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A Simple Approach for the Design and Development of 6 – phase winding for high slot – pole count PMBLDC Hub Motor used in EV Applications

Mahesh Gaddam*[1,2], Charkravarthy M[3], Mangu B[4]

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Abstract: All teeth concentrated winding layouts are popular in 3 – phase PMBLDC Hub motors used for two – wheel EV applications. A well-known Cros' method is often used for determination of winding layouts of 3 – phase BLDC motors, yet this requires an in-depth winding layout knowledge to design for more than 3 – phase winding layouts and leads to more complexity as the number of phases, slot -pole count increases. This paper proposes a simple direct approach method for design and development of poly phase winding layout for high slot – pole count PMBLDC Hub motors. This method reduces the number of iterations to get the proper phase sequence and phase offset among the phases. In this paper, first the regular Cros' method is presented for Six – phase winding layout determination and next in the second authors' simple direct method is presented for the Six – phase winding layout determination. Both methods are compared. Discussed which one of the methods is better, and conclusions are drawn.

Keywords: *BLDC motor, Concentrated winding, Design of BLDC, Hub motor, Six – phase winding*

1. Introduction

The PMBLDC Hub motors are widely used in two – wheel electric vehicle applications because of their compact size, lesser losses, absence of drive belt or gear, higher efficiency and reliability compared to other motors [1] [2]. The PMBLDC Hub motors used in EV applications are also due to their good torque-speed characteristics, low noise level, and simple design [2] [3]. In these Hub motors, all teeth concentrated winding layouts are used popularly. Compared to traditional distributed double layer winding layouts, all teeth concentrated winding layouts have significantly reduced overhang portion [4] resulting in compact coil size [5] and lowered copper consumption [6] [7]. The PMBLDC Hub motors have smaller axial length and a larger diameter of the stator, which gives lesser active coil side length [8]. Manufacturing of these Hub motors is simple and cost saving as the consumption of lamination material and copper is lower [9]. A concentrated winding BLPMDC Hub motor performance relays on the slot-pole count [10] [12] and hence it must be chosen wisely. For low-speed direct drive EV applications, concentrated all teeth winding layouts usually have SPP in the range of 0.25 – 0.5 [11]. The PMBLDC Hub motors have fractional slots per pole per phase, causing lower alignment among the stator teeth and the rotor pole, resulting in lesser cogging torque [13]. The PMBLDC Hub motors are of out-runner topology, have their own limitations and In-runner topology PMBLDC motors suitable for high-speed applications [14].

[1]*Osmania University College of Engineering, Hyderabad – 500007, INDIA*
ORCID ID : 0000-0002-1790-6488
[2] *Vasavi College of Engineering, Hyderabad – 500031, INDIA*
ORCID ID : 0000-0002-1790-6488
[3] *Vasavi College of Engineering, Hyderabad – 500031, INDIA*
ORCID ID : 0000-0003-0486-3551
[4]*Osmania University College of Engineering, Hyderabad – 500007, INDIA*
ORCID ID : 0000-0003-1335-9656
** Corresponding Author Email: mahesh@vce.ac.in*
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2. Methodology

VARCAS, a Hyderabad (India) based automobile pvt. Ltd company, which imports the BLDC Hub motor from China and uses it in their Electric scooter manufacture, approached the authors to design and develop the Hub motor locally with some improvements in its performance and reliability. This has triggered the work of a poly phase PMBLDC Hub motor. The PMBLDC Hub motor specifications are 850 W, 36V, 550 R.P.M. A 48 slot, 52 pole count is considered for the design and development of a Six – Phase BLDC Hub motor because this slot-pole count gives a winding factor of 0.9494 for 3-phase winding layout [15] and 0.9801 for 6-phase winding layout. A winding factor value greater than 0.94 gives better performance of the motor as the performance is influenced by the winding factor. The Six-Phase all teeth concentrated winding layout is determined first by using Cros' method [16] and later by a simple approach method.

2.1. Cros' method

The following are the Cros' method steps followed to place the coils in the stator slots to obtain a six – phase winding layout.

