Course Name: Design of Electric Motors

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Title: Stator Winding Design-Single Layer Winding

Greetings to all. In this lecture, we will discuss the stator winding design with an example on single layer full pitch winding. Here, with respect to the single layer full pitch winding, how to select the number of coils, coil pitch and how to place the different coils in different slots and winding diagram and how to select the number of turns per phase, etcetera, we will discuss in detail. Let us consider a 24 slot 3 phase 4 pole winding and 24 slot stator core frame. We can see here the slots are marked 1 to 24 and the winding design procedure will be same for any type of machine. First, we have to analyze with respect to the given data, how many slots given, how many number of phases and what is the number of poles.

Then, we have to calculate the pole pitch, coil pitch and all those things. Then, we have to calculate the number of turns per phase as per the Faraday's law of voltage equation. Then, we have to make the coils. After making the coils one by one, we have to insert in different slots.

After inserting all coils with stubbed winding and arrow check approach, we have to make the connections. Then, verification of magnetic pole formations with right hand thumb rules and winding check with respect to the short circuit with phase to phase or phase to the body, neutral to the body. If nothing is wrong, then we can complete the windings and we can bring all 6 terminals out from the machine and we can test at the operating conditions. The basic equations we can consider here. Slots are equal to number of phases into number of poles into slots per pole per phase.

For a given example, 24 slots, 3 phase, 4 pole winding, the slots per pole per phase is equal to 2. That means, phase spread or phase span or phase belt with respect to each and every phase under one particular pole. If you will take 6 slots are coming under one pole, first the 6 slots. So, 2 slots will be accommodated for each and every phases and pole pitch is equal to 6 and with respect to the full pitch winding coil pitch is equal to pole pitch and that is 6 slots. So, the conductors in first slot as well as second slots are connected.

As a first step, we have to calculate the number of turns per phase as per the Faraday's law of voltage equation and then, we have to calculate the wire SWG. After knowing these two things and how many number of coils required, we have to find that is 12 coils required. So, these 12 coils with respect to the coil pitch 6 slots, we have to make and given number of turns per slot, n phase is the total number of turns per phase and n slot or n coil, coils per each slot or conductors per each slot, we have to calculate. Based on that thing, we have to make the coil. Each coil set consists of n coils, n number of turns per coil.

So, after making the 12 coils, we have to insert these 12 coils one by one in different slots. The slot opening width is 2 to 5 times the conductor cross sectional area. So, 2 2 conductors are 3 3 conductors with respect to each and every coils, we have to insert into the slots. So, with respect to the coil 1, the first coil side we have to place in slot 1. I am considering slot 1 as reference.

So, the first 6 slots with respect to the pole 1, this is for reference to make the winding. So, I am considering slot 1 as a starting point and this coil side will be placed in slot number 1 and the second coil side of this coil 1 is placed in slot number 7. 1 plus 6 is equals to 7 or 1 minus 6 also we can do. So, coil sides we have placed in slot number 1 and slot number 7. We can see here after making the coil one by one, we have to insert this is slot number 1 and this side slot number 7.

Next, coil 2, one coil side we have to place in slot number 2 and other coil side we have to place in slot number 20. How we are getting slot number 20 means 2 minus 6, it will give minus 4 plus 24 slots will give plus 20. One coil we have to place in a forward direction, other coil we have to place backward direction to make the winding symmetry with respect to end rings. Next, same fashion the conductors with respect to the next phase like 2 slots are related to the A phase, then 2 slots are related to the next phase and other 2 slots are related to the third phase. The slots per pole will be 6 in that slots per pole per phase are equals to 2 only.

So, the second phase conductors are coil we are placing in slot number 3 and slot number 9. This is slot number 3 and this is slot number 9. Next, coil we have to insert slot number 4 and slot number 22 in this slot as well as in this slot with respect to my reference point fourth slot is here and twenty second slot is here. These two are already connected. Once we have done the coil like this fashion, one coil side we are placing in fourth slot, other coil side we are placing in twenty second.

