Course Name: Design of Electric Motors

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Title: Variable Pole Machine Stator Winding Design (Pole-Phase Modulation)- 1

Greetings to all, in this lecture we will discuss the stator winding design for variable pole machines. Here how to change the number of poles and phases without changing the stator winding connections by utilizing the pole phase modulation techniques for induction machines we will discuss in detail. Let us consider an example 18 slot 3 phase 2 pole winding slots per pole per phase is equals to 3. Since it is an integer the integral slot winding is possible pole pitch is equals to 9 that is 18 by 2. Let us consider it is a full pitch winding then coil sides per slot will be 1 and single layer winding and coil pitch is equals to pole pitch 9 slots is nothing, but coil pitch. Assume the winding is already done for 3 phase 2 pole and all 18 terminals are taking out.

Here each coil has 2 terminals right this is 1 and 2 like this 9 coils we have. So, total 18 terminals are taken out. Now, we are assume that winding is already done we will not discuss the stubbing approach and how to make the coil connections. The coil is already coils are already placed and complete winding is done with respect to one particular current instant how the flux loops will form we will discuss.

This is the first 3 coils related to the A phase. The coil first coil is placed in slot 1 and slot 10, second coil is placed in slot 2 and slot 11, third coil is placed in slot number 3 and slot number 12. These are the 3 coils. And next the coils related to the C phase are placed in respective slots under the each pole and B phase also we can see. The phase span here 3 3 slots we can observe from this image 3 slots under 1 pole 9 slots are there from this point to this point each phase is occupied 3 slots.

Let us current consider a 3 phase currents which are displaced by 120 degrees and we will excite the these 9 coils to make the 3 phase winding symmetrical 3 phase winding. For that we have to connect these 9 coils in series manner. So, these 2 coils are connected in this fashion next 2 coils are connected here. So, series connection I am doing with respect to all 3 phases and in order to give make the 3 phase star connection

here neutral connection also I have done. So, from these 3 terminals we have to give the 3 phase supply.

Let us consider an instant where A phase current is positive, B phase current is also positive, C phase current is equals to negative with respect to this currents how the flux loops will form we can analyze now. So, with respect to the A phase positive current here all are cross. So, for current is entering means flux loops are in clockwise manner if current is leaving flux loops are in anticlockwise direction and if current is entering for dot current is entering for cross and current is leaving for dot and the flux loops direction is represented here then this side it is dot where the flux loops are in opposite direction anticlockwise manner same way for B phase also we can analyze the flux loops and this side current is coming out flux loops are in the opposite direction and for C phase current is negative that means, at the C starting terminals current is coming out that is dot polarity and at the C dash side current is entering. So, with respect to the dot and crosses we can see the resultant flux loops for all 18 cell sites if we will observe from this point to from starting point A to the ending point B the flux loops are in additive manner this 9 flux loops and this side these 9 flux loops are in the same direction these also in additive and we can see the resultant flux loops are in this fashion this side north and that side south 2 poles are forming with respect to this type of winding connections in order to change the number of poles from 2 pole to 4 pole these winding connections we have to remove and we have to change the mechanical connections as well as excitation also here we can see the slots per pole per phase is coming 3 right if we will change the number of poles to 6 slots per pole per phase will come 1 that means, in this duration is A and then in this duration it is B and then in this duration we have to place the C phase conductors slots per pole per phase should come 1 in order to make 6 pole combination that means, we have to change the excitations also. So, let us consider the 3 phase currents which are displaced by 120 degrees and in order to make the 6 pole arrangement whatever the coils are which are connected in series has to be disconnected and excited with 0 degree 120 degrees and 240 degrees here it will be 0 and 0 0 all 3 phase 3 coils are in series and having the same current, but in order to make slots per pole per phase is equals to 1 as per the 6 pole winding arrangement we will change the excitation like A B and C dash the opposite side the return conductors are A dash C and B dash because the winding is already done for 3 phase 2 pole that means, coil pitch is 9 slots with respect to the conventional representation conductors in first slot and fourth slot has to be connected for coil span of 3 for 6 pole winding, but we have already done the winding for 3 phase 2 pole manner with respect to the 3 phase 2 pole winding how to achieve the 6 pole combination we are doing now for that purpose we have to change the mechanical connections and we have to give the excitation in this fashion 0 120 240.