1. The number of slots per pole per phase reduced to a non-divisible fraction given by

$$Spp = \frac{Ns}{Nm*Nph} = \frac{48}{52*6} = \frac{2}{13} = \frac{a}{b} \quad (1)$$

2. Using the Equation 1 a repeatable sequence of 0's and 1's determined. Here the number of 1's equals to 'a' and the number of 0's equals to '$a - b$' in the sequence. That means the number of 1's are two and 0's are eleven. So, the repeatable sequence is

$$1\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0 \quad (2)$$

3. As per the Cros' method [16], the most regular sequence as possible yields the greatest winding factor. The other possible repeatable sequence is

$$1\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 0 \quad (3)$$

4. The repetition of the above sequence for, (Ns / a) times. In this case the sequence repeats 24 times.

Use either SI (MKS) or C

Fig. 1. The optimal sequence repeated for 24 times.

5. The distribution of whole winding is periodic, if the 'b' is an even number otherwise the distribution is antiperiodic.

6. The above repetitive sequence is associated with the phase sequence AD'BE'CF'DA'EB'FA' of six-phases.

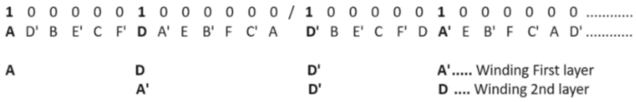

Fig. 2. Associating the phase sequence to the optimal sequence repeated for 24 times.

7. The phase associated with '1' is selected and these will form the first winding layer. A', B', C', D', E', F' are return coil conductors of A, B, C, D, E, F phases, respectively.
8. Then by shifting the first layer winding one slot and changing the direction of the phase second layer winding is obtained.

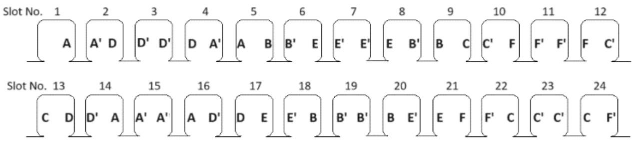

Fig. 3. Placement of phase coils in the stator slots.

9. The above phase coils placement in the slots will repeat for the remaining slots from the slot no. 25th to 48th.
10. The number of coils per phase obtained is 8. Each slot has two coil sides.

The six – phase winding layout determined for 48 slots, 52 poles Hub motor using Cros' method is shown in the table 11 under results and discussion section.

2.2. Proposed method

The assumptions for determining the six - phase balanced winding layout for valid pole and slot combinations are:

1. There are no empty slots in the stator.
2. Two coil sides are placed in each slot.
3. A slot – pole count that allows the winding layout to get back EMF magnitudes equal in all phases and 60 ^{0} E off set from each other are considered.
4. The number of turns in all the coils and span is the same. Hence the resistance and inductance of all the phases are equal.
5. The value of SPP is assumed to be less than one. Most low speed BLPM motors having a significantly more magnet poles fulfill this requirement.

The above assumptions give a winding layout capable of high performance and easy to wound. The coil span should be as close to 180 ^{0} E as possible, but seldom exceeds it, when the number of magnets is greater than slots. The coil pitch value is set to minimum of one slot when the slot pitch exceeds 180 ^{0} E. Coil span (CS) determined by

$$CS = \max(\text{fix}(Ns / Nm), 1) \quad (4)$$

In a Six – phase motor, each of the six-phase windings produce a back EMF of the same amplitude, shape and shifted by an angle 60^0 E from the other. The slot angle (θ_{sl}) relative to the first slot can be used to determine phase difference.

$$\theta_{sl} = (S\text{-}1)\,(Nm / Ns)180\ ^0\text{E} \quad (5)$$

Where S is the slot number. These angles are valid, but they extend the range -180^0 E ≤ θ ≤ 180 ^{0} E outside. A reminder function is used to determine the principle angle related to each of these angles.

$$\theta_{sl} = \text{rem}\{(S-1)\,(Nm / Ns)180\ ^0\text{E},\ 360^0\text{E}\} \quad (6)$$

Alternately the Equation 6 can be further modified such that it avoids use of the rem function and used to get the phase offset.