We can see here this one is sitting in fourth slot and this one we are placing in twenty second slot. So, like same fashion we can place the coils related to the C phase or third phase. At the end, we will see which one is A phase, which one is B phase, which one is C phase with respect to the symmetrical 120 degree distribution, we can give the excitation. So, the coils we have next coil we have to place in slot number 5 and slot number 11. This is slot number 5 and this is slot number 11.

5 plus 6 is equals to 11 and 6 plus or 6 minus 6 is equals to 0 plus 24 is nothing but twenty fourth. So, this coil is a representation of the actual coil like this fashion. This is the coil representation we are showing as an inductor form. So, one coil side we will place in slot number 6 and other coil side we will place in slot number 24 in this fashion. The next thing is already seventh slot is filled.

So, the next eighth slot we have to fill. So, for that the coil we have to fill in eighth slot and fourteenth slot. 8 plus 6 is equals to 14. So, these two slots are filled with next coil. Next ninth is already filled.

So, tenth slot we have to fill. So, 10 plus 6 is nothing but 16. So, tenth slot and 16 slots are filled with next coil. So, it has two terminals. One terminal is 10, other terminal is 16.

So, whatever it may be the coil, we are placing in slot number 10 and 16 means the starting point will be at tenth slot and ending point will be at sixteenth slot. Next, with respect to the next coil, we are placing in slot number 12 and slot number 18. 12 plus 6 will give 18. So, this is the slot coil we can see here. So, we have to make like this kind of coils initially 12 coils.

So, each coil side we have to place one by one. This coil side we are placing here in twelfth slot. This coil side we are placing in eighteenth slot. So, this is the stator core lamination. So, the opening of this stator core lamination is 2 to 5 times the conductor cross sectional area.

So, this much, this many number of turns we cannot place directly. So, one by one we have to place in the slot. So, keep it in mind that this coil side we have to place in one slot and this coil side we are placing in other slot. So, that is we can see here twelfth slot and eighteenth slot. Next coil we have to place in thirteenth slot and 13 plus 6, it will be nineteenth.

Thirteenth and nineteenth slots are filled with next coil. So, the next empty slot is already fourteen slot is filled. So, fifteenth slot we have to place the coil. So, this is one coil side. Next coil side will go fifteen plus sixth that is twenty one slot.

We can see that one fifteenth plus twenty one. So, fifteenth to twenty one we are placing the next coil and same fashion seventeen to twenty three because already sixteenth slot is filled. So, the next empty slot is seventeen. So, seventeenth slot and twenty three slots are filled with one coil. So, all twelve slots or twelve coils with respect to the twenty four slots are filled now.

That means, twelve coils we have placed and end terminals we can see here. Twenty four end terminals we are getting with respect to twelve coils placements in twenty four slots. We can see here n number of terminals coming out while doing the experiment or rewinding at the lab. In this image, we can see the n number of terminals coming out that is twenty four terminals came out. Now, how to connect these coils or these terminals to make the symmetrical three phase machine winding.

So, the traditional way we can go ahead with the developed winding diagrams and other things, but the easiest way to do the winding connections will make the stubbing approach with arrow representation. We can see what is the meaning of stubbing here to make the connections. The stubbing is nothing but these four coils with respect to the a phase, next four coils with respect to the b phase, next four coils with respect to the c phase. We will represent as a stubbed winding manner and each and every stubbed winding we can assign one arrow. We will assign one arrow based upon that arrow.

You will connect the windings. We can see here the coil which is placed in slot number 1 and slot number 7. I am representing with one stubbed winding. The number of coils for each stubbed winding will vary with respect to the single layer winding or double layer winding or fractional slot windings etcetera. For single layer winding, each stubbed winding consist of only one coil that is 1 to 7. We have represented here 1 and 7 that stubbed winding starting will be 1 and ending will be 7.

It is a virtual representation. We are utilizing to make the connections. The number of coils per one stubbed coils, we can see here for single layer winding, it will be 1. For double layer winding, it will be slots per pole per phase. Let us say slots per pole per phase is coming to for double layer winding. Each stubbed winding consist of two coils.