Next similarly B phase winding also we have to disconnect the mechanical connections and we have to give the excitations in this fashion same way C phase also we have to

remove the mechanical connections and excitations are given in this manner. Now, we can see under each pole 3 3 slots are there and all these coils related to those 3 slots are related to 3 individual phases and slots per pole per phase is equals to 1 only here in order to make the 3 phase operation with respect to the 3 phase machine these windings has to be connected in this fashion. So, for C phase it will be opposite manner for A phase it will be in this fashion A dash is connected to A and next A dash is connected to A this is ending terminal this is starting terminal of A, here for C phase starting terminal will be this thing and C dash is connected to the C terminal of next coil C dash is connected to the starting of next coil this is the ending, next for B phase this is starting B and B dash ending is connected to this thing and B dash ending is connected to the starting of next coil, and this is ending for B phase one side we will make it as star other side we will give the three phase supply. Let us consider an instant this one where A phase current is equals to positive B phase current is equals to positive and C phase current is equals to negative. So, with respect to this instant of currents we can see the flux loops here A phase current is positive that means cross C phase current is negative with respect to the C dash means it is again cross here also cross.

So, the flux loops are in clockwise direction other side flux loops are in opposite direction for a dot current which is current is coming out same manner here current is entering with respect to these three loops and current is leaving here and here remaining three loops like three conductors here dot and this side it will be cross. As per the cross and dots with respect to the right hand thumb rule we have drawn the flux loops for cross it will be clockwise direction for dot it will be anticlockwise direction. The resultant flux loops will form in this manner we can observe six flux loops are forming and that means six poles are formed here with respect to this type of winding arrangement from this type of winding arrangement to this type of winding arrangement we have changed case 1 to case 2 where it is 2 pole and this one is 4 pole sorry 6 pole it is this winding arrangement will give 6 pole. You can see here we are changing the manual mechanical connections manually we are changing and number of terminals required in order to change from 3 phase to 4 6 pole is more that are the drawbacks with respect to conventional pole changing techniques higher number of terminals required and manually we have to change the connections and customized winding design also required. If the winding is designed for two different type of pole combinations let us say one winding is for 2 pole other winding is for 6 pole then the copper utilization factor is less in order to make the symmetrical pole formation without changing the stator terminals here we are changing the stator terminals with respect to case 2 in this fashion with respect to the case 1 in this fashion right in the series manner we can see this is case 1 left side and right side case 2.

So, no need to change this kind of connections in pole phase modulation and we can change the number of poles symmetrically how to achieve the symmetrical pole formation without changing the stator terminals we will discuss now. The pole phase

modulation without changing the stator winding connections means we have to utilize the multi phase machines whereas, the conventional pole changing techniques with manually changed mechanical connections has been done for 3 phase machines. So, with multi phase machines the pole phase modulation is possible the generalization with respect to the pole phase modulation equation will be simple for q is equals to 2 into number of phases into number of pole phase into slots per pole per phase is the basic equation from that in order to change from one pole combination to other pole combination this is pole phase combination 1 and this is pole phase combination 2.

The pole change ratio is the key parameter the pole change ratio should be an odd positive integer in order to change from one pole combination to other pole combination.

\Let us say initially pole combination will be 2 next pole combination is 6 as per this equation 6 poles means 3 pole pairs divided by 2 poles means 1 pole pair it will give 3 for this example if we are changing from 2 pole to 6 pole the pole change ratio is 3.

So, if pole change ratio is equals to 2 what it will happen if pole change ratio is equals to 4 what it will happen if pole change ratio is equals to 3 how the flux loops will form we will see now. The generalization states that with respect to the pole phase modulation the pole change ratio should be odd positive integer first I will consider the pole change ratio is equals to 2 in order to change from the change the number of poles from 2 to 4. Here the current instant is considered A phase equals to positive B phase equals to positive C phase equals to negative currents and the windings are placed in this manner where the coil pitch is equals to 12 with respect to 24 slots and 2 pole 24 divided by 2 is nothing, but pole pitch. So, for pole pitch winding it is same as the coil pitch. So, first slot and thirteenth slot conductors are connected.