$$M_o = (1/2 + 2q)\,(2Ns/3Nm) \quad (7)$$

Where q is an integer. While laying out a winding, coils with a span of 'S' are placed in slots such that relative angular coil midpoints are as close to 0^0 E and 180^0 E apart. Coils close to 0^0 E are wound in one direction and the coils close to 180^0 E are wound in the reverse direction since the magnetic flux direction reverses at 180^0 E. It is not possible to align all coils at 0^0 E or 180^0 E separation in motors with fractional slot. The coil locations must be chosen that are as close as possible to 0^0 E and 180^0 E separation. The number of coils per phase is given by

$$Ncph = Ns/Nph \quad (8)$$

For the considered 48 slots and 52 poles Hub motor, the nominal coil span S = 1, the Slot angle $\theta_{sl} = 195^0$ E i.e. Each coil offset angle is 195^0 E w.r.t the consecutive coil. The phase offset M_o = 4 slots and the coils per phase Ncph = 8. The total number of coils in the stator is equal to 48. Each coil offset angle and associated *In* and *Out* slots are listed in Table 1. These coils offset angles are valid, but they extend the range $-180^0 E \leq \theta \leq 180^0 E$ outside. The principle angle (θ) related to each of these angles is determined by

$$\theta = \text{rem}\,(\theta + 180^0, 360^0) \quad (9)$$

Table 2 provides the angle (θ) of each coil with respect to the first coil. The coil's winding direction is modified (inter change of *In* slot & *Out* slot) whose angle (θ) is greater than 90^0 E and their corresponding angle by 180^0 E. This will provide the prospective coils for phase A. Table 3 shows the details along with *In* and *Out* slots. Eight coils should be selected from Table 3 to lay a valid winding for phase A. Coils, which are close to 0^0 E should be used and its angular spread of the winding should be minimum. Since eight coils are required per phase for the considered Hub motor, the coils numbered 1, 2, 3, 4, 25, 26, 27, and 28 are closest to 0^0 E and have a total spread of 45^0 E are chosen. Table 4 shows the phase A winding layout. Since the phase offset of M_o = 4 slots leads to an angle 60^0 E offset between phases A and B, hence each coil in phase B is shifted by 'M_o' slots with respect to the corresponding coil in phase A. Table 5 shows the prospective coils for phase B, selecting those closest to 0^0 E.

Selecting coils numbered 5, 6, 7, 8, 29, 30, 31, and 32 from table 5 to form the phase B winding coils and its layout as shown in Table 6. Keeping phase offset of 60^0 E (4 slots) w.r.t the phase B coils, phase C coils can be placed in the slots. Selecting coils numbered 9, 10, 11, 12, 33, 34, 35, and 36 gives the phase C winding coils and its layout is shown in Table 7.

Table 1. Each Coil offset angle and its associated *In* & *Out* slots

Coil No	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
Coil Angle	0	195	390	585	780	975	1170	1365	1560	1755	1950	2145
In Slot	1	2	3	4	5	6	7	8	9	10	11	12
Out Slot	2	3	4	5	6	7	8	9	10	11	12	13
Coil No	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***
Coil Angle	2340	2535	2730	2925	3120	3315	3510	3705	3900	4095	4290	4485
In Slot	13	14	15	16	17	18	19	20	21	22	23	24
Out Slot	14	15	16	17	18	19	20	21	22	23	24	25
Coil No	***25***	***26***	***27***	***28***	***29***	***30***	***31***	***32***	***33***	***34***	***35***	***36***
Coil Angle	4680	4875	5070	5265	5460	5655	5850	6045	6240	6435	6630	6825
In Slot	25	26	27	28	29	30	31	32	33	34	35	36
Out Slot	26	27	28	29	30	31	32	33	34	35	36	37
Coil No	***37***	***38***	***39***	***40***	***41***	***42***	***43***	***44***	***45***	***46***	***47***	***48***
Coil Angle	7020	7215	7410	7605	7800	7995	8190	8385	8580	8775	8970	9165
In Slot	37	38	39	40	41	42	43	44	45	46	47	48
Out Slot	38	39	40	41	42	43	44	45	46	47	48	1

Table 2. Principle angle of each coil with respect to the first coil and its associated *In* & *Out* slots

Coil No	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
Principle Angle	0	-165	30	-135	60	-105	90	-75	120	-45	150	-15
In Slot	1	2	3	4	5	6	7	8	9	10	11	12
Out Slot	2	3	4	5	6	7	8	9	10	11	12	13

