AN INTERACTIVE DESIGN OF THE WINDING LAYOUT IN PERMANENT MAGNET MACHINES

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This paper presents a winding design technique for three phase permanent magnet (PM) motors. The winding factor and the emf total harmonic distortion are provided. A computer-aided design (CAD) program was developed and implemented using the Visual Basic language. Finite element analysis (FEA) program was linked into the CAD program to calculate the motor performances.

1. **INTRODUCTION**

The layout of a winding in an electric machine affects the mmf distribution and the performance of the machine. The machine designer must determine the best way of placing the windings in a machine in the most effective manner. For simple configurations this can be done by hand, but for any valid pole and slot count combinations of a machine, a CAD is virtually essential. However, relatively little has been reported in detail on describing a procedure for the placement of windings in a motor [1–4]. Hanselman [2], Cros *et al*. [3], and Hwang *et al*. [4], presented the winding layout procedure for finding the highest value of winding factor for PM machines with concentrated windings. This paper describes the extentions of the previous works [1–4] to determine the procedure of the winding layout for any valid pole and slot combinations of PM machines for both concentrated and non-concentrated windings. A CAD program has been developed and implemented using the Visual Basic language. It is linked to an FEA program for calculating motor performances. Three examples are considered for illustration.

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2. **BASIC ASSUMPTIONS**

There are an infinite number of possibilities for pole and slot count combinations and for winding layouts. To limit the scope and simplify the problem, the following assumptions are made:

a) The motor is three-phase.
b) A balanced winding is considered.
c) Double-layer per slot is used.

Based on the above assumptions, the combinations of slots (N_s) or teeth and poles (N_m) must satisfy the following relationship:

$$\frac{N_s}{\mathrm{GCD}(N_s, N_m)} = 3k, \tag{1}$$

where k is an integer and GCD stands for the greatest common divisor. The total number of coils (N_c) is equal to N_s for the double layer windings. Before considering the details of laying out a winding, it is beneficial to define some items that lead to the following formulation.

3. **DEVELOPMENT METHODOLOGY**

In this section, four items for determining the winding layout are defined. Coil span is the circumferential width of a coil. It is convenient to describe the coil span in terms of slots. Generally speaking, the coil span for a coil should be as close to 180 electrical degrees (^0E) as possible but seldom exceeding this [2]. The coil span S in slot can be formulated as

$$S = \begin{cases} \max\left[\mathrm{fix}\left(\dfrac{N_s}{N_m}\right), 1\right], & \text{for lap windings} \\ 1, & \text{for concentrated windings} \end{cases}, \tag{2}$$

where max(·,·) returns the maximum of its two arguments and returns fix(·) the integer portion of its argument.

The relative angle of the k^{th} coil (or teeth) is defined as

$$\theta_c(k) = (k-1)\frac{N_m}{N_s}180^0 E \qquad k = 1, 2, \ldots, N_c. \tag{3}$$

When the coil angle $\theta_c(k)$ has a magnitude greater than 360^0E, it is corrected by applying the function.

$$\hat{\theta}_c(k) = \mathrm{rem}\left(\theta_c(k),\quad 360^0 E\right), \tag{4}$$

where rem(x, y) is the remainder function which returns the remainder of the division x/y.

For balanced three-phase motors, each of the three phase windings must produce the same amplitude and shape back emf, and each emf should be shifted in phase by $120^0 E$ from the other two phases. Hence, the individual phase coils must be displaced by $120^0 E$ from the coils in other phases. The phase offset in slots K_0 is an integer value computed by

$$K_0 = \frac{2N_s}{3N_m}(1+3q), \tag{5}$$

where q is an integer value of 0, 1, 2,… , $(N_m/2)-1$. If no suitable integer value of q can be found, then the chosen pole and slot combination can not be adopted to construct a balanced three phase motor.

The winding factor (K_w) for each winding group can be calculated as

$$K_w = \frac{1}{N_{ph}} \sum_{k=1}^{N_{ph}} \mathrm{e}^{\mathrm{j}\theta_c(k)}, \tag{6}$$

where N_{ph} is number of coils per phase.

