MultiCraft

International Journal of Engineering, Science and Technology
Vol. 2, No. 10, 2010, pp. 79-86

INTERNATIONAL JOURNAL OF ENGINEERING, SCIENCE AND TECHNOLOGY
www.ijest-ng.com

Multi-phase alternative current machine winding design

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Abstract

In this paper, a generalized formula is proposed for the selection of number of slots required for n-phase alternative current (AC) machine design and the criterion for selecting the starting points of each phases. The analytical model is verified using a four-pole machine with a 36-slot stator. Each coil of the stator winding of this machine is brought out to a patch board that enables the stator to be configured for single-phase to 18-phase excitation. Experimental results of a five-phase induction machine supplied from a static five-phase supply are provided to support the proposed design.

Keywords: AC machine, Multi-phase machine, Stator winding, Five-phase

1. Introduction

Variable speed electric drives predominately utilize the three-phase machine, however, since the variable speed ac drives require a power electronic converter for their supply (in vast majority of cases an inverter with a dc link), the number of machine phases is essentially unlimited. This has led to an increase in the interest in multiphase ac drive applications, since multiphase machines offer some inherent advantages over their three-phase counterparts. a number of interesting research results have been published over the years and detailed reviews are available in (Jone *et al*, 2002, Iqbal *et al*, 2003).

Major advantages of using a multi-phase machine instead of a three-phase machine are detailed in (Jone *et al*, 2002, Iqbal *et al*, 2003)and are reduced inrush current, higher torque density, greater efficiency, reduced torque pulsations, greater fault tolerance, and reduction in the required rating per inverter leg (and therefore simpler and more reliable power conditioning equipment). Additionally, noise characteristics of the drive improve as well. The applications of multi-phase motor are rail wagon tippler, ‘more electric’ aircraft, electric ship propulsion, traction and *EV/HEVs*. The detailed design of electric machines is given in (Sawhney, 2002, Say, 2003). The special design of stator core, rotor core, stator teeth, rotor teeth, stator winding, rotor winding, air-gap flux, machine enclosure, machine ventilation, machine efficiency optimization etc is explained in (Ohtsuka *et al*, 1996, Bianchi *et al*, 2006, Zhang *et al*, 2007, Granner, 2008, Choi *et al*, 2007, Ting *et al*, 2007).

2. N-phase AC Machine Design

The paper presents a generalized relationship for determining the number of slots to be used and their starting point. Specific example of three, four and five-phase machines are taken up first followed by presentation of generalized design for n-phase machine.

(A) Three-phase AC machine

(i) Three-phase two pole ac machine

For a three-phase ac machine the phase angle between any two consecutive phases is given as:

$$\phi = \frac{360°}{3}(electrical) = 120°(electrical) = 120°(mechanical)$$; for two pole ac machine.

For example, the number of slots required and their allocation for three-phase two pole ac machine are given in Table 1.

Table 1: Three-phase two pole machine stator slots allocation

POLE-1			POLE-2			NO. OF SLOTS
A	C	B	A	C	B	
1	1	1	1	1	1	6
2	1	2	1	2	1	9
2	2	2	2	2	2	12
3	2	3	2	3	2	15
3	3	3	3	3	3	18
4	3	4	3	4	3	21
4	4	4	4	4	4	24
….	….	….	….	….	….	….

Here A, B, C represent three phases of machine. All phases (A, B & C) are under each pole as shown in the "Table 1,". The last column lists the no. of slots required to wind a 3-phase, 2-pole machine. The minimum no. of slots required to design such machine should be 6. The increment in the slots should be in the step of 3. There is no limit imposed on the maximum no. of slot, however the optimum design require a suitable no. There are some constraints in the selection of stator slots and are

(i) Number of slots per phase should be same for each phase.
(ii) Minimum number of slots =n*P, where n is the no. of phases of a machine and P is the no. of poles of a machine.
(iii) For symmetrical winding, the slot/pole should be an integer and for asymmetrical winding, the slot/pole should be a non-integer.

In general, the number of slots required are [6+3*K*]=3*[2+*K*], where *K*=0, 1, 2, 3,………..

$$\text{Therefore per slot angle} = \frac{360°}{3*[2+K]} = \frac{120°}{[2+K]} \text{(mech)} \tag{1}$$

And required phase angle between any two consecutive phases in terms of slots= $120° / slot.angle = [2+K] slots$.

This suggest that if phase-A starts from slot no.1 then phase-B will starts from [2+*K*]th slot and phase-C from 2*[2+*K*]th slot.