Coil No	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***
Principle Angle	-180	15	-150	45	-120	75	-90	105	-60	135	-30	165
In Slot	13	14	15	16	17	18	19	20	21	22	23	24
Out Slot	14	15	16	17	18	19	20	21	22	23	24	25
Coil No	***25***	***26***	***27***	***28***	***29***	***30***	***31***	***32***	***33***	***34***	***35***	***36***
Principle Angle	0	-165	30	-135	60	-105	90	-75	120	-45	150	-15
In Slot	25	26	27	28	29	30	31	32	33	34	35	36
Out Slot	26	27	28	29	30	31	32	33	34	35	36	37
Coil No	***37***	***38***	***39***	***40***	***41***	***42***	***43***	***44***	***45***	***46***	***47***	***48***
Principle Angle	-180	15	-150	45	-120	75	-90	105	-60	135	-30	165
In Slot	37	38	39	40	41	42	43	44	45	46	47	48
Out Slot	38	39	40	41	42	43	44	45	46	47	48	1

Table 3. Changed winding direction of coils whose principle angle > 90^0 E and its associated *In* & *Out* slots

Coil No	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
Principle Angle	0	15	30	45	60	75	90	-75	-60	-45	-30	-15
In Slot	1	3	3	5	5	7	7	8	10	10	12	12
Out Slot	2	2	4	4	6	6	8	9	9	11	11	13
Coil No	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***
Principle Angle	0	15	30	45	60	75	-90	-75	-60	-45	-30	-15
In Slot	14	14	16	16	18	18	19	21	21	23	23	25
Out Slot	13	15	15	17	17	19	20	20	22	22	24	24
Coil No	***25***	***26***	***27***	***28***	***29***	***30***	***31***	***32***	***33***	***34***	***35***	***36***
Principle Angle	0	15	30	45	60	75	90	-75	-60	-45	-30	-15
In Slot	25	27	27	29	29	31	31	32	34	34	36	36
Out Slot	26	26	28	28	30	30	32	33	33	35	35	37
Coil No	***37***	***38***	***39***	***40***	***41***	***42***	***43***	***44***	***45***	***46***	***47***	***48***
Principle Angle	0	15	30	45	60	75	-90	-75	-60	-45	-30	-15
In Slot	38	38	40	40	42	42	43	45	45	47	47	1
Out Slot	37	39	39	41	41	43	44	44	46	46	48	48

Similarly, phases D, E and F coils are placed in the slots keeping phase offset of 60^0 E with respect to each phase and choosing the coils close to 0^0 E. The winding layouts of phases D, E and F are shown in table 8, table 9 and table 10, respectively.

3. Development Results and Discussion

The Table 11 gives Six – phase winding layout determined for 48 slots, 52 poles Hub motor using Cros' method and Table 12 shows the Six – phase winding layout determined using proposed simple direct approach method. The Six – phase winding layout designed and developed is depicted from figure 5 to figure 10. The copper conductor used in the winding has 15 strands and each strand gauge is 25SWG.

Table 4. Phase A coils with *In* & *Out* slots

Coil No	***1***	***2***	***3***	***4***
Coil Angle	0	15	30	45
In Slot	1	3	3	5
Out Slot	2	2	4	4
Coil No	***25***	***26***	***27***	***28***
Coil Angle	0	15	30	45
In Slot	25	27	27	29
Out Slot	26	26	28	28

Table 5. Potential coils of Phase B with phase offset of 60^0 E

Coil No	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***
Coil Angle	-	-	-	-	0	15	30	45	60	75	90	-75	-60	-45	-30	-15
In Slot	1	3	3	5	5	7	7	9	9	11	11	13	13	15	15	17
Out Slot	2	2	4	4	6	6	8	8	10	10	12	12	14	14	16	16
Coil No	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***	***25***	***26***	***27***	***28***	***29***	***30***	***31***	***32***
Coil Angle	0	15	30	45	60	75	-90	-75	-60	-45	-30	-15	0	15	30	45
In Slot	17	19	19	21	21	23	23	25	25	27	27	29	29	31	31	33
Out Slot	18	18	20	20	22	22	24	24	26	26	28	28	30	30	32	32
Coil No	***33***	***34***	***35***	***36***	***37***	***38***	***39***	***40***	***41***	***42***	***43***	***44***	***45***	***46***	***47***	***48***
Coil Angle	60	75	90	-75	-60	-45	-30	-15	0	15	30	45	60	75	-90	-75
In Slot	33	35	35	37	37	39	39	41	41	43	43	45	45	47	47	1
Out Slot	34	34	36	36	38	38	40	40	42	42	44	44	46	46	48	48

