Course Name: Design of Electric Motors

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Week: 05

Lecture: 27

Title: Electric Machine Sizing Equations-Output Power and Volume (D2L) Product Equation

Greetings to all in the last lecture we have discussed the basic principles and standards of standards involved in the design of a electrical machines we have seen right. In this lecture we will discuss the basic and generalized equations to design the any type of electrical machines. Basically the torque produced by a electrical machine is directly proportional to the two magnetic fields or two currents right that is what we have discussed. The basic principle for any type of electrical machine is attractions and repulsions of two magnetic fields. So, the developed torque also proportional to the two fields or two currents and if you will add the inductance the variation with respect to the angular motion or angular rotation d m by d theta will come. For reluctance based machines we will make it self inductances and I 1 and I 2 will be equal.

So, the torque is proportional to phi 1 and phi 2 we have concluded right or I 1 and I 2.

And also the developed torque is directly proportional to the amount of iron what we are utilizing and amount of copper we are utilizing for designing a machine. So, the amount of iron represents the magnetic materials with respect to the magnetic field density flux per unit area that we will call it as a magnetic loading and units are Weber per meter square and the symbol is BG we will call it as a magnetic loading and BG equals to phi by A.

And the amount of copper represents the mmf per unit length.

mmf per unit length we will call it as a electric loading and symbol is EL. This electric loading is nothing, but the ampere turns placed around the armature structure we can see here this is the machine. So, here the conductors are placed around the armature structure right or stator structure ok. With respect to that how many ampere turns are there per unit length is nothing, but your electric loading. The magnetic loading depends upon the saturation limits and type of material and losses with respect to the core, core losses and type of coolant or thermal mechanism what kind of thermal mechanism we are utilizing.

Based on these four aspects the magnetic loading will be decided these are the four parameters which are limiting the magnetic loading value. We cannot increase the BG value above the certain limits with because of these four things. And similarly electric loading is limited with respect to the I square or losses and winding type and type of coolant or thermal mechanism and finally, skin effects with respect to the frequency of operation. These are the factors which are limiting the electric loading ok. The electric loading units are ampere turns per meter.

So, we have to select the iron as well as copper amount precisely in order to achieve the required torque ok or we can say we have to select the magnetic loading as well as electric loading values appropriately to design the electrical machine. Now, let us consider a machine this is the electrical machine. You can see here this is a type of electrical machine having the enclosures and this is the rotor and this is the stator, this is the stator and consist of windings and the stator is designed with n number of laminations ok. For bigger machines we can see the laminations in this manner. This is the laminations for bigger machines single lamination I am showing here with the n number of slots and each lamination will be thickness of 0.

5 mm to 1 mm we can see here. So, now, we will see what kind of parameters we have to see. The first step in the design what we have discussed we have to identify the volume right. So, volume is nothing, but with respect to the air gap diameter or with respect to the stator inner diameter. The stator inner diameter is nothing, but DIS that is what I am showing here ok.

The machine structure will be like this here the outer diameter is Dis and lg is nothing, but air gap and Dis is the inner diameter of the stator and Dor is the outer diameter and Dir is the inner diameter of the rotor. So, we have considered the AC machine with the dimensions D0s or Dos and Dis, Dor and Dir and lg are the dimensions with respect to the stator and rotor and le is the effective length of a iron including the air ducts ok. This is the length of the core ok. How many number of laminations we are stamping together to make the stator core that is the length if it is in between ducts are there air ducts like some gaps will be there in for a bigger or high power applications including that gaps also the effective length is le ok. Let us take the machine this is the machine and input to that particular machine we are giving P in and output we are taking Po that is mechanical output and in between losses are there ok and efficiency of the system is nothing, but P0 by Pin.

Here for an AC machine the input power is nothing, but M into input power is nothing, but M is the number of phases B phase RMS and I phase RMS into power factor right and at the output side mechanical output power 2 pi NT by 60 here N is the synchronous speed and Te is the output torque and in between losses are there. If we will consider the losses and energy conversion inside the machine in detail if you will take. So, this is the Pin = m Vphase Iphase cos phi we are giving and here there is a stator copper loss ok.

