Second step sizing equations. So, what is the volume of stator? So, we can see here what is the inner diameter of the stator and length of the core is this one. This is the length of the core and this is the inner diameter of the stator and outer diameter of the stator.

These are the main dimensions of a machine or volume of a machine. In order to find the main dimensions we have discussed the power equations with respect to D square l that is volume product. We have discussed the one equation with respect to D square l product and second equation with respect to D cube l product and third equation with respect to D power 2.5 l product. So, we can use any one of these equations and we can find the inner diameter of the stator and length of a core and outer diameter of the stator.

Outer diameter of the stator is possible only with the D cube l product equation as well as D power 2.5 l product equation. Because in the equation 2 and 3 we have considered the flux densities at different parts of the iron like flux density at the air gap, flux density at the core, flux density at the teeth and similarly the actual current density with respect to the stator circumference we have considered. In the equation 1 what we have considered only the magnetic loading at the air gap and electric loading or surface current density with respect to the air gap. Because of these things we can design or we can calculate only inner diameter of the stator and length of a core, but in these two equations we can find outer diameter of the stator also.

Similarly we will utilize D square l product equation that is output power equals to pi square by 120 that is a constant value and then efficiency power factor and then synchronous speed, magnetic loading, electric loading and then volume product into winding factor this is equation 1 what we have derived in the segment of generalized principles for machine design. This is the volume product we have to find with respect to a given power rating. So, here pi square by 120 is a constant term efficiency we have to assume and power factor also we have to assume initially and then synchronous speed as per the torque and speed requirements we can calculate the synchronous speed and electric magnetic loading and electric loading how to select we have already discussed. Again I will show you how to select the magnetic loading and electric loading values and winding factor also.

If sinusoidally distributed ah winding structure winding factor is equals to 0.955. So, all variables are known numbers then we can find the D square le product number ok. After knowing the D square l product number we have to decouple the D and l values this is one method. Other method is by utilizing the D cube le product that is equation 2 output power is equals to output function minus some constant delta into lambda divided by outer diameter of the stator square into efficiency power factor and then synchronous speed magnetic loading actual surface current density with respect to the conductors winding factor copper fill factor D cube le product and then constant pi square by 240 root 2 this is equation number 2.

This equation also we have derived in this equation we have considered the slot geometry B g value B t value and B c flux densities at different parts of the iron and actual current density with respect to the stator winding we have considered. From this equation if we will do the analysis we are able to find the inner diameter of the stator and outer diameter of the stator and length of the core, but here the main thing we have to consider is output function f naught of lambda.

We have to maximize the output function to get the maximum output power within the known volume. If we will maximize the f naught of lambda function then we can maximize the output power within known volume. Here also efficiency we know power factor also we can assume and speed we know based upon this initial data of torque and speeds and magnetic loading and electric loading how to select I will show the some numbers with respect to the different materials with respect to the standards also. Winding factor for sinusoidally distributed one 0.955 and for different winding patterns different value will come that we will discuss it later and copper fill factor this also we know the copper fill factor generally 0.6 to 0.7 and this is the D cube le product and this one is the constant. So, all variables we know then we can find the output function. Here delta into lambda divided by D naught s square we can neglect initially at the end we can modify the number in a iterative manner. Initial version we can neglect this term and we can find the D cube le product. Now, we will see how to select the magnetic loading and how to select the electric loading with respect to the different parts of the core.

These are the standards with respect to the different parts of the machine at the air gap the maximum possible flux density we can select 0.7 to 0.9 and stator yoke we have to consider 1.4 to 1.7 and tooth is nothing, but at this particular point this is the teeth portion and this is the core portion and this is the air gap portion.

And then rotor side also rotor core consist of 1 to 1.6 test law and pole and commutating poles with respect to DC machines and synchronous machine we can see the different numbers here. For example, for salient pole synchronous machine 1 to 1.5 tesla we can select it the maximum flux density values. If we will see the current density or electric loading values A is the electric loading we have discussed with the symbol El electric loading will be 30 to 65 ampere per mm or kilo ampere per meter we can select it.