Table 6. Phase B coils with *In* and *Out* slots

Coil No	***5***	***6***	***7***	***8***
Coil Angle	0	15	30	45
In Slot	5	7	7	9
Out Slot	6	6	8	8
Coil No	***29***	***30***	***31***	***32***
Coil Angle	0	15	30	45
In Slot	29	31	31	33
Out Slot	30	30	32	32

Table 7. Phase C coils with *In* and *Out* slots

Coil No	***9***	***10***	***11***	***12***
Coil Angle	0	15	30	45
In Slot	9	11	11	13
Out Slot	10	10	12	12
Coil No	***33***	***34***	***35***	***36***
Coil Angle	0	15	30	45
In Slot	33	35	35	37
Out Slot	34	34	36	36

Table 8. Phase D coils with *In* and *Out* slots

Coil no	***13***	***14***	***15***	***16***
Coil angle	0	15	30	45
In slot	13	15	15	17
Out slot	14	14	16	16
Coil no	***37***	***38***	***39***	***40***
Coil angle	0	15	30	45
In slot	37	39	39	41
Out slot	38	38	40	40

Table 9. Phase E coils with *In* and *Out* slots

Coil No	***17***	***18***	***19***	***20***
Coil Angle	0	15	30	45
In Slot	17	19	19	21
Out Slot	18	18	20	20
Coil No	***41***	***42***	***43***	***44***
Coil Angle	0	15	30	45
In Slot	41	43	43	45
Out Slot	42	42	44	44

Each coil of phase has 6 turns and total coils in phase are Eight. The winding was designed in such a way to keep the stator slot fill factor in practical limits.

Table 10. Phase F coils with *In* and *Out* slots

Coil No	***21***	***22***	***23***	***24***
Coil Angle	0	15	30	45
In Slot	21	23	23	25

Out Slot	22	22	24	24
Coil No	***45***	***46***	***47***	***48***
Coil Angle	0	15	30	45
In Slot	45	47	47	1
Out Slot	46	46	48	48

Fig. 4. Unwound stator slots of Hub motor.

Fig. 5. Winding layout of Phase A.

Fig. 6. Winding layout of Phase A & B.

Table 11. Six – phase winding layout of 48S – 52P Hub motor using Cros' method

Slot No.	***Phase A***	***Phase B***	***Phase C***	***Phase D***	***Phase E***	***Phase F***	***Slot No.***	***Phase A***	***Phase B***	***Phase C***	***Phase D***	***Phase E***	***Phase F***
1	In					In	***25***	In					In
2	Out			In			***26***	Out			In		
3				Out, Out			***27***				Out, Out		
4	Out			In			***28***	Out			In		
5	In	In					***29***	In	In				
6		Out			In		***30***		Out			In	
7					Out, Out		***31***					Out, Out	
8		Out			In		***32***		Out			In	
9		In	In				***33***		In	In			
10			Out			In	***34***			Out			In
11						Out, Out	***35***						Out, Out
12			Out			In	***36***			Out			In
13			In	In			***37***			In	In		
14	In			Out			***38***	In			Out		
15	Out, Out						***39***	Out, Out					
16	In			Out			***40***	In			Out		
17				In	In		***41***				In	In	
18		In			Out		***42***		In			Out	
19		Out, Out					***43***		Out, Out				
20		In			Out		***44***		In			Out	

21					In	In	***45***					In	In
22			In			Out	***46***			In			Out
23			Out, Out				***47***			Out, Out			
24			In			Out	***48***			In			Out

On observation of two winding layouts, placement of coils of phase, in the slots around the stator periphery is not symmetric and angular symmetry doesn't exhibit by the Cros' method winding layout, hence these two winding layouts' flux linkage and back EMF determined [17] differ from each. Both the winding layouts result trapezoidal back EMF waveforms, but the width of the flat region is less for the winding layout determined by Cros' method due to the winding coils disposition.