So, this point. So, conductors placed in this slot and conductors placed in this slot are connected A and A dash. So, in order to change the number of poles the slots per pole per phase should come 6 and phase spread also should be 2. The red color representation we can see here symmetrically A A and then C phase then B phase 2 2 slots are occupied by 3 different phases even though the coil pitch is 12. The coil pitch is done is 12 here and winding is already done for slot number 1 to slot number 13 next slot number 2 to slot number 14 in this fashion winding is done with respect to this winding we can change the number of poles that is in this fashion red color excitations we can see.

So, with respect to the red color representation the flux loops for this kind of currents we can see here that is cross with respect to the A and again for C phase negative current that means, at C dash again it will be cross for B phase also it will be cross. So, all conductors having the same current that means, flux loops are in the same direction we can observe that thing it is in a clockwise direction all 6 flux loops. Next in the other side the current is coming out that is dot and flux loops are in the anticlockwise direction and

in order to change from 2 pole to 4 pole we have changed the excitation here earlier here current is coming in and flux loops are in the clockwise direction. Now, we can see the flux loops are in anticlockwise direction. So, because of that reason we can see with respect to the dot the flux loops are in the opposite direction and in this manner 4 flux loops resultant flux loops will form here if you will observe that the flux lines are in this direction with respect to the flux loop 1 and 2 and 3 and 4.

So, the resultant flux loops will form in this manner only 2 poles are forming if we will consider the pole change ratio is equals to 2 even though we are trying to change from 2 pole to 4 pole the at the end we are seeing only 2 poles there is no change in number of poles if the pole change ratio is equals to 2. Now, we will analyze if the number of pole change ratio is equals to 4 same example 24 slot 3 phase 2 pole if we will try to change from 2 pole to 8 pole how the flux lines will form we will see same way here excitations are changed with respect to the 8 pole the slots per pole per phase should come 3 now for 8 pole. So, from this point to this point related to 1 particular pole that is this 1 to this 1 and next 3 slots related to 1 particular pole and these 3 slots like this 3 slots are related to 1 particular pole and slots per pole per phase should come 1 8 into 24 divided by 8 into 3 that is 1 slots per pole per phase and how the flux lines will form for 2 pole already I have presented in the left side in order to change from 2 pole to 4 pole each pole has to be divided into 4 parts that we have already done and excitation also changed with respect to this particular excitation a phase current is positive c phase current is negative means again here cross will come and b phase current positive means current is entering all 3 are cross. So, for cross current flux loops will be in clockwise direction for dot flux loops are in opposite direction because these 2 conductors are connected the coils are placed in slot 1 and slot 13 are connected because of the winding related to the 2 pole we are trying to utilize the same winding and we are trying to change the number of poles here and the flux loops with respect to the next 3 conductors we can see here these are the 3 flux loops where the current is changed now it is dot and flux loops are in the opposite direction same way related to the other 4 conductors and other 3 conductors we can see which are in the different having the different current and different flux loops we can see the resultant flux loops will form in this manner the flux loops which are having the same direction with respect to that thing the resultant flux loop will form. So, finally, these 2 flux loops are in additive manner this is loop 1 and loop 2 and these 2 loops also in additive manner are in the same direction it will form 1 bigger loop if we will see only 6 poles are forming we are trying to change from 2 pole to 8 pole, but here only 6 poles are formed that means unequal strengths of the magnetic poles and unequal widths of the flux loops are formed with respect to the pole change ratio 4.