And actual current density J is nothing, but 3 to 8 for stator winding 3 to 8 for copper rotor winding and if aluminum bars if you are utilizing then it is 3 to 6.5. Similarly for synchronous machines and then permanent magnet synchronous machines and DC machines we can see here different electric loading values as well as magnetic loading values depends upon the power rating and depends upon the type of cooling mechanism we are selecting, we have to select the magnetic loading as well as electric loading values. The next thing is depends upon the material also the whatever the numbers I have shown in the table 1 in this table is not limited. For example, for iron the maximum possible flux density will be 1.5 tesla for silicon steel it may be different for cobalt steel it may be different. These are the materials used in electrical machines core generally for all type of electrical machines we will utilize the cobalt steel, nickel steel and SIFE steels in different portions or different magnitudes of silicon. For example, cobalt steel 49 percent of cobalt and 49 percent of iron and 2 percent of remaining thing if you will utilize it sheet thickness we can see here the lamination thickness each lamination of a thickness 0.2 to 0.5 mm in order to make length of for example, 10 100 mm we have to make the core length then such laminations we have to stack together and we can make a 100 mm stator core length.

Why we require the laminations means to minimize the eddy current losses here flux density at 0.5 0.8 kilo ampere per meter we can see 2.1 test law. Similarly flux density at

2.5 ampere kilo ampere per meter with respect to the electric loading 2.5 kilo ampere per meter we are able to achieve 2.23 test law resistivity and material density also we can observe from this table for the other material nickel steel sorry nickel iron Fe is nothing, but iron 40 percent of nickel and 60 percent of iron if you will utilize it then the maximum possible flux density will be 1.44 at a current density of 0.8 kilo ampere per meter and similarly 1.48 at a current density of 2.5 kilo ampere per meter and silicon steel we can see here SIFe and 6.5 percent of silicon and remaining iron balanced one then sheet thickness is 0.1 to 0.2 mm and the maximum flux density is 1.29 at a current density of 0.8 kilo ampere per meter and 1.4 test law for a current density of 2.5 kilo ampere per meter. Similarly different portions and different materials DEFG different type of materials we can see different flux density values here and different material density also from the material density value we can find the mass of the particular core as well as volume also we can find later. So, these are the factors we have to consider while calculating the volume product.

So, after selecting the magnetic loading and electric loading values then we can find either D cube l product or D square l product. Once we know this product values we have to decouple the D value as well as l value. What is the diameter of the stator and length of the core we have to decouple it here we have two unknowns, but only one equation is there to calculate the two unknown values we have to consider one more equation with respect to the aspect ratio. Aspect ratio is nothing, but length of the core to pole pitch it is a ratio between length of the stator core to pole pitch that is l e by tau p. This aspect ratio we have to select depends upon the machines that already we have discussed for an induction machine the aspect ratio will be 0.5 to 2, 0.5 to 2 the aspect ratio there is no units because both are in mm. And if we will take the approximate equation we can select directly some number l e by tau p ratio for example, 1 then we can proceed for to calculate the D and l e values here l e equals to 1 into tau p 1 into pi into D I s by p number of poles we know from the synchronous speed synchronous speed equals to 120 f by P from this equation we can find the number of poles. So, that poles we can substitute here then l e in terms of diameter we can get it this equation we have to substitute in the volume product then we can decouple the D value and l e value this is a iterative process as well as depends upon the application we have to select it. The approximate equation to find the l e by tau p ratio is equals to cube root of pole pace for example, 4 poles are there here pole pairs equals to 2 then cube root of 2 is nothing, but your l e by tau p ratio this is an approximate equation to find the aspect ratio. Once we know the D value and l e value the main dimensions of the stator side is are calculated and if we will see the D cube l product equation we can find the D naught s value also additionally.