This is one stubbed winding representation that is the virtual representation with respect to the physical coils. This is coil 1 and coil 2. These two coils are placed in four different slots, but starting will be 1 and ending will be 7. Let us say that 1 and 7 starting and ending terminals, we are representing with respect to the stubbed winding. For multi layer winding also, it will be slots per pole per phase.

If it is a fraction, let us say it is coming as a fraction 3 by 2. So, one stubbed coil consist of 2 and other stubbed coil consist of one coil because fraction we cannot make it. These windings cannot split into two parts. So, half winding here and half winding in other stubbed coil, we cannot make it because of that reason. If 3 by 2 is coming, in that case, one stubbed coil with two windings and other stubbed coil with one winding.

So, this is stubbed coil winding 1 and stubbed winding 2. It is the virtual representation of physical two coils related to one phase and one coil representation with respect to the same phase. How many stubbed windings will come? Like this, how many stubbed windings are there to make the winding connections? For that, the equation is total number of phases into slots per pole per phase into pole phase. It will give the total number. For the given example, 24 slots, 4 pole, 3 phase machine, 12 stubbed windings are there.

So, for first coil, we are representing with one stubbed winding that is this one. That is the starting will be 1 and ending will be 7. Same fashion will represent remaining 12 coils with 12 stubbed windings. The number of stubbed windings depends upon the number of coils and number of poles also.

We can see this one here. Number of stubbed winding depends upon the number of pole piles as well as number of phases and slots per pole per phase. So, the stubbing with respect to the coil 2 that is 3 and 9. The coil which is placed in slot number 3 and 9, this is this one and this one, I am representing as a slubbed coil 2 and first one is 1 and 7. Third coil with respect to the C phase or third phase, I am representing with 5 and this thing and which is placed in fifth slot and eleventh slot, this one.

So, this is fifth and this is eleventh. This is the stubbed coil representation with respect to the third winding or third coil. Same way, we can represent all 12 stubbed coils. We can see here red color, 4 stubbed coils are there. Then, brown color, 4 stubbed coils and blue color, another 4 stubbed coils are there. So, all 12 stubbed coils we have to connect to complete the winding.

So, these stubbed coils are representing the virtual manner of the physical winding. Let us say this is the coil 1 means coil 1 representation. I am making as a stubbed virtual representation. Starting will be 1 and ending will be 7. So, how to connect this stubbed coil means simply arrow representation approach.

We will utilize it. Let us say first stubbed coil, one arrow will be forward. The arrow representation rules will be the symmetrical machines and the greater than 3 phases machines. One arrow will go forward and other arrow will go backward. For asymmetrical machines and even number of phases like 2 phase machines, 2 arrows will go forward and 2 arrows will go backward. The number of arrows vary with respect to the number of stubbed windings.

Here, it is a symmetrical 3 phase machine. One arrow will go forward manner and other arrow will come backward manner. So, this arrow with respect to each and every stubbed coils will represent now. So, with respect to the first stubbed winding, the arrow will be forward manner S1. We can see here with respect to the second stubbed winding that is this one B related one, which is starting will be 9 and ending will be starting will be 3 and ending will be 9.

That arrow will be backward manner. We can see here. So, the third stubbed coil arrow will be forward, then again backward, then forward, then backward. So, one arrow forward and one arrow backward, one arrow forward and other arrow will be backward. We can see here 6 arrows I have drawn here with respect to first 6 stubbed windings. Next 6 also we can see here total 12 stubbed terminals we have and 12 arrows I have represented here S1 to S12. Since, it is a symmetrical machine one arrow forward, one arrow backward, one arrow forward, one arrow will be backward.

So, with respect to the arrows direction, we will connect all these stubbed windings. Stubbed winding is nothing but virtual representation of these terminals. So, these terminals we will connect by utilizing the arrow check representation.