This unequal pole widths and unequal strength of the magnetic poles results in torque pulsations and stress with respect to the different conductors and losses temperature rise and etcetera in order to avoid this thing we have to keep the pole change ratio always

positive and odd integer. Now, we will try to make the pole change ratio from 2 pole to 6 pole that is ratio is 3 here also excitations has been changed with respect to the 3 phase 6 pole and we can see the flux loops how it is forming in between the 3 conductors we are changing the excitation, but the symmetricity we are not losing and the resultant flux loops will form in this fashion for 6 pole 3 phase 6 pole and 6 poles are forming here. In order to make the symmetrical pole formation from 1 pole combination to other pole combination the pole change ratio should be an odd positive integer. In order to minimize the number of terminals as well as without changing the stator connections to make the or to change the number of poles we have to utilize the multi phase machines the advantage with respect to the multi phase machines are lesser space harmonics higher efficiency and better power distribution. We can see the torque per phase or power per phase will be one third in 3 phase machines it for example, for 9 phase torque per phase or power per phase will be one ninth and improved fault tolerant capability if 1 phase or 2 phases become faulty the machine is capable to machine will not function in the 3 phase case and whereas, in multi phase machine if 1 phase or 2 phases becoming faulty also the machine will work with reduced power and reduced ratings of the semiconductor devices like in 3 phase machines the ratings of the voltage and current will be V and I in the multi phase machine for example, for 9 phase machine either voltage or current will come down by 3 times with respect to the 3 phase machines and torque enhancement by injecting the lower order harmonics like fundamental third harmonic and fifth harmonics and fifth seventh and ninth harmonics by injecting these things how the torque can be enhanced in multi phase machines.

We can see in this reference paper and lesser space harmonics with respect to the 3 phase machines fifth and seventh are the lower order dominant harmonics with respect to the 9 phase machines seventeenth and nineteenth are the lower order dominant harmonics. The generalized equation with respect to the pole phase modulation is this thing where Q is equals to number of phases into number of poles into slots per pole per phase in order to change from one pole combination to other pole combination the pole pair should be P1 should be less than P2 that is let us say from 2 pole to 6 pole we are changing the ratio should be 2 pole to 6 pole we are changing. So, initially pole pairs will be 1 should be less than the second case pole pairs will be 3 and pole change ratio should be odd integer and it should be a positive number greater than or equals to 1. If pole change ratio is 1 then there is no change in number of pole pairs and if pole change ratio is 3 then number of poles are changed from 1 to 3 and if pole change ratio is equals to 5 the number of poles we can change in a ratio 1 is to 5 and the number of poles and phases will change with respect to the excitation from the power converter in the pole phase modulation and there is no need to change the mechanical connection and slots per pole per phase should be a constant number that we can see here. Let us consider an example 36 slot machine where Q is equals to 36.

How we can change the number of poles and phases in a symmetrical manner? We can see here Q is equals to m into p into q in order to change from 1 pole combination to other pole combination. Let us consider slots per pole per phase is equals to 1 and here also slots per pole per phase should be 1 and number of poles the minimum number of poles is 2 and phases will be 18 in order to meet the same 32 number and here from 2 to 6 where pole change ratio should be odd positive integer 2 into 3 will be 6 poles and 6 phase because 6 into 6 will become 36 from this case we can see that 18 phase 2 pole and 6 phase 6 pole and next pole change combination 2 to 10 right 10 pole ratio should be odd positive integer earlier it will be 3. Now, we are changing from 2 to 5 10 pole means 10 into what like 36 is not divisible with 10 right the fraction will come it is not divisible. So, this combination will not work. So, only possible combinations will be 18 phase 2 pole and 6 phase 6 pole with respect to slots per pole per phase is equals to 1.

Next we will see slots per pole per phase is equals to 2. If slots per pole per phase is equals to 2 and number of poles the minimum number of poles are I am considering 2 again the number of phases will be 9. So, the total product will be 36 in order to change from one combination to other combination the ratio should be odd positive integer. So, 2 into 3 is nothing, but 6 next combination 2 into 5 it will be 10. So, first 6 pole we will see with respect to the 6 pole 3 phase should be there and 10 pole means 36 is not divisible with 10.

