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Analytical Determination of Electrical Machine Winding Layout

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ABSTRACT: *In this article, the idea of electrical machine winding layout had been rediscovered and further explained by means of analytic mathematics, which led to practical understanding of the approach towards machine winding layout. This is to enable machine designers and technologist know precisely how to place coils in slotted machine to achieve the best in performance because when windings are properly laid out following applicable principles, the output characteristics of such machine follows closely to that of the input thereby generating the desired result. A key feature of this article is the clear (explicit) procedure used for phase offset determination (i.e. position of slot where the next phase coils should be placed, to obtain purely or close to pure sine wave output as in the case of sinusoidal machines. A 24 slot 4 poles motor was use to illustrate the application of phase offset analytic mathematics derived in this article.*

Keywords: *Electric machines, winding, Phase offset, Chording, Coil Span, Winding layout*

I. INTRODUCTION

Electrical machines form integral part of virtually all engineering and technological implements; from simple machine tools to industrial and even military equipments alike.

National development and thus world development had depended and will continue to depend on engineering and technological achievement which electrical machine is one of the key elements. Thus invention and re-invention of knowledge and further practical interpretation of ideas through analytics continues to bolster the life and feat of engineering sciences and technology.

Winding is a section of machine design which deals with the distribution of coils in slotted armature core in a suitable form. Due to the fact that the coil is the current carrying element of the machine and accomplishes the task of energy transfer by electromagnetic induction to other elements of the machine such as the rotor through the air gap and the core by flux linkage; care must be taken to properly position the coils in the core slots else the desired output characteristics will be distorted.

A good number of authors had written and published works on machine windings and its distribution in core slots. [1] Brushless Permanent Magnet Motor Design explained various type of winding and derived some mathematical relations used to determine the position of coils in armature core.

In [2, 3], double layer and single layer distributed and concentrated winding arrangement was examined. The principle of chording or pitching was well stated with formulas and diagrams. [4-6], all highlighted the same principle and coil connections and groupings with emphasis on series arrangement due to its additive emf effect.

II. WINDING

In electrical machine, depending on the machine application, coils can be arranged in single layer or double layer mode. The single layer configuration can be lap wound, full pitched or chorded, concentrated or distributed. In multiphase machines, multiple coil groups are arranged and connected either in series or parallel. Study has revealed that there are infinite numbers of possibilities for winding layouts, pole and slot count combinations [1]. Winding Illustrations are shown below.

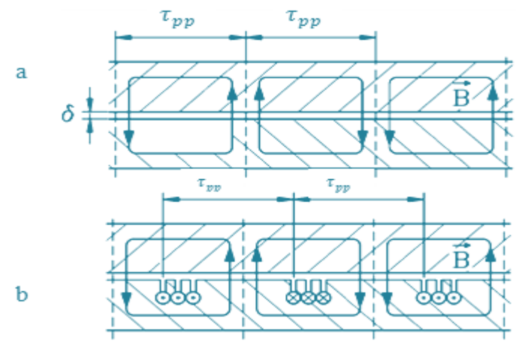


Figure 1.1: Single layer winding – (a) One coil group, (b) Three coils group.

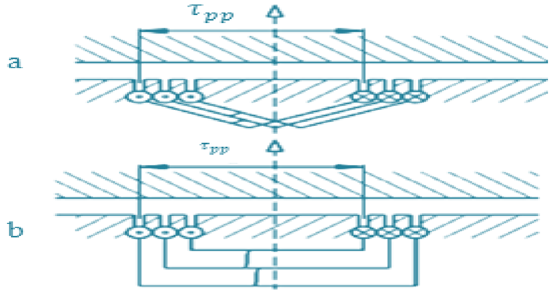


Figure 1.2: Single layer winding –(a)Coils with Identical span, (b)Concentric layer coils.

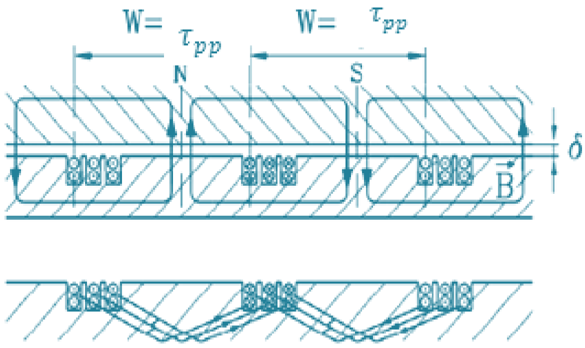


Figure 1.3: Double layer winding – Coils with Identical coil span.