4. WINDING LAYOUT PROCEDURES

Based on the above formulas and assumptions, the essential steps for determining valid winding layouts are summarized as follows:

a) Input number of slots, N_s and number of magnet poles, N_m.

b) Determine coil span S using (2), phase offset K_0 using (5), and coil angles $\theta_c(k)$ or $\hat{\theta}_c(k)$ using (3) or (4).

c) Layout all coils by the same coil span and assign coil number for all coils sequentially. Select coil number 1 to be the phase reference.

d) Determine coils for phase A, and then determine the coils for phases B and C sequentially. The phase B coils are shifted K_0 slots from phase A, and phase C coils are shifted $2K_0$ slots from phase A. Generally, coil number 1, $N_c(1)$ is assigned to be the first coil of phase A. The second coil of phase A is selected from the residual coil numbers other than $N_c(1+K_0)$ and $N_c(1+2K_0)$. The third coil of phase A is selected from the coil number other than selected coils of phase A, B, and C. According to this procedure, select $N_{ph} = 1/3N_c$ coils for phase A, B, and C respectively. If it is unable to find a suitable value for K_0, that means the combination of N_m and N_s can not be used for constructing a three phase balanced winding motor.

e) Link to the FEA program and calculate the motor performances.

f) Determine the total harmonic distortion (THD) of the phase back-emf for each winding group. The THD is defined by

$$THD = 100\left(\sum_{k=2}^{K} U_k^2\right)^{1/2} \Big/ U_1, \tag{7}$$

where U_1 is the fundamental component of the back-emf and U_k is the k^{th} order harmonic component.

A flow diagram showing the main routine is illustrated in Fig. 1. The method used for finding possible winding layout sets shown in Fig. 1 is illustrated in detail in Fig. 2. A CAD program has been developed and implemented using the Visual Basic language. It is linked to an FEA program for calculating motor performance.

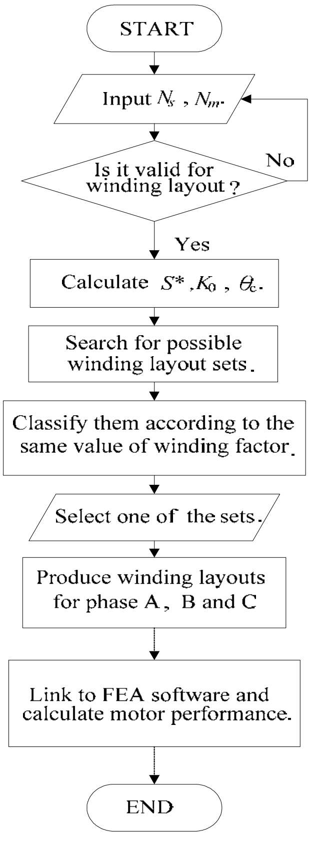


Fig. 1 – A flow-chart for winding layout.