The input electrical input we are giving to the electrical machine and the input power is nothing, but m into V phase I phase cos phi and V phase and I phase are the RMS quantities and after that because of the stator winding there is a loss I square R loss and then output is at the air gap that is Pg and this air gap power we are giving as a input to the rotor and in the rotor side or in the rotor also we have the I square R losses ok. There will be a I square R loss because of the winding structure in the rotor and the rotor output is nothing, but the mechanical power, but there will be a mechanical losses also like friction and windage losses will be there and then output will be P mechanical or P naught we can represent it.

So, along with this I square R loss there will be a iron losses also in the stator core as well as rotor core in terms of hysteresis and eddy current losses we have the iron losses. So, the system what we have represented earlier is this one. We are giving electrical input and getting mechanical output. So, efficiency is nothing, but P naught or P mechanical output divided by electrical input and if I will consider the efficiency with respect to the air gap power air gap power is nothing, but this one efficiency with respect to the air gap power is nothing, but P naught divided by PG ok.

Here the input power is equals to power at the air gap plus losses power at the air gap is nothing, but m into V phase I phase cos phi g plus m into I square R losses will be there I phase plus iron loss at the stator side.

So, input will be m into V phase I phase cos phi. So, here V phase and I phase will be with respect to the air gap side and here with respect to the supply side. If we will neglect the losses these two losses if we will neglect it then the input power whatever we are giving the same power we are seeing at the air gap right. So, from this power equation we will realize the physical dimensions of the machine or in terms of volume that is the first step to design to start the design process of the electrical machine right. So, we have to take the output power or output power requirement based on that we have to select the D square L that is volume product power is proportional to the volume product.

So, depends upon the given power we have to select the volume product. If we will neglect the losses at the stator side the output power P naught is nothing, but efficiency into P in right and here efficiency I am considering with respect to the air gap and the input I am considering it is equals to the Pg the power at the air gap. Here losses with respect to the I square R loss plus core losses are neglected because of that reason P in equals to Pg, I am considering here the electrical input equals to the power at the air gap.

Efficiency with respect to the air gap reference and P g is nothing, but m into V phase RMS at the air gap I phase RMS at the air gap and cos phi g. Here the voltage or induced voltage at the air gap is same as the supplied voltage if I neglect the losses that is V phase RMS we have to calculate with respect to the input and I phase RMS we have to calculate in terms of electric loading.

Next we will see the what is voltage before going to that thing if we will replace the V phase RMS and I phase RMS quantities in terms of peak quantities m by 2 m is the number of phases and V phase peak at the air gap and I phase peak current at the air gap into power factor cos phi g.

So, here voltage the induced voltage as per the Faraday's law is equals to N d phi by d t, N is the number of turns per phase and phi is nothing, but b into a flux density over a area divided by d t here a is cross sectional area of the core is constant that is N phase into Ac and then d B by d t the d B by d t represents the flux swing over a period. So, then d B by d t we can replace it with the change in B fields it is 2B for a time t by 2 for each and every half cycle the B fields are changing from plus b to minus B. So, 2B is the change in a half cycle t by 2 period then it will be equals to 4 number of turns into area into B fields area into B fields is nothing, but phi and 1 by t is nothing, but frequency this is nothing, but V phase average voltage with respect to 1 particular winding while making the winding we have to select the some winding factor that is K w this is the winding factor. Then the final equation will be 4 into phi average n phase into f into K w this is the voltage equation in order to find the peak voltage average to peak voltage if you want to convert V phase peak is equals to pi by 2 into V phase average by assuming the sinusoidal quantity of the voltage to convert the average quantity to peak quantity we have to multiply with a factor pi by 2 then V phase peak is nothing, but 2 into pi phi average into N phase into f into winding factor.