So, this is step 2 where we have calculated the inner diameter of the stator and outer diameter of the stator we can see here this is the stator core outer diameter of the stator we have calculated and inner diameter of the stator we have calculated and length of the core we have calculated. Next step 3 is stator core design. We can see here this is the stator core. Now, with respect to the stator core design what we have to calculate is the stator geometry if I will consider the single lamination of a stator core it will be looks like in this way here we have to find the number of slots and type of winding which type of winding we have to utilize for designing the machine and to deliver the required torque. So, which type of winding we have to utilize and which how many number of slots we have to take and what is the slot shape and slot geometry how much depth we have to keep and how much depth of back iron we have to keep what is the thickness of teeth we have to keep those things we have to calculate in the stator core design.

So, to start the stator core design the first parameter we have to know is the number of slots. Once we know the number of slots we can design the or we can select the suitable stator winding. After that we can select the slot shape then slot geometry. So, these are the three major parameters we have to calculate with respect to the stator core design. So, first we will see how to select the number of slots.

In order to select the number of slot there is no straight forward equation we have to select based upon the output power rating for a large power rating machine we require higher number of slots for smaller rated machines we require the lesser number of stator slots. The output power is directly related to the number of poles or we can say synchronous speed instead of number of poles we can consider synchronous speed and also inner diameter of the stator. So, to find the number of slot we will define the variable slot pitch that is tau s slot pitch is nothing but we can see here this is the stator lamination the distance between two slots the center from the center of each slot to the center of other slot that is nothing but slot pitch. If 36 slots are there slot pitch is nothing but 360 by 36 like that. So, with respect to the inner diameter if we will calculate slot pitch is nothing but pi Di s by Qs this is the slot pitch equation Qs is equals to number of stator slots and Dis is the inner diameter of the stator and t s is the slot pitch.

The slot pitch is defined or we have to select depends upon the type of machine and power rating. For induction machines or small rated synchronous machines the slot pitch is 7 to 45 mm we have to select the slot pitch 7 to 45 mm range then we can calculate the number of slots. In this equation we know the if we will select the slot pitch then already we know the inner diameter of the stator then it is easy to calculate the number of slots. For induction machines and small rated synchronous machines the range of slot pitch is 7 to 45 mm. And similarly for larger rated synchronous machines the slot pitch will be 14 to 75 mm and for DC missions slot pitch is 10 to 30 mm.

So, depends upon the type of machine and depends upon the power rating. We have to select the slot pitch with respect to this range approximately we have to select once we have selected the slot pitch we can calculate the number of slots. But the number of slots if we cannot select too high for small rated machines why because if we will increase the number of slots automatically the coils also will increase because we are placing the conductors in each and every slot. So, coils also will increase coils is nothing but Q s by 2 if 12 slots are there then we require 6 coils to make the winding. So, if we are increasing the number of slots automatically coils also the number of coils also will increase then design cost will increase because of this thing.

And next thing is teeth width here slot pitch what we have discussed is these are the 2 slots and from the midpoint of one slot to other slot is nothing but slot pitch that is tau s. The iron portion is nothing but teeth that is teeth width is t and slot width if we will assume w then tau s is approximately is equals to w plus t. If we are increasing the number of slots that means, this portion if we are increasing this portion then automatically the teeth width will come down right teeth width will come down once the teeth width is coming down if this region came down. Let us consider the another example for the same slot pitch. Here we can see teeth width came down that means, the flux density at this particular point will be very high as compared to this particular point this is Bt 1 and this is bt 2 Bt 1 is less than Bt 2 by reducing the teeth width the flux density at that particular portion is increasing that means, there is a chance for saturation.

Otherwise in order to avoid the saturation material we have to change. The material which is capable to handle with the higher flux densities we have to utilize if you want to increase the number of slots without any saturation. So, the procedure to select the number of slots will be first considered the slot pitch that is t s as per the range 7 to 45 mm for induction machine. Then we know already in a in a diameter of the stator calculate the Q s from the equation tau s equals to pi Dis by P from this pi Dis by Qs sorry here.