(ii) Three-phase four pole ac machine

For a three-phase ac machine the phase angle between any two consecutive phases is given as:

$\phi = \frac{360°}{3}(electrical) = 120°(electrical) = 60°(mechanical)$; for four pole ac machine.

Similarly, the number of slots and winding disposition required for three-phase four pole ac machines can be found.

In general, the number of slots required are 6*[2+*K*], where *K*=0, 1, 2, 3,………..

$$\text{Therefore per slot angle} = \frac{360°}{6*[2+K]} = \frac{60°}{[2+K]} \text{(mech)} \tag{2}$$

And required phase angle between two consecutive phases in terms of slots= $60° / slot.angle = [2+K] slots$.

If phase-A starts from slot no.1 then phase-B will starts from [2+*K*]th slot and phase-C from 2*[2+*K*]th slot.
In general for P number of poles three-phase ac machine, the number of slots required are:

$$S = \frac{3}{2}.P.[2+K] slots \text{..........} \tag{3}$$

where K=0, 1, 2, 3,……

(B) Four-phase AC machine

(i) Four -phase two pole ac machine

For a Four-phase ac machine the phase angle between any two consecutive phases is given as:

$\phi = \frac{360°}{4}(electrical) = 90°(electrical) = 90°(mechanical)$; for two pole ac machine.

In general, the number of slots required are 4*[2+*K*], where *K*=0, 1, 2, 3,………..

$$\text{Therefore per slot angle} = \frac{360°}{4*[2+K]} = \frac{90°}{[2+K]} \text{ (mech)} \quad (4)$$

And required phase angle between any two consecutive phases in terms of slots= $90°/slot.angle = [2+K]slots$.

If phase-A starts from slot no.1 then phase-B will starts from [2+*K*]th slot, phase-C from 2*[2+*K*]th slot and phase-D from 3*[2+*K*]th slot.

(ii) Four -phase four pole ac machine

For a Four-phase ac machine the phase angle between any two consecutive phases is given as:

$\phi = \frac{360°}{4}(electrical) = 90°(electrical) = 45°(mechanical)$; for four pole ac machine.

In general, the number of slots required are 8*[2+*K*] where *K*=0, 1, 2, 3,………..

$$\text{Therefore per slot angle} = \frac{360°}{8*[2+K]} = \frac{45°}{[2+K]} \text{ (mech)} \quad (5)$$

And required phase angle between any two consecutive phases in terms of slots= $45°/slot.angle = [2+K]slots$.

If phase-A starts from slot no.1 then phase-B will starts from [2+K]th slot, phase-C from 2*[2+*K*]th slot and phase-D will starts from 3*[2+*K*]th slot .

In general for P number of poles four-phase c machine, the number of slots required are:

$$S = \frac{4}{2}.P.[2+K]slots \ \ldots\ldots \quad (6)$$

where *K*=0, 1, 2, 3,………..

(C) Five-phase AC machine

(i) Five –phase two pole ac machine

Five –phase ac machine the phase angle between any two consecutive phases is given as:

$\phi = \frac{360°}{5}(electrical) = 72°(electrical) = 72°(mechanical)$; for two pole ac machine.

In general, the number of slots required are 5*[2+*K*] where *K*=0, 1, 2, 3,………..

$$\text{Therefore per slot angle} = \frac{360°}{5*[2+K]} = \frac{72°}{[2+K]} \text{ (mech)} \quad (7)$$

And required phase angle between two consecutive phases in terms of slots= $72°/slot.angle = [2+K]slots$.

If phase-A starts from slot no.1 then phase-B will starts from [2+K]th slot, phase-C from 2*[2+K]th slot, phase-D from 3*[2+K] and phase-E from 4*[2+K]th slot.

(ii) Five –phase four pole ac machine

For a Five –phase ac machine the phase angle between any two consecutive phases is given as:

$\phi = \frac{360°}{5}(electrical) = 72°(electrical) = 36°(mechanical)$; for four pole ac machine.

In general, the number of slots required are [20+10K]=10*[2+K] where K=0,1,2,3,………..

$$\text{Therefore per slot angle}=\frac{360^\circ}{10*[2+K]}=\frac{36^\circ}{[2+K]}\text{ (mech)} \quad (8)$$

And required phase angle between any two consecutive phases in terms of slots= $36^\circ / slot.angle = [2+K]slots$.

If phase-A starts from slot no.1 then phase-B will starts from [2+K]th slot, phase-C from 2*[2+K]th slot, phase-D from 3*[2+K]th and phase-E will starts from 4*[2+K]th slot .
In general for P number of poles five-phase ac machine, the number of slots required are:

$$S=\frac{5}{2}.P.[2+K]slots \text{ ……..} \quad (9)$$

where K=0, 1, 2, 3,………..