Let us consider the number of poles. 4 poles are there. Each pole consists of 6 slots. We can see here pole representation. At the end after making the winding connections, we will see based upon the magnetic principles, the number of poles are forming or not. So, remove the mechanical or physical representation of the conductors with respect to all coils.

We will follow only arrows now. The stubbed windings with respect to the A phase are these 4. The coil which is placed in slot 1 and slot 7, the slot 8 and slot 14, slot 13 and slot 19, slot 2 and slot 20. The virtual representation of stubbed windings will be like this and arrow for each and every stubbed winding we can see here. Based upon this arrow direction, we will connect the windings.

This arrow is representing only how we can connect the windings. It is not representing the current. We can see here the head point of the S 1 is connected to the tile point of S 4. That is what we have done here. Let us consider this is the reference point and tail point of S 1. I have considered the reference point A and head of the S 1 is connected to the tail of the next arrow.

Walk through along the arrow directions and red color arrow, we can see here in this fashion and here arrow will be in this fashion. S 1, I am redrawing here as blue color 1 and this head point I am connecting to the tail point of this arrow. Then, next point this arrow head will be connected to the next arrow tail point that is S 7. So, S 4 head point is connected to the S 7 tile point.

The next S 7 head point is connected to the S 10 head point. We can see this is the S 10 tile point. This is the S 10 one. Finally, we can make the connections. So, initially we are coming from this point and we are travelling through this stubbed winding. So, with respect to the arrow, this head is connected to the this tile arrow S 4 winding and this head of S 4 arrow is connected to the tile of S 7 arrow that is this connection and head of the S 7 arrow is connected to the tile of S 10 arrow and finally, head of the S 10 is coming out that is A dash.

So, we can see the 4 coils related to the A phase winding are connected in this fashion and forming two terminals A and A dash. Based upon the star delta, we can connect in that fashion either it is star or delta. Same manner, the stubbed windings with respect to the B phase are 4 coils are there, 4 stubbed windings. Follow the arrows. Let us consider one starting point that is B and the head point of S 5 is connected to the tile point of S 8 and same thing you can visualize in this image.

This one is connected to this thing and S 8 head point is connected to the S 11 tile point that is this one S 8 head point. This is S 8. So, this head point is connected to the S 11 tile point and S 11 head point is connected to the S 2 tile point that is this connection and finally, S 2 head is coming out that is B dash. So, all 4 coils related to the B phase are connected in this fashion and the winding connections with respect to B phase also done with arrow representation.

Only we are following the arrow head and tiles. It is the simplest way to make the winding connections. Same fashion for C phase S 3 arrow is in this direction. So, head of arrow will be connected to the tile of next arrow S 6, then other arrow tail point, then head of the S 9 arrow is connected to the tile point of S 12 arrow, then S 12 head we are bringing out as C dash terminal.

The starting will be C. We can connect any arrow with any manner. Let us say S 3 is in this fashion and in this fashion, right. Initially, I can connect S 3 to S 9 and S 9 head to S 6 tile point and S 6 head point. I can connect to S 12 and S 12 head point.

I can bring it out any manner. I can connect it. One more connection with red color one already we have seen in this fashion. These 4 arrows with respect to the head and tiles, we have to connect. So, head to next arrow tile and head to another arrow tile in that fashion, we have to connect. Then we can make the symmetrical windings with respect to all these 3 phases.

This is the 3 phase, sorry, C phase winding connection. So, all 3 phase connections we can see in this image by utilizing the stubbed winding approach and arrow check representation. This is the mission winding finishings with threading and other things. Now, these are the connections with respect to the 3 phases, right. Let us consider an instant where A phase current is positive, B phase current is positive and C phase current is negative. Whether with respect to these winding connections, the magnetic poles are forming or not, we will see now.

With respect to the A phase positive current, current is entering at coil side placed at the slot number 1, right. So, here it will be cross at slot 1 and same fashion current is leaving out from the slot number 7 coil side. So, we can apply the right hand thumb rule and we can see the flux lines in this fashion clockwise manner. Here, flux lines will be in anticlockwise manner in this direction and here it is in the clockwise direction and same fashion at 14th, the coil side placed at the 14th slot is current is entering and 8th slot current is leaving.