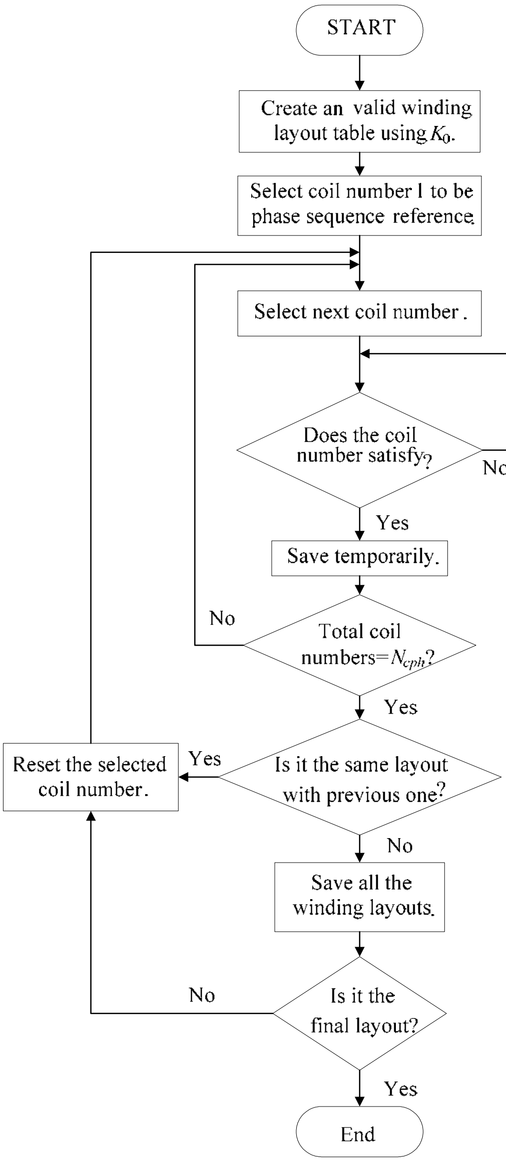


Fig. 2 – A flow-chart for finding possible winding layout sets in Fig. 1.

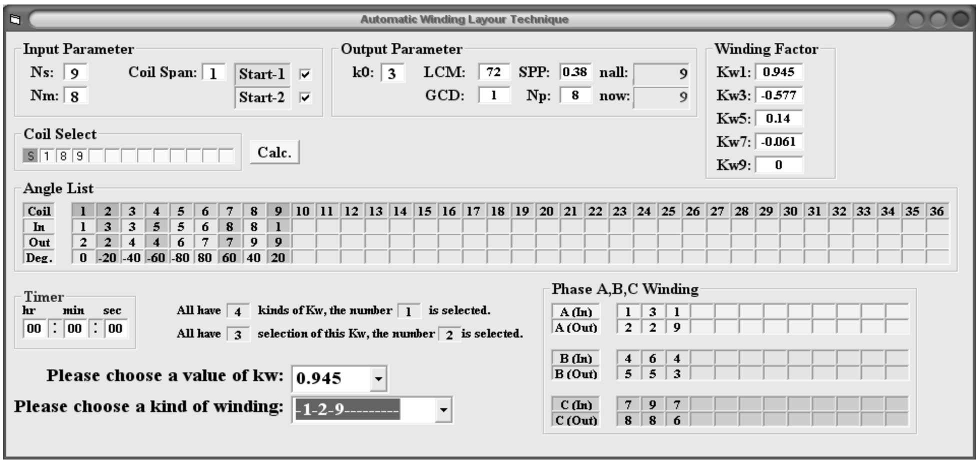
5. EXAMPLES

Table 1 shows an example of the winding layouts for an 8-pole/9-slot (8P/9S) permanent magnet brushless dc motor. It has four different values of K_w and therefore classifies four groups of winding configurations. Screens for winding Group 1 Type 1 and Group 2 Type 4 are displayed in Figs. 3 and 4.

Table 1

Winding layout for 8p/9s motor

Winding method		Phase A	Phase B	Phase C	K_w	THD (%)
Group 1	Type 1	1-$\underline{2}$-$\underline{9}$	4-$\underline{5}$-$\underline{3}$	7-$\underline{8}$-$\underline{6}$	0.945	17.50
	Type 2	1-$\underline{2}$-3	4-$\underline{5}$-6	7-$\underline{8}$-9		
	Type 3	1-$\underline{9}$-8	4-$\underline{3}$-2	7-$\underline{6}$-5		
Group 2	Type 4	1-3-8	4-6-2	7-9-5	0.831	3.16
	Type 5	1-3-5	4-6-8	7-9-2		
	Type 6	1-8-6	4-2-9	7-5-3		
Group 3	Type 7	1-5-$\underline{9}$	4-8-$\underline{3}$	7-2-$\underline{6}$	0.725	23.54
	Type 8	1-$\underline{2}$-6	4-$\underline{5}$-9	7-$\underline{8}$-3		
Group 4	Type 9	1-5-6	4-8-9	7-2-3	0.442	15.89