So, Qs we can calculate it here. So, the approximate number will come that number we have to select with respect to the standard stator slot frames. We can see one frame here this is the stator core having the 36 slot frame as per the standards. So, we cannot make 33 slots or we cannot make it 31 slot like that. If we will make the customized frame like 31 slot frame we require for certain application then the cost of manufacturing will increase this is the customized machine right. If we will go ahead with the standards like 36 slots or other number as per the standard then cost can come down.

The standard number of slots are 18, 24, 30, 36, 48, 54, then 60, 72, 96, 120, 144 etcetera. Whatever the number we will get it here let us say 23.5 we are getting then approximately we can select it 24 slots. If let us say 32.6 is coming this Qs value by selecting some number slot pitch then we have to select the nearest number either 30 or 36 and appropriately we have to design the stator winding.

We will see some examples to find the number of slots. Let us consider the high power machine for a rating of P naught is equals to 3.8 megawatt and inner diameter of the stator is equals to 5.2 meter and poles equals to 144 poles. We have to find the slot pitch as well as number of slots.

So, the slot pitch is in the range of 7 to 45 mm right. Let us consider it is a high power machine right 38 mm I am considering. So, with respect to 38 mm 38 is equals to pi Dis by Q s here in turn inner diameter of the stator is 5200 mm divided by Q s this side also 38 mm then Q s is equals to pi into 5200 divided by 38. So, it will come 429. So, the nearest number of slots we can consider 432 slots as per the standards.

The why I considered 432 slots here is if it is a 3 phase and 144 poles is given in order to make the symmetrical winding whatever the number of slots we have got 429 divided by 3 into 144 should come as some integer to make the integral slot type of winding and the most of the standard slots will be divisible by 6. So, based on that assumptions and some equations we can select the number of slots. Here the number of slots will be 432 here there is no integer, but if I will consider 432 then slots per pole per phase will come 1. Similarly, if I will consider one more example with respect to the 5 HP machine and in inner diameter of the stator is 150 mm and slot pitch I am considering 13 mm and poles equals to 4. Then Q s equals to what pi into Dis by slot pitch 150 pi divided by 13 is nothing, but 36.25 is the slot number. So, to make the nearest integer 36 we can select this 36 is there with respect to the standard number of stator slots based on that we can select this number whatever the standard numbers we have discussed in that 36 is there. So, we can go ahead with 36 number of slots. This is how we can select the number of slots. Next thing is once the number of slots have been identified then we have to select the type of winding. In type of winding already we have discussed with respect to different type of winding structures for AC machines as well as DC machines.

So, that is short pitch and full pitch windings and integral slot or fractional slot. Similarly, concentrated or distributed windings and single layer or double layer winding. These are the different type of windings we have discussed in the segment of AC machine windings as well as DC machine windings. So, depends upon the application we have to select either short pitch winding or full pitch winding. For example, we have to minimize the harmonics during that situation we can go ahead with short pitch winding to minimize certain harmonics at the MMF waveform side as well as time harmonic side and integral slots or fractional slot.

For example, our slot number is coming 30 and we have 3 phase 4 pole winding we have to make it. In that condition the winding will be fractional slot winding here 30 slots 3 phases and 4 pole then it will be 15 by 6 then 2 into 3 by 6 2 into 1 by 2 is the 2 and of is the fractional slot 2 into 1 by 2 is the fractional slot we have to do. And say concentrated and distributed windings concentrated windings we will utilize it for DC machines and special machines and synchronous machine rotor side also. Distributed windings in the induction machine stator side as well as synchronous machine stator side what type of windings are available with respect to all machines also we have seen already and single layer and double layer windings. If fractional slot and short pitch windings required then we have to go ahead with double layer winding where the winding is not possible with single layer then we have to utilize the double layer winding.

So, after deciding the what type of winding we are utilizing then we have to find the number of turns per phase. The number of turns per phase we have to calculate from the voltage equation. The induced voltage with respect to the air gap without any loss directly I can take it V phase equals to as per the Faraday's law N phase into number of turns into d phi by d t. If we will solve this equation flux equals to B into A then finally, V phase peak is equals to root 2 pi N phase phi average frequency into winding factor or V phase RMS is equals to peak by root 2 sorry here V phase peak is equals to 2 pi N phase phi average a frequency into winding factor RMS is equals to peak by root 2 then it will be root 2 pi N phase phi average frequency into K w this is the voltage equation.