Cros' method creates ambiguity in obtaining the possible repeatable sequence (step 3 and step 4 in Cros' method). This may lead to a greater number of iterations to get the most regular repeatable sequence with the highest winding factor. In Cros' method determination of the distribution of whole winding is periodic or antiperiodic, the association of the repetitive sequence with the phase sequence becomes complex as the number of phases increases in the Hub motor.

The number of coil groups [19] in a phase of winding layout obtained by Cros' method is 8/5. Which is not an integer resulting in unbalanced dynamic radial forces on the rotor and leads to the source of vibration and noise. Whereas in the proposed method of winding layout, the number of coil groups in a phase is 8/4. It gives integer greater than one and results in balanced dynamic radial forces on the rotor.

Table 12. Six – phase winding layout of 48S – 52P Hub motor using simple approach method

Slot No.	***Phase A***	***Phase B***	***Phase C***	***Phase D***	***Phase E***	***Phase F***	***Slot No.***	***Phase A***	***Phase B***	***Phase C***	***Phase D***	***Phase E***	***Phase F***
1	In					In	***25***	In					In
2	Out, Out						***26***	Out, Out					
3	In, In						***27***	In, In					
4	Out, Out						***28***	Out, Out					
5	In	In					***29***	In	In				
6		Out, Out					***30***		Out, Out				
7		In, In					***31***		In, In				
8		Out, Out					***32***		Out, Out				
9		In	In				***33***		In	In			
10			Out, Out				***34***			Out, Out			
11			In, In				***35***			In, In			
12			Out, Out				***36***			Out, Out			
13			In	In			***37***			In	In		
14				Out, Out			***38***				Out, Out		
15				In, In			***39***				In, In		
16				Out, Out			***40***				Out, Out		
17				In	In		***41***				In	In	
18					Out, Out		***42***					Out, Out	
19					In, In		***43***					In, In	
20					Out, Out		***44***					Out, Out	
21					In	In	***45***					In	In

22	Out, Out	***46***	Out, Out
23	In, In	***47***	In, In
24	Out, Out	***48***	Out, Out

Fig. 7. Winding layout of Phase A, B & C.

Fig. 8. Winding layout of Phase A, B, C & D.

Fig. 9. Winding layout of Phase A, B, C, D & E.

Fig. 10. Winding layout of Phase A, B, C, D, E & F.

4. Conclusion

The Six – Phase all teeth concentrated winding layouts were determined for 48 slots, 52 poles PMBLDC Hub motor using Cros' method and proposed a simple, direct approach method. On comparison, both winding layouts have winding factor of 0.98 and the no-load cogging torque pulsations over one revolution of the rotor determined is 624. Each slot is full and occupied by two coil sides in two winding layouts. Cros' method doesn't indicate phase offset and angular spread of coils around the slots of the stator periphery is unsymmetric even though the number of coils in a phase is even number. Whereas in the proposed method phase offset is clearly indicated and it is symmetric with minimum angular spread. This has resulted in varied flux linkage and back EMF in these two winding layouts. In Cros' method determination of the distribution of whole winding is periodic or antiperiodic, the association of the repetitive sequence with the phase sequence of poly phases becomes complex as the number of phases increases. Cros' method winding layout produces unbalanced dynamic radial forces on the rotor resulting vibration and noise. Hence the presented simple, direct approach is a better choice for determining the winding layout for high slot-pole count Six – phase Hub motors. It is also valid for other poly – phase winding layouts of more than three – phases.

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Author contributions

Mahesh Gaddam: Methodology, Visualization, Data curation, Writing-Original draft preparation, Validation, Investigation, Field study **Chakravarthy M:** Conceptualization, Methodology, Visualization, Investigation **Mangu B:** Conceptualization, Investigation, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

References

[1] Anqing He, Chenxi Zhou, et.al. "Evaluation of Fractional Slot Concentrated Winding Permanent Magnet Synchronous Machine for Electric Vehicle Appli cation", IEEE International Electric Machines & Drives Conference (IEMDC), May, 2019, DOI: 10.1109/IEMDC.2019.8785223.