Now, we have derived the voltage in terms of flux number of turns and frequency and winding factor. Now, flux average we have to represent in terms of magnetic loading. So, the magnetic loading is nothing, but Bg and electric loading is nothing, but el. So, I phase peak we have to represent in terms of El and voltage we have to represent in terms of Bg the voltage related to flux and flux related to the bg value. So, here in order to bring the relation let us consider the flux average is equals to 2 by pi flux peak value 2 by pi is nothing, but a constant in order to convert average to peak values flux is nothing, but Bg peak into a.

In the air gap how the flux lines are flowing with respect to that we have to find the area here area is nothing, but pi D l by P, D is nothing, but inner diameter of the stator and l is nothing, but length of the core and bg peak will be there as it is and 2 by pi that will give flux average equals to this one. Here how to find the area means let us consider the slots like this. This is the rotor structure. So, this one is the air gap. In the air gap how the field lines or flux lines are entering means in this manner in each and every teeth the flux lines are entering in this manner.

So, the cross sectional area with respect to this flux lines we have to see here we have to bisect perpendicular and we have to find the cross sectional area here Ac is nothing, but x into y length into width. So, x direction we have the length per pole is nothing, but pi d by p in y direction we have the total length of a core is le then the area will be pi dl by p. So, flux average equals to this one. This is equation 2 earlier one we will represent with equation 1 and this one voltage equation is equation 2 and this flux equation is 3 and now we have to find the electric loading in terms of I phase peak.

Electric loading is nothing, but mmf per unit length mmf is nothing, but what the conductors ampere turns into I phase peak divided by length where we are placing the number of conductors or total conductors.

We can observe here we have placed the conductors in a entire stator structure around the armature or around the stator circumference we have placed the conductors. That means, total length is what pi into d the circumference of the stator with respect to the inner diameter of the stator I am considering the length where the conductors have been placed. In length we have to consider, but I am assuming the length will be with respect to the inner diameter of the stator that is pi into d I s here number of turns equals to what total how many number of phases are there and then number of turns per phase into 2 the conductors right here z is nothing, but conductors into 2 also will come into I phase peak by pi d I s in inner diameter of the stator this equation is 4.

So, from equation 4 we can find the I phase peak. So, from the equation 3 we can see the phi average and from the equation 2 we can find the V phase peak in terms of phi average just use the equation 2 equation 3 and equation 4 and substitute in the power equation output power equation in terms of air gap power efficiency cos phi g into m by 2 the equation 1 I am rewriting it here V phase peak I phase peak right here efficiency will be there as it is and m by 2 V phase peak is nothing, but what from the equation 2 into 2 pi flux average n phase into frequency into K w 2 pi n phase flux average into f into K w this is V phase I phase peak is nothing, but electric loading into pi into inner diameter of the stator divided by total number of conductors ok.

Here substitute the flux average value in terms of peak flux densities then efficiency power factor and number of phases and constant value by 2 2 pi n phase flux average is nothing, but 2 by P, B g peak into d I s into le that is what we have derived in equation 3 2 by pi is there, but pi pi will be cancelled here. So, directly 2 by p we have taken here into I phase peak terms in terms of electric loading and inner diameter of the stator solve this equation at the end we will find the equation will be pi square by p into efficiency at the air gap cos phi g the power factor into electric loading and magnetic loading values both are peak values and d square L product into frequency winding factor and then these are the terms will be there in the power equation. Now, the speed term also will come that is N s synchronous speed, synchronous speed term we have to get it from the frequency term. So, the synchronous speed of a machine is nothing, but 120 f by p. So, from here f is nothing, but N s into 1 p divided by 120.

Substitute this one in the above equation then power equation is equals to pi square by 120 into efficiency power factor and then winding factor electric loading and magnetic loading and volume product into speed. This is the final power equation number 5.

In the equation number 5 this part represents the output constant because while designing the machine we will select efficiency constant some value power factor also some value winding factor also constant B g value as well as El value like electric loading as well as magnetic loading values we will consider to find the D square l product. D square l product is nothing, but volume and Ns is the synchronous speed. So, the power equation we can rewrite it P naught equals to output constant into volume product D square l and speed.