So, it is not possible. So, the possible number of pole phase combinations are 9 phase 2 pole and 3 phase 6 pole. And one more example we can consider if slots per pole per phase is equals to 1 what it will happen. Let us consider the same number of slot 36 slots q value I am considering 1 and 4 poles I will consider and here in order to change from one combination to other combination the ratio should be 3 one pole to other pole. So, 12 pole will come and number of phases here will be 9 to get the 36 slots number here number of phases should be 3 into 12 will come 36 again. And next number from 4 to 5 like 4 into 5 will be 20.

So, 36 will not be divisible with 20 again it is a fraction number. So, 20 pole is not possible and the possible number of pole phase combinations are 2 9 phase 4 pole and 3 phase 12 pole. This is 3 phase and 12 pole. So, here we are changing the speed or number of poles in 1 is to 3 speed ratio ratios that is 4 pole to 12 pole we are changing right ratio will be 1 is to 3. Next we will discuss with respect to the 60 slot q is equals to 60 slot that means, same equation m 1 p 1 and q 1 it should be equals to m 2 p 2 and q 2 here the p is nothing, but pole pairs if you are mentioning 2 and if we are considering capital P that is number of poles the pole change ratio should be odd positive integer.

Let us consider the slots per pole per phase is equals to 1 and number of minimum number of poles will be 2 and we are trying to change from 2 pole to 6 pole that is ratio will be 3. Next ratio 5 means 2 to 10 2 into 5 and next 2 to 7 if will change then 14 pole

will come. So, first combination with respect to 6 pole and slots per pole per phase is 1 and the number of phases to make 60 slots will be 30 phases are required and here the number of phases will be 10 phase 6 pole and slots per pole per phase is equals to 1 and next thing will be 2 to 10 pole we can change that means, slots per pole per phase also I am considering 1 and 6 phases. This is the next combination 6 phase 10 pole and slots per pole per phase is equals to 1. The final next combination 2 to 14 where the pole change ratio is odd integer 7 will come.

So, 30 phase 2 pole slots per pole per phase is 1 next 10 phase and then 6 pole then 6 phase and 10 pole. You can see here 1 pole to other pole combination it is varying in a odd positive integer. Next possible combination is 14. So, 60 is not divisible with 14. So, this pole combination is not possible in order to make the symmetrical distribution.

So, 2 pole 6 pole and 10 pole only possible the pole change ratio is 1 is to 3 is to 5. In this manner we can change the number of poles. If we will consider the q value differently like q is equals to 2 is there then the number of phase value will change. If q value is equals to 2 for example, then here 15 phase will come 15 phase 2 pole then 2 pole to 6 pole we are changing q value is 2 then it will be 5 phase 6 pole and slots per pole per phase is equals to 2. Then the next combination is the third combination slots per pole per phase will not change and the number of poles is equals to 10 that is 2 to 5 ratio 2 pole to 10 pole we are changing and it will be 3 phase and slots per pole per phase is equals to 2 and next is 14.

60 is not divisible with 14. So, this combination will not work that means 15 phase 2 pole then 5 phase 6 pole and 3 phase 10 pole. These are the 3 combinations are possible as per the generalization of pole phase modulation and symmetrical poles will form in this manner. The next case for 90 slot machine where q is equals to 1. So, 45 phase 2 pole and 15 phase 6 pole 9 phase 10 pole mode and 5 phase 18 pole and 3 phase 30 pole modes are possible where the pole change ratio will be 2 is to 6 is to 10 is to 18 is to 30 that means 1 is to 3 is to 5 and 9 and 15. In this ratio we can change the number of poles from one combination to other combination where the pole change ratio should be odd positive integer from 2 to 9 means 5 and then from 2 to 18 means it will be 9 and 2 to 30 means it will be 15.

In between 7 means 90 is not divisible with 14, 90 is not divisible with 11 in this manner. In between 7 is not possible, 11 also not possible and 13 also not possible that means 26 poles will not form with respect to this combination and 22 poles also will not form and 14 is not there means 28 poles also will not form. In this manner as per the generalization we can find the possible number of pole phase combinations. With this I am concluding this lecture. We will discuss the example for pole phase modulation drives. Thank you.