It is dot, it is anticlockwise flux lines we can see here. Same way, current is entering at 13th slot coil side and leaving at 19th slot coil side entering here. That means, clockwise direction of flux lines and leaving at the 19th slot coil side in opposite direction, the flux lines we can see. Next, the current is entering at coil side which is placed in slot 2. Here also, current cross with respect to the cross, we can see the clockwise direction of flux lines and at 20th slot current is coming out. That means, opposite direction of flux lines just apply a thumb rule and identify the flux line direction.

Same manner, we can see for B phase, current is entering at 10th slot, 21 and 22 and 9th slot. So, 10th slot is here, current is entering, 9th slot also current is entering and 21 slot and 22nd slot current is entering. Clockwise direction of magnetic flux lines we can see in these four conductors. In the remaining conductors like 16, 15, 14 and 3rd, we can mark it 3, 4 and 15, 16.

The current is coming out with respect to these connections. So, where the flux lines are going in opposite direction, we can see here, this is the opposite direction as compared to the clockwise direction. It is anti-clockwise. Same manner C phase also, we can analyze at the end. If you will see the flux loops, the flux loops under slot 2 and slot 3 are different.

We can see here, this slot number 2 and slot number 3 are different. Flux lines loops are in opposite direction. The flux loops are in same direction from slot number 2 to slot number 21. So, these six loops will be in additive manner and it will form a bigger flux loop in this manner and next six loops, which are in same direction will form another flux loop. Here also, one more flux loop will form and fourth flux loop also will form. That means, four number of poles are forming with respect to these three windings connections and given current instant.

If you will change the current instant, A equals to plus and B equals to negative and C equals to positive current, same number of poles will form, but this field poles will be, the angle will be changed with respect to the rotating magnetic field. Now, how to calculate the number of turns per phase? For that thing, we will consider the Faraday's law of voltage equation, where the voltage is equals to number of turns into d phi by dt change in flux and the flux, if you will represent in terms of B into A. Here, A is nothing, but area of cross section with respect to the flux lines under one particular pole with respect to air gap and finally, we can get the voltage is equals to 4 into number of turns per phase into area of cross section with respect to one pole at the air gap and average flux density and frequency of operation. To convert average voltage to RMS voltage, we have to multiply with pi by 2 root 2 and at the end, we can add the winding factor with respect to the type of winding.

Then, we will get the complete voltage equation in terms of RMS. From here, we can calculate the number of turns per phase. We have to consider the phase voltage RMS from the given problem statement and we have to calculate the air gap flux cross sectional area with respect to one pole that is pi into Dis by P into l e. Here, Dis is nothing, but stator inner diameter and L e is nothing, but core length and average flux density.

We can consider 0.5 to 1.2 Tesla and f is nothing, but frequency of operation and k 1 is the fundamental winding factor. It is a combination of pitch factor, distribution factor, skewing factor and slot opening factor.

Cumulatively, we can select the winding factor from 0.9 to 0.98. After substituting all these numbers, voltage we know and air gap cross sectional area also, we can calculate by knowing the number of poles and inner diameter of the stator and length of the core. We can select the air gap flux density of operation with respect to the given material or type of machine and frequency operation also, we know and consider the winding factor. Then, we can calculate the number of turns per phase. After calculating the number of turns per phase, in order to calculate the number of turns per each slot or conductors per each slot, we have to consider first how many coils are there.

Here, each phase has 4 coils. So, that 4 coils into number of turns in each and every coil. So, n coil we have to select that is equals to total number of turns per phase divided by coils per phase will give the number of turns per each coil. That equation is this one. Coils per phase we can calculate with respect to this equation slots per pole per phase into pole pairs into number of layers or coil sides per each slot.

After knowing the number of turns per each and every coil, we have to verify the window area. Here, the area with respect to the slot is nothing but A s into window factor is nothing but K w how much window we are utilizing to make the winding because this slot area we are utilizing for conductors.