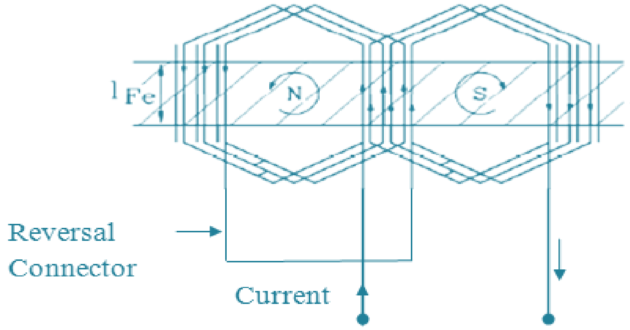


Figure 1.4: Double layer winding- Scheme of winding branch of one phase.

III. ANALYTICAL APPROACH TO MACHINE WINDING LAYOUT

This involves mathematical principles which help the designer properly design and field technologist to place coils appropriately in machine slots. This can be illustrated under the sub-headings that follow;

A. Coil Span

Coil span or coil pitch is the circumferential width of a coil. Coil span can be specified in terms of mechanical or electrical measures. In other words it can be defined as the number of slots covered by one coil loop. In slotted motors, it is convenient to describe the coil span in terms of slots. For example, if a coil goes from slot *k* to slot k+2, the coil span is 2 slots. The coil span for a coil should be made as close to 180 °E as possible but seldom exceed it. Doing so maximizes the flux linked to the coil and therefore maximizes the back EMF induced in the coil.

The nominal coil span as described above is found by defining the number of slots per magnet pole (i.e. the number of slots per 180^0E) as

$$N_{sl/P} = c_{span} = \frac{Q}{P} \tag{1}$$

Or

$$c^*_{span} = max\left[\frac{Q}{P}, 1\right] \tag{2}$$

The function {= max (a, b)} in the equation above ensures that the coil span is at least one slot when $Q < P$.
Sometimes, the winding span differs from the nominal span given in eqn. 2 above. Under such circumstances, the span chosen most often is usually equal to $c^*_{span} - 1$, the effect of which decreases the length of the end turns and changes the amplitude and harmonic content of the flux linkage and resulting back EMF. When this is done, the winding is said to be short pitched or ***chorded***. [1]

For three phase motors, the number of slots must be a multiple of three or not all slots will be filled with two coil sides. Before considering the details of laying out a winding, it is beneficial to identify the subset of magnet pole and slot count combinations that lead to valid windings.

For three phase motors, each of the three phase windings must produce a back EMF of the same amplitude and shape. More important here is that each back EMF be shifted in phase by 120°E from the other two phases. When these three criteria on the amplitude, shape, and relative phase are met, the winding is said to be ***balanced***.

The amplitude and shape of the phase back EMFs will be identical if the coils in each phase have the same number of turns and the same coil span and are distributed in the same way around the stator.

B. Phase Offset.

With reference to Fig. 1.5 below, if the first coil of phase **A** uses slot **0** and slot c^*_{span}, where c^*_{span} is the chosen coil span, then the first coil of phase **B** must use a slot ***k*** and $k+c^*_{span}$, where k is chosen so that slots **0** and ***k*** are separated by 120°E. If no such slot can be found, the chosen pole and slot count combination does not support a balanced winding.

When a slot ***k*** is found, each coil in phase **B** is shifted by ***k*** slots with respect to the corresponding coil in phase **A**. This span of K_0= ***k*** slots is called the ***phase offset***. For each coil in phase A, each corresponding coil in phase B is shifted K_0 slots, thereby assuring that the individual coil back EMF of phase B are shifted 120°E relative to those of phase A [1].

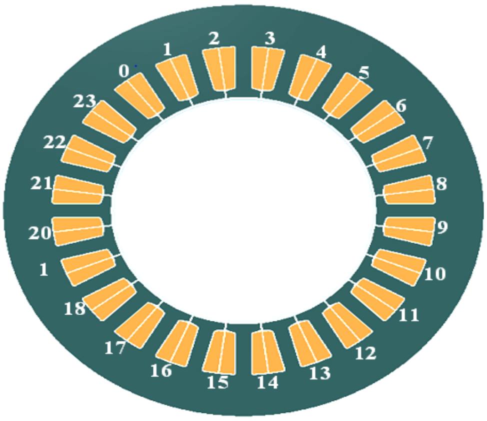


Figure 1.5: Machine slot configuration and slot span, drawn with MotorSolve 5.1.

To obtain the phase shift of phase C, phase C coils are shifted by K_0 slots from those of phase B thereby creating a balanced winding.