Ns: 9 Coil Span: 1 Start-1 ☑
Nm: 8 Start-2 ☑

k0: 3 LCM: 72 SPP: 0.38 nall: 9
GCD: 1 Np: 8 now: 9

Kw1: 0.945
Kw3: -0.577
Kw5: 0.14
Kw7: -0.061
Kw9: 0

Coil Select: S 1 8 9

Coil	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
In	1	3	3	5	5	6	8	8	1																											
Out	2	2	4	4	6	7	7	9	9																											
Deg.	0	-20	-40	-60	-80	80	60	40	20																											

hr min sec
00 : 00 : 00

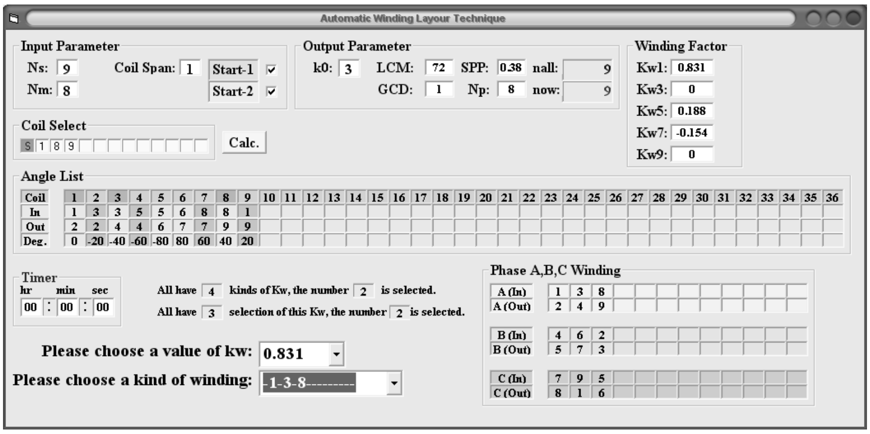
All have 4 kinds of Kw, the number 1 is selected.
All have 3 selection of this Kw, the number 2 is selected.

Please choose a value of kw: 0.945
Please choose a kind of winding: -1-2-9---------

A (In)	1	3	1
A (Out)	2	2	9
B (In)	4	6	4
B (Out)	5	5	3
C (In)	7	9	7
C (Out)	8	8	6

Fig. 3 – Screen for winding Group 1 Type 1.

Fig. 5 illustrates the winding layout for phase A winding of Type 1. Figs. 6 and 7 show a family of back-EMF waveforms at a speed of 1 000 rpm and the phase back-emfs harmonic contents for Types 1, 2, 3, and 4. It is seen that Type 1 (Group1) has the highest amplitude and the most trapezoidal phase emf waveform due to the highest winding factor. This makes it the most appropriate for brushless dc operation. Type 4 (Group 2) has the lowest THD, and hence makes it most suitable for synchronous operation. Type 9 (Group 4) has the lowest amplitude, and it has the smallest winding factor.



Automatic Winding Layour Technique

Input Parameter

Ns: 9
Nm: 8
Coil Span: 1
Start-1 ☑
Start-2 ☑

Output Parameter

k0: 3
LCM: 72
GCD: 1
SPP: 0.38
Np: 8
nall: 9
now: 9

Winding Factor

Kw1: 0.831
Kw3: 0
Kw5: 0.188
Kw7: -0.154
Kw9: 0

Coil Select

S 1 8 9

Calc.

Angle List

Coil	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
In	1	3	3	5	5	6	8	8	1																											
Out	2	2	4	4	6	7	7	9	9																											
Deg.	0	-20	-40	-60	-80	80	60	40	20																											

Timer

hr : min : sec
00 : 00 : 00

All have 4 kinds of Kw, the number 2 is selected.
All have 3 selection of this Kw, the number 2 is selected.

Please choose a value of kw: 0.831
Please choose a kind of winding: -1-3-8---------

Phase A,B,C Winding

A (In)	1	3	8
A (Out)	2	4	9
B (In)	4	6	2
B (Out)	5	7	3
C (In)	7	9	5
C (Out)	8	1	6

Fig. 4 – Screen for winding Group 2 Type 4.