From this equation we have to find the number of turns. So, voltage per phase we have to consider as per the application or as per the designer given data initial data itself we have to consider the V phase RMS. For example, 3 phase machine 415 RMS is the line to line voltage and phase RMS is 230 RMS and the number of turns we have to calculate it and phi average we know and frequency also we know and winding factor also we know for K w is nothing, but winding factor for N number of conductors and sinusoidally distributed MMF wave the winding factor will be 0.955. In general winding factor is equals to pitch factor into distribution factor that is what we have discussed during the winding segment. So, here K p is nothing, but pitch factor K d is nothing, but distribution factor.

So, with respect to the short pitch or full pitch winding segment a full pitch winding and short pitch winding we have to select the K p value and distribution factor means the phase winding is distributed in how many number of slots. We will discuss in detail about the winding factor K w because remaining all terms we know right 2 pi is root 2 pi is a constant and flux average also we know from the Bg value Bg already we have considered some value and here area we know then flux we can calculate it right Bg is nothing, but phi by A from here we can calculate the flux frequency known and winding factor we have to calculate it now. So, winding factor is a combination of pitch factor and distribution factor. The pitch factor will come into the picture with respect to the short pitch winding. To minimize certain harmonics if you are doing the short pitch winding or to save the copper also we can go ahead with the short pitch winding some advantages will be there over the full pitch winding then the value of K p is nothing, but cos alpha by 2 here alpha is nothing, but short pitch angle or short pitch angle in terms of degrees or in terms of mm also we can calculate it.

For example, 36 slot machine is there 3 phase 4 pole for full pitch winding this alpha will be 0 where the full pitch winding means it is equals to pole pitch that is 180 degree is the coil pitch for short pitch winding the coil pitch is not equals to coil pitch or coil span is not equals to pole pitch short pitch by 1 slot or short pitch by 2 slot like that we will represent it. So, if for example, slot pitch by certain angle alpha then the K p value is nothing, but cos alpha by 2 for fundamental for nth harmonic K p n is equals to cos n alpha by 2 if anyone is interested to derive this K p just calculate the EMF with respect to the different conductors in a short pitch winding and EMF with respect to the all conductors in a full pitch winding here EMF with respect to the short pitch winding above EMF with respect to the short pitch winding is a phasor sum and EMF with respect to the full pitch winding is arithmetic sum they can calculate and they can derive the cos alpha by 2 already we have discussed in earlier lectures and the other factor K d is nothing, but distribution factor distribution factor is with respect to the distributed winding type or concentrated winding here EMF it is a ratio between EMF induced in distributed winding to the EMF induced in the concentrated winding. If we derive the equation then finally, Kd is equals to sin q into beta by 2 divided by q into sin beta by 2 here q is equals to slots per pole per phase if q equals to 1 that is concentrated winding for example, here we can see the all conductors we are placing in one slot only here also all conductors we are placing one slot and we are making the winding this is concentrated winding instead of doing winding structure like this you distribute the windings in n number of slots same number of conductors distribute in n number of slot then slot per pole per phase is greater than 1 this is distributed winding and if it is equals to 1 it is concentrated winding and beta is nothing, but slot angle slot angle is nothing, but 360 divided by Qs is the slot angle with respect to the mechanical if requires in the electrical into P by 2 we have to take then slot angle in electrical degrees also we can get it 360 by Q s into P by 2 is nothing, but beta electrical with this we can find the pitch factor as well as distribution factor that is equals to winding factor.

So, we can find the K p value and we can find the K d value and then we substitute we can substitute in the voltage equation and find the number of turns per phase with this I am concluding this lecture in this lecture we have discussed the design procedure for the induction machine step 1 with respect to the initial data and step 2 with respect to the sizing equations and step 3 we have started the stator core design in the next lecture also we will continue with respect to the stator design. Thank you.