Mathematically, the phase offset can be determined by identifying the angle of each slot relative to slot 0[1]. Since the angular slot pitch is

$$\tau_{(sp^0)} = \frac{360^0}{Q} = \frac{360^0}{P*N_{sl/P}} (mec\ degrees) \tag{3}$$

the angle of the K_{th} slot is

$$\tau_{(sp^0(k))} = k\frac{P}{2}\frac{360^0}{Q} = k\frac{P}{Q}180^0, for\ k = 1,2, \ldots . Q-1 \tag{4}$$

The principle angle associated with each of these angles can be determined by using Phase offset function ***[=MOD(x,y)],*** which returns the remainder of the division *x/y*. The above function is an abstraction of Dr. Duane Hamselman's phase offset relation [=rem(x,y)] derived in Brushless Permanent Magnet Motor Design Second Edition [1,7].

$$\tau_{(sp^0(k))} = MOD\left(k\frac{P}{Q}180^0, 360^0\text{E}\right) \quad (5)$$

The phase offset K_0 is the value of ***k*** in the relation above for which the above equation evaluates to 120°E.

C. Alternative Approach To *Phase Offset* Determination

Engr. Samson Ugochukwu while referencing Relationship between Mechanical and Electrical Degrees stated in a master's thesis: *permanent magnet synchronous industrial motor design* [7] derived alternative approach to Phase Offset determination as follows:

Since $\boldsymbol{\theta^0}$**E** is equal to $\boldsymbol{2\theta^0}$**M**, the spatial or mechanical displacement of slots from each other is proportional to the electrical displacement of same slot from each other. Thus for a balanced 3 phase system in which each phase coil must be displaced from each other by $\mathbf{120^0}$**E or** $\mathbf{2\pi/3}$ **rad**, the phase offset can be obtained as follows:

$$\theta_{(sl)Mec} = \frac{2\pi}{Q}, \theta_{(sl)Elec} = 2\theta_{(sl)Mec} \quad (6)$$

Since $\theta_{(sl)} = 2\theta_{(sl)Mec}$, a phase shift of 120^0E must be equivalent to 60^0M, thus the number of slots shifted before the next phase begins know as ***Phase Offset*** is given by,

$$K_{(0)} = \frac{120^0\text{E}}{2\theta_{(sl)Mec}} = \frac{60^0\text{E}}{\theta_{(sl)Mec}}(deg) = \frac{2\pi}{6\theta_{(sl)Mec}}(rad) \quad (7)$$

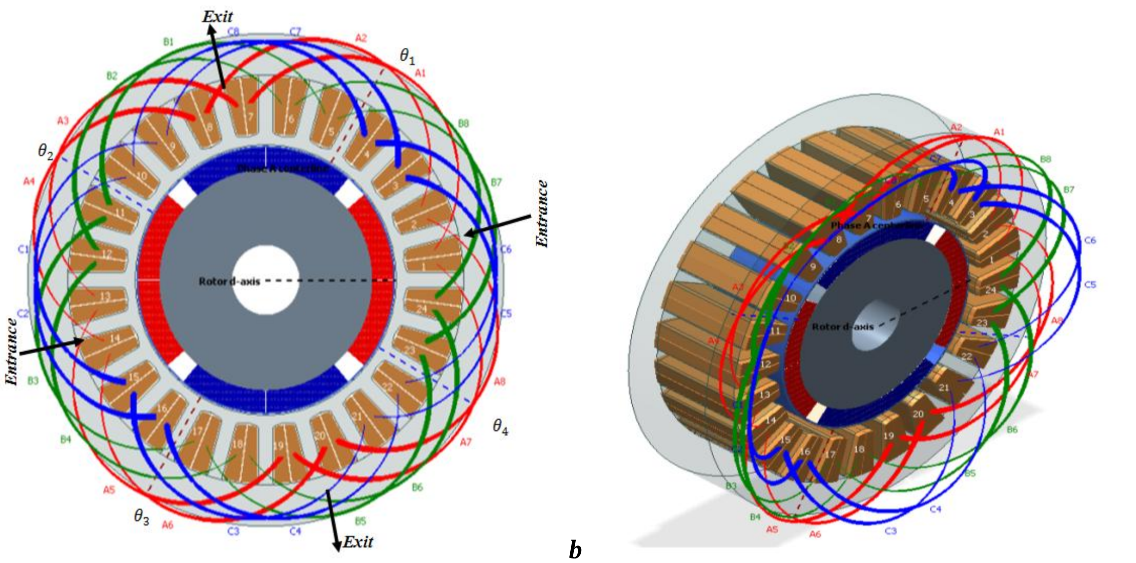
This is the number of coil locations that must be found for each phase. The coil locations for other phases are found by applying the phase offset K_0 twice to the coil locations found for phase A. The second and third phases are shown with blue and green strip in fig. 1.6 below.

IV. WINDING LAYOUT

In fig. 1.6, coils having midpoints at θ_1 and θ_3 are at the same angle designated 0°E and are wound in one direction. On the other hand, coils having midpoints at θ_2 and θ_4 are 180°E away from θ_1 and θ_3; respectively and are wound in the opposite direction. To signify the relative coil direction, the terms ***Entrance*** and ***Exit*** are used as shown in Fig. 1.6 below. ***Entrance*** refers to the coil side entering a slot and ***Exit*** refers to a coil side leaving a slot.