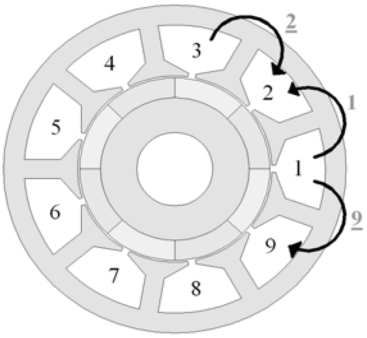


Fig. 5 – Phase A winding layout for Type 1.

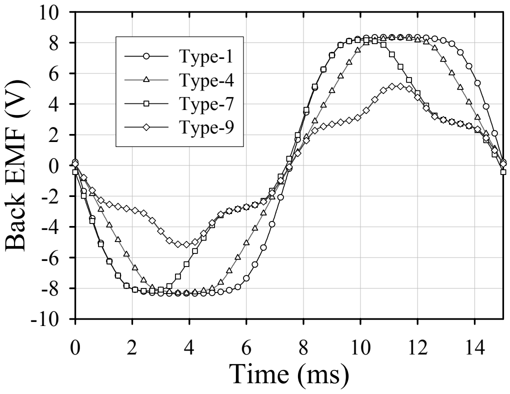


Fig. 6 –Back emf waveforms for Types 1, 4, 7, and 9.

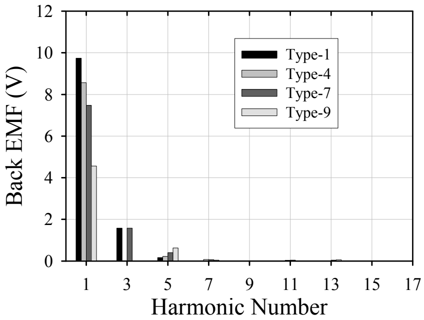


Fig. 7 – Back emf harmonic content for Types 1, 4, 7, and 9.

Results for two more examples for 4P/9S and 12P/9S are listed in Tables 2 and 3. It is seen that 4P/9S has four groups and nine types and 12P/9S has only one group and one type winding layouts.

Table 2

Winding layout for 4p/9s motor

Winding method		Phase A	Phase B	Phase C	K_w	THD (%)
Group 1	Type 1	1-$\underline{8}$-3	7-$\underline{5}$-9	4-$\underline{2}$-6	0.945	20.35
	Type 2	1-$\underline{8}$-6	7-$\underline{5}$-3	4-$\underline{2}$-9		
	Type 3	1-5-$\underline{3}$	7-2-$\underline{9}$	4-8-$\underline{6}$		
Group 2	Type 4	1-2-6	7-8-3	4-5-9	0.831	5.95
	Type 5	1-5-9	7-2-6	4-8-3		
	Type 6	1-5-6	7-2-3	4-8-9		
Group 3	Type 7	1-2-$\underline{3}$	7-8-$\underline{9}$	4-5-$\underline{6}$	0.725	27.73
	Type 8	1-$\underline{8}$-9	7-5-$\underline{6}$	4-$\underline{2}$-3		
Group 4	Type 9	1-2-9	7-8-6	4-5-3	0.442	23.44

Table 3

Winding layout for 12p/9s motor

Winding method		Phase A	Phase B	Phase C	K_w	THD (%)
Group 1	Type 1	1-4-7	3-6-9	5-8-2	0.866	7.08

6. **CONCLUSIONS**

This paper has proposed a winding design technique for three-phase PM motors. Detailed graphic design methods are provided with a Visual Basic program. It is linked with an FEA program for calculating motor performance. The technique was illustrated with three examples of different numbers of magnet poles and the same numbers of slots. This technique can be applied to any valid pole and slot combinations of three-phase PM motors, it is very efficient to find all possible winding configurations for any PM motors and list all winding configurations by the value of winding factor.

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