These are the conductors and some liners that is insulating paper between the slot and winding. This is the one and we have to place some spacers if it is a multilayer winding and closers and some wooden sticks for closing the slot with respect to the conductors. All those things we have to consider with respect to the slot area. It is a combination of windings, liners and spacers and wooden parts and closers. All those things we have to consider. The slot area into window factor should be greater than the number of layers or coil sides per each slot into number of coils per each slot or number of turns per each slot into cross sectional area of each conductor.

Here, if it is a two layer winding, the number of turns per each coil will be half. We can say like that manner and here n is equals to 2 and then area of cross section with respect to each wire is nothing but current divided by current density that is I phase RMS. We have to calculate from the given power and voltage and power factor. Next thing is how we can make the winding symmetry with respect to the end winding. We can see here, this is the machine where all coils are placed in forward direction.

Here some gap is there on both sides. We can see here in this place, highlighted red color place, there is no windings. All end windings are placed at one particular place. The width of the stator back iron is required here. Let us say 6 coils are there means 6 into coil width that much width is required to accommodate or to place this type of windings.

Here there is no windings. In this width, we have to place 6 coils. In some machines where the back iron width is small means we can see here this is the back iron width. In this place, we have to place the 6 coil sides width of 6 coil sides. Here there is no symmetry with respect to the method 1 where all coils are coming forward direction only. So, the end windings will accommodate or will come into one particular place and this width is exceeding the back iron width that is dc.

Let us consider depth of the back iron. If the end windings width is let us say x is greater than the back iron depth, then the rotor placement is not possible. It is difficult to place the rotor and end winding leakage flux component also will vary and it may increase also. To make the winding symmetry with respect to the end windings in this place, we have to make one coil will be forward manner, other coil will be backward direction. Same fashion 3 to 9 will be forward, 4 to 21 will be backward.

Like this fashion, we have to connect one will go forward, one will go backward. So, always we will see the width will be 2 coil sides at the end ring side. Like this way, we can make the symmetry in the winding. We can see here the width of end rings at any given point along the stator circumference is same. The width I am talking about this width, the red color one. The width with respect to the end windings always 2 windings because one coil is going forward, other coil is coming backward manner.

Whereas in the earlier case, if we will see all 6 coils are coming together that means, the coil width or end winding width will be 6 times the coil width. Another way to get the symmetry with respect to the end rings in this place, 2 coils we can place forward manner and 2 coils we can place backward manner. In this fashion, we can place that means, 1 to 7 slot we can place one conduct coil and 2 to 8 slot we can place second coil. Thus, coil sides related to the next adjacent phase. Let us say these 2 coils are related to

A phase and next 2 coils that is 3 to 21 and 4 to 22, those 2 coils will go backward manner.

Then 5 to 11 and 6 to 12 coils will come forward. Then 9 to 10 and 9 and 10 coils will go backward. In that fashion, it will go one coil, one phase will be backward, other phase will be forward. In that fashion, the windings we have to distribute. Then only we can see the symmetry with respect to the end windings that is this arrow mark. Otherwise, at this particular place that is at this particular place, you will see the all end windings are overlapped each other and this width is greater than the depth of the back iron, then rotor placement is not possible. The same difference we can see here for a symmetrical machine in the entire core, the width of the end windings is same.

This end winding I am talking here. We can see in this portion and in this portion, there is no end winding. In this portion, red color circled portion, there is no end winding. All windings are coming at this particular point. If this width is exceeding the back iron depth, then the rotor placement is difficult. Whereas, in symmetrical distribution, we can see all windings are symmetrically distributed and enough space is there to make or to place the rotor.

The difference is end winding distribution is symmetrical and end winding distribution is asymmetrical in this condition. With this, I am concluding this lecture. In this lecture, we have discussed the winding design example with respect to single layer full pitch, where we have discussed how to make the winding diagram, how to select the number of coils, coil pitch and how to make the stubbing approach based connections, etcetera. Thank you.