For those coils closest to 120°E or 180°E, the reverse or opposite winding direction is used. This effectively shifts the coil angle by 120°E or 180°E back toward 0°E. The number of slots is always a multiple of three for three phase motors. Since each coil fills two slots one-half full, (as in double layer winding) each coil effectively fills one slot. As a result, the number of coils per phase is

$$N_{coil/ph} = \frac{Q}{m}, but\ Q = qPm; \therefore N_{coil/ph} = qP \quad (8)$$



a ***b***

Figure 1.6: Machine coil span and phase offset of three phases drawn with MotorSolve 5.1.(a) Plain View (b) Isometric View

A. Pitching (Chording) of Coils W < τ_{pp}

Coil pitching can be applied to two-layer winding. It is defined as shortening of coil span *W*, counted in number *S* of slot pitches as shown below.

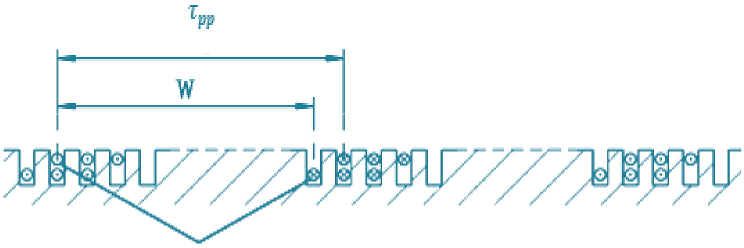


Figure 1.7: Coil pitching

$$W = \tau_{pp}\frac{m.q-S}{m.q} = \tau_{pp}\frac{Y_Q}{m.q}, S\ is\ an\ integer\ number \quad (9)$$

When coils are pitched, the resultant field curve fits better to ideal sinusoidal shape [3]. E.g Four-pole machine with m = 3, Q = 24, q = 2; Pitching is possible for *S<mq* = 3*2 = 6; S = 1, 2, 3, 4, 5. E.g let *S = 1*, then chording becomes

$$\frac{W}{\tau_{pp}} = \frac{3*2-1}{3*2} = \frac{5}{6} \quad (10)$$

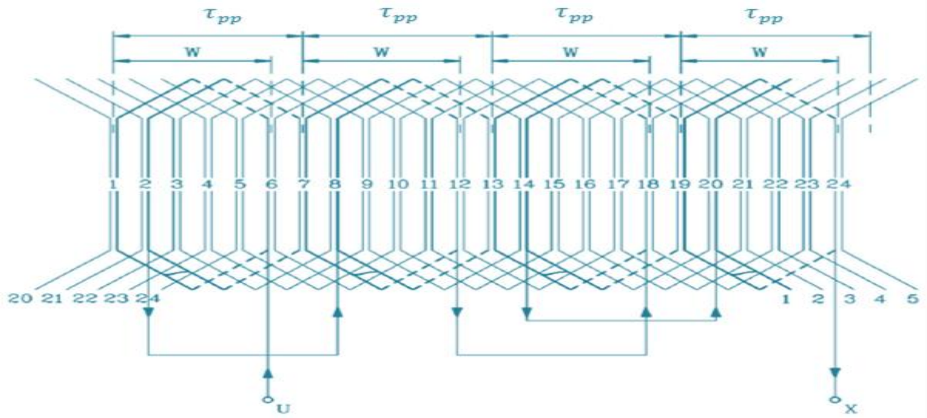


Figure 1.8: A four pole machine, with m = 3, Q = 24, q = 2, and pitching $W/\tau_p = 5/6$

V. BRIEF DISCUSSION OF WINDING LAYOUT

Before coils are placed in electric machine slots, the coil span as well as phase offset must be systematically determined, eqns. 1-7. Once these two parameters are determined, the windings can be laid out as shown in fig. 1.6. Note if the designer does not intend to use full pitch configuration in the design, a chording value has to be determined according to eqn. 9 and 10. This further guides the technologist or the engineers establish the positions of each coil in the machine slots. In fig. 1.6 a double layer side-side winding layout for a 24 slots 4-poles motor is shown. The red strip represents phase A, green strip phase B and blue strip phase C. Each slot of the machine contains two (2) coils of the same group placed side by side with coil span of 6 slots and phase offset of 4 slots. Fig. 1.8 shows the case of 5/6 pitching which resulted in shortening of the coil span by one slot.

VI. CONCLUSION

Mathematical means of determining various parameters required to properly layout coils especially in multiphase winding had been clearly specified in this article. Thus the aim of the author(s) which is practical interpretation of design paradigms which eventually leads to physical construction had been achieved. This approach can be applied to any slotted electrical machine regardless of the number of phases and poles of the machine.

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