This is the final power equation number 6. From this power equation we can design any type of AC machine for special machines and DC machines we have to select the output power equation accordingly. For AC machines we have selected the input power equation m into V phase I phase cos phi for AC machines. So, for special machines and DC machines also the P naught has to be derived from the associated input power equations. Next thing is power equation depends on what are the factors.

First we will see power equation is directly proportional to from the equation 5 electric loading and magnetic loading and volume speed and then power factor. These are the 5 factors are influencing or limiting the output power. How if we will change the some parameter how power output power will be varied we will discuss now. So, output power is directly proportional to the electric loading. If we will increase the electric loading then output power also will be increased, but the challenges will be I square R losses will increase and copper weight will increase and thermal management we have to take care properly.

These are the limitations with respect to the electric loading. We can increase the electric loading to increase the output power and the second case output power is directly proportional to the magnetic loading that is Bg. If we will increase the magnetic loading output power also will be increased, but the saturation effects and materials what kind of material we are utilizing and type of thermal mechanism we have to consider it and iron losses with respect to the core. So, these are the limitations in order to increase the magnetic loading. The next case where we can increase the volume power is directly proportional to the volume product.

If we will increase the volume automatically output power will be increased, but as per the standards as per the application aspect this volume also has certain limitations. So, we have to work along with that particular line to achieve the required output power. So, the limitations for the volume are with respect to the applications and type of materials we are utilizing and weight of the materials and type of cooling we are adopting. Next one is speed, peripheral speed. The speed is directly relation to the with respect to the frequency.

So, if we will increase the speed or if we will increase the frequency, we can increase the output power, but the rotational speed the speed will be limited with respect to the shaft structure and inertia and torque acting on the machine. For example, type of machine if we will take the DC machine then we require the brushes and commutators. So, if we will increase the peripheral speed or speed of the machine we have to design the brushes and commutators arrangement appropriately and core losses and cooling and saturation limits all the other restricting factors with respect to the speed. Finally, power factor. If we will increase the power factor automatically the output power also going up.

The max to max the power factor we can attain it is equals to 1 in a ideal case or low power rated machines, but greater than 1 is not possible. Always in an electrical machines because of the air gaps and leakage inductances there will be a power factor value. Some power factor will be there less than 1 will be exist in the machine and the magnetizing currents also another restricting factor. So, based on this aspects we can increase or decrease the output power depends upon the available materials, available thermal management and available structures with respect to the application like DC machine we are designing. So, we have to design the brushes and commutators accordingly or synchronous machine we are designing only brushes requirement is there for induction machine there is no need of any brushes.

So, we can go for higher speeds also. So, depends upon the limitations. So, with respect to the these 5 parameters we have to design the machine and we have to select the D square l product. Now, we will see what is the relation of the output power and torque developed by the machine with respect to the volume. To achieve the certain torque densities what kind of how much volume of the machine we have to select that we will see now. So, the power equation I am rewriting it again.

This is the power equation we have derived right. Now, the torque is nothing, but in terms of output power P naught equals to 2 pi synchronous speed into electromagnetic torque divided by 60 right. So, substitute this equation in the actual power equation then 2 pi Ns into T e divided by 60 is equals to pi square by 120 power factor efficiency magnetic loading and electric loading volume product and synchronous speed. So, the synchronous speed will be cancelled and 1 pi also will be cancelled and this will be like this. So, the final torque equation for a particular machine with respect to the volume is nothing, but pi by 4 power factor and efficiency and electrical load magnetic loading and electric loading volume product.

So, this is the torque equation the equation number 7. Torque equation in terms of volume, in terms of magnetic loading and electric loading and others. So, here we can see that torque also directly proportional to the magnetic loading and electric loading El and also proportional to the volume product. So, if we increase the volume product or if we increase the magnetic loading or electric loading then we can increase the torque capability of a particular machine. With this thing I am concluding today lecture the summary of today lecture is for a given power rating or for a given torque rating how to decide the main dimensions of the electrical machine or volume product with respect to D square l thing.

So, here D is nothing, but inner diameter of the stator and l is nothing, but length of the structure stator core. So, by considering the D and l value in terms of volume how to decide the dimensions we have discussed. Thank you.