Generalized Design

From the above discussion it can be concluded that

For 3-Phase ac machine no. of slots is: $S=\frac{3}{2}.P.[2+K]slots$ (10)

For 4-Phase ac machine no. of slots is: $S=\frac{4}{2}.P.[2+K]slots$ (11)

For 5-Phase ac machine no. of slots is: $S=\frac{5}{2}.P.[2+K]slots$ (12)

Therefore following the same trend, in general for n-phase ac machine, the no. of slots required is

$$S=\frac{n}{2}.P.[2+K]slots \text{ …..} \quad (13)$$

where S= no. of machine slots required
n= no. of machine phases
P= no. of machine poles
and K= 0, 1, 2, 3,………..
And starting points (slots) of the different phases are given as:

$$1+\gamma[2+K] \text{ ….} \quad (14)$$

In general $\gamma=(n-1)$ for nth phase.
Also for symmetrical ac winding: K= 0, 2, 4,……..
And for asymmetrical ac winding: K= 1, 3, 5,……..

3. Experimental Results

A five-phase induction motor of 30 slots, four pole and asymmetrical winding has been designed using the derived formula. The coil-pitch is fixed 6-slots. The experimental results are obtained by direct fed supply from a special connection scheme of transformer termed as AMR (Atif-Moinuddin-Rizwan) connection (Iqbal et al., 2010). The developed transformer connection scheme transforms available three-phase supply system to a five-phase supply system. A patent has been sought for this product. The slot selection is shown in Figure 1, and winding distribution of each phase is shown in Figure 2. The experimental results are illustrated in Figure 3 to Figure 10. Figure 1 shows a complete distribution of windings, starting points and finishing points. The number of slots occupied per pole pair is 15. This is a special way to show the phase windings of a multi-phase machine. Figure 2(a) to Figure 2(b) shows each phase winding in different poles.

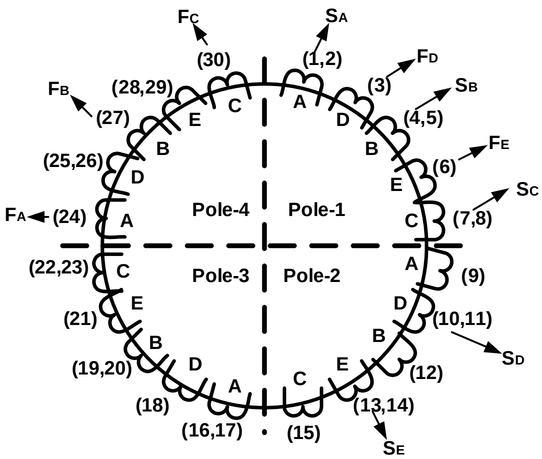
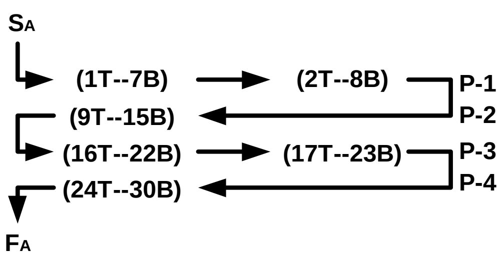
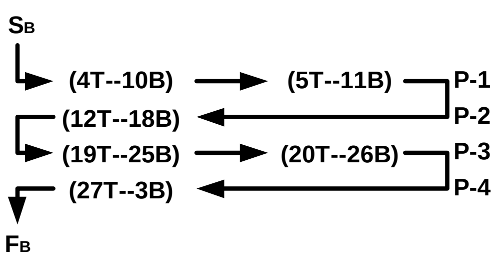


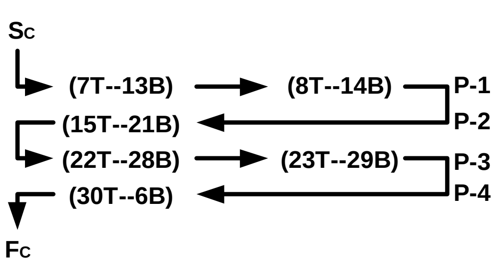
Figure 1: Slots distribution, phase sequence, starting and finishing points of different phases.