[2] Chang-liang Xia, Tianjin University, P.R. China, "PERMANENT MAGNET BRUSHLESS DC MOTOR DRIVES AND CONTROLS", ISBN:9781118188330.

[3] Y.B. Adyapaka Apatya, Aries Subiantoro and Feri Yusivar, "Design and Prototyping of 3-Phase BLDC Motor", International Conference on Quality in Research (QiR) : International Symposium on Electrical and Computer Engineering, July, 2017, DOI:10.1109/QIR.2017.8168483.

[4] Dieter Gerling, "Electrical Machines Mathematical Fundamentals of Machine Topologies",pp-449, ISBN:9783662520321.

[5] Vladimir Dimitrov, "Overview of the Ways to Design an Electric Bicycle", National Conference with International Participation (ELECTRONICA), May, 2018, DOI:10.1109/ELECTRONICA.2018.8439456.

[6] T. D. Strous, H. Polinder, Member, IEEE, J. A. Ferreira, Fellow, IEEE, "Inductance calculations for PM machines with concentrated windings", IEEE International Electric Machines & Drives Conference (IEMDC), May, 2011, DOI:10.1109/IEMDC.2011.5994636.

[7] Chun Tang, Wen L. Soong, Gene S. Liew and Nesimi Ertugrul, "Ef fect of Pole and Slot Number Changes on the Performance of a Surface PM Machine", International Conference on Electrical Machines, Sep, 2012, DOI:10.1109/ICElMach.2012.6349867.

[8] Design and Optimization of Interior PM Machines with Distributed and Fractional-Slot Concentrated-Windings for Hybrid Electric Vehicles, IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia Pacific), Sep, 2014, DOI:10.1109/ITEC-AP.2014.6941169.

[9] Freddy Magnussen, Member, IEEE, and Heinz Lendenmann, Member, IEEE, "Parasitic Effects in PM Machines With Concentrated Windings", IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 43, NO. 5, SEPTEM BER/OCTOBER 2007, DOI:10.1109/TIA.2007.904400.

[10] F. Libert, J. Soulard, "Investigation on Pole-Slot Combinations for Permanent Magnet Machines with Concentrated Windings", Jan, 2004.

[11] Florence Meier, "Permanent-Magnet Synchronous Machines with Non Overlapping Concentrated Windings for Low-Speed Direct-Drive Applica tions".

[12] K. Latha Shenoy, M. Satyendra Kumar, "Design Topology and Elec tromagnetic Field Analysis of Permanent Magnet Brushless DC Mo tor for Electric Scooter Application", International Conference on Elec trical, Electronics, and Optimization Techniques (ICEEOT), March 2016, DOI:10.1109/ICEEOT.2016.7754942.

[13] Z.Q. Zhu and D. Howe, "Influence of Design Parameters on Cogging Torque in Permanent Magnet Machines," IEEE Trans. Energy Conv., vol. 15, no. 4, pp. 407- 412, Dec. 2000., DOI:10.1109/60.900501.

[14] Aditya Raj, B.Tech theses, "Investigations on Permanent Magnet Machines for Electric Vehicle Applications".

[15] S. E. Skaar, Ø. Krøvel, R. Nilssen. "Distribution, Coil-span and Winding Factors for PM Machines with Concentrated Windings". In ICEM-2006, Chania (Greece). 2006.

[16] J. Cros and P. Viarouge, "Synthesis of high performance pm motors with concentrated windings", IEEE Transactions on Energy Conversion, vol. 17, no. 2, pp. 248-253, Jun. 2002.

[17] Dahaman Ishak, Z.Q.Zhu, "Comparision of PM Brushless Motors, Having Either All Teeth or Alternate Teeth Wound", IEEE Transactions on Energy Conversion, vol. 21, no. 1, pp. 95-103, March 2006.

[18] J. R. Hendershot and T. J. E. Miller, Design of Brushless Permanent-Magnet Machines, Motor Design Books, Venice, FL, USA, 2010.

[19] D. C. Hanselman, Brushless permanent magnet motor design, The Writers' Collective, Cranston, RI, USA, 1994.