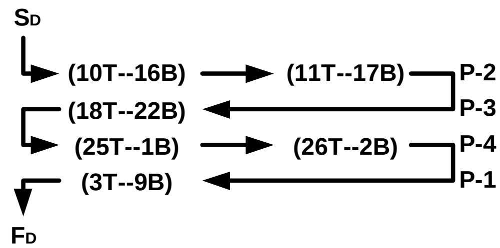
(a) Phase-A winding arrangements



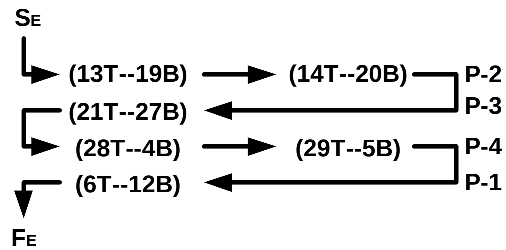
(b) Phase-B winding arrangements



(c) Phase-C winding arrangements



(d) Phase-D winding arrangements



(e) Phase-E winding arrangements

Figure 2: Phase A to E winding arrangement under different poles.

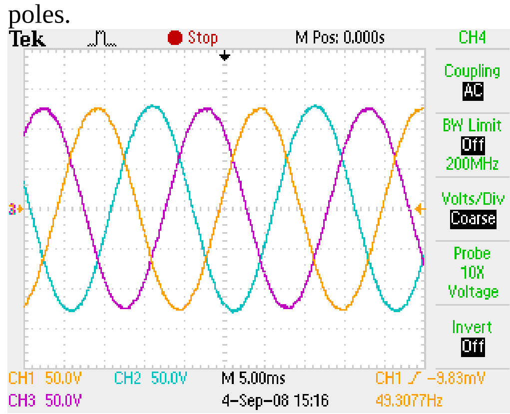


Figure 3: Transformer input phase voltages *Va*, *Vb*, *Vc* at no-load.

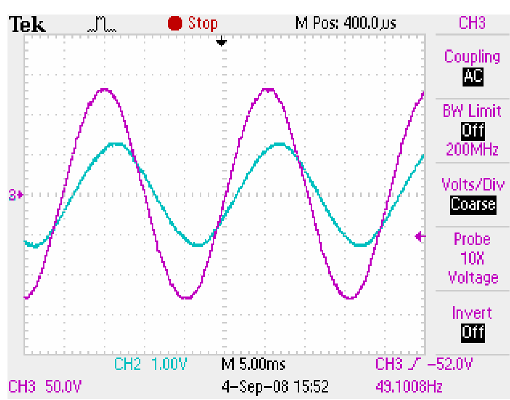


Figure 4: Five-phase motor input phase voltage V_a and current I_a at load.

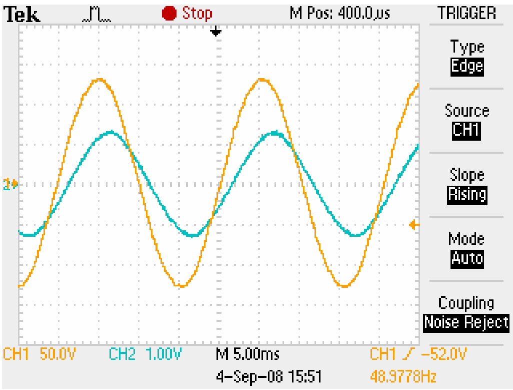


Figure 5: Five-phase motor input phase voltage V_b and current I_b at load.

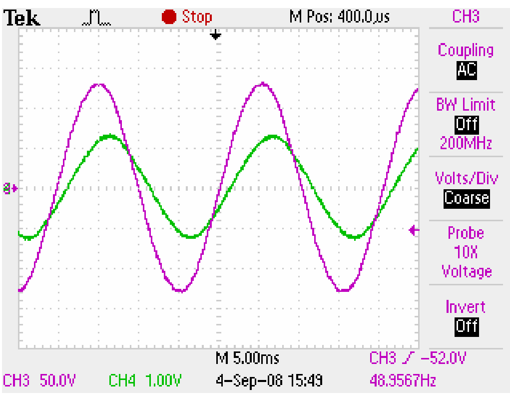


Figure 6: Five-phase motor input phase voltage V_c and current I_c at load.

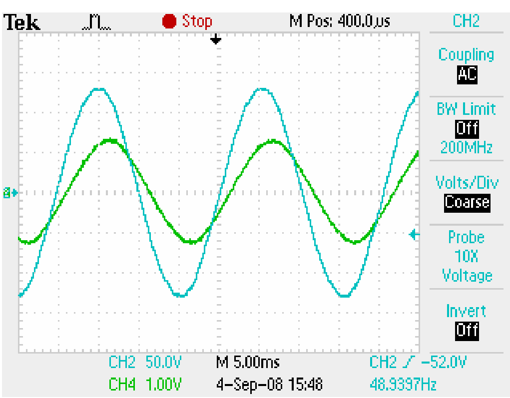


Figure 7: Five-phase motor input phase voltage *Vd* and current *Id* at load.

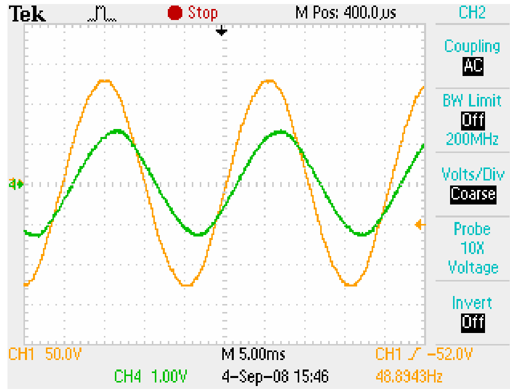


Figure 8: Five-phase motor input phase voltage V_e and current I_e at load.

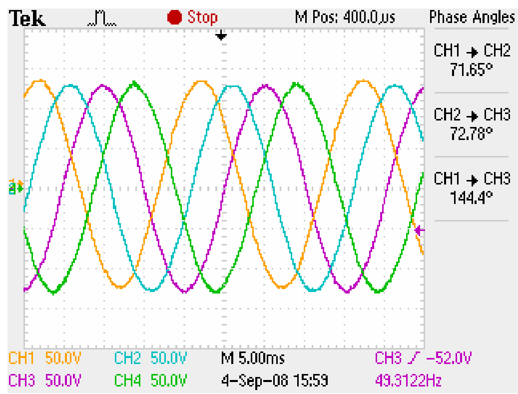


Figure 9: Five-phase motor input phase voltages V_a, V_b, V_c, and V_d at load.

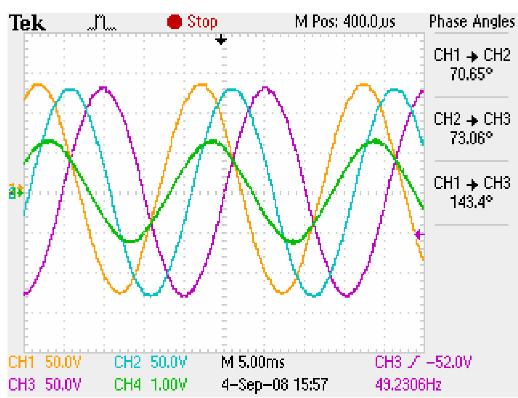


Figure 10: Five-phase motor input phase voltages V_a, V_b, V_c and current I_a at load.

4. Discussion

At no-load, the voltage input to the 3-to-5 phase transformer (AMR-connection) is kept at 90 volt. The no-load speed of five-phase motor is 1440 rpm. At load, input voltage to transformer is 90 volt. An eddy current load is connected to the five-phase motor through shaft coupling for loading purpose. The eddy current loading (armature) voltage is 10 volt, load current (per phase) is 0.85 amp and motor speed is 1412 rpm. Figure 3 show the three-phase transformer input phase voltages V_a, V_b, V_c at no-load. Figure 4 to Figure 8 show Five-phase motor input phase voltages V_a , V_b, V_c, V_d, V_e and currents I_a, I_b, I_c, I_d, I_e at load, respectively. Figure 9 show the five-phase motor input phase voltages V_a, V_b, V_c, and V_d and Figure 10 show the five-phase motor input phase voltages V_a, V_b, V_c and current I_a at load conditions. All the presented results are typical to any five-phase induction machine and hence validating our design. In experimental results, the voltages and currents input to the transformer and input to the motor are sinusoidal. The currents having no harmonics, the reason for this is that a short pitch winding in stator has been used. The results obtained with five-phase induction machine are satisfactorily in terms of phase difference between any two phases which is 72° (Electrical) and the phase relationship between phase voltage and phase current.

5. Conclusions

This paper presents an approach for the selection of number of slots for n-phase ac machine and their selection of starting and finishing points. The developed technique can be used for any number of phases of an ac machine. The slots distribution and winding distribution are also presented for 3-phase, 4-phase and 5-phase. Also experimental results of a five-phase induction machine are presented for the verification of the findings.

Acknowledgement

The work reported is funded by Council of Scientific and Industrial Research (CSIR), India, File No. 22(0462)09/EMR-II, 2009.

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Received August 2010
Accepted October 2010
Final acceptance in revised form November 2010