INTERSPERSED WINDINGS: WHAT ARE THEY?

By Chuck Yung
Technical Support Specialist
Electrical Apparatus Service Association, Inc.
St. Louis, Missouri

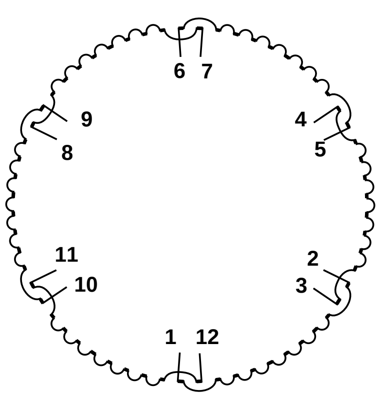
INTRODUCTION

Interspersed windings have been in use for many years, primarily on 2-pole machines. Sometimes called "cyclic shift" windings, they were used by only a handful of motor manufacturers (only one still does), so information about them was closely held.

While interspersed windings are not new, they are rare enough that many winders lack a clear understanding of their purpose or overlook the interspersion when taking data. That can lead to problems. Failure to duplicate an interspersed connection, for example, can result in a motor that cannot accelerate its load. With a large motor, the effect may be so severe that it cannot even accelerate to speed uncoupled.

This paper explains what interspersed windings are and how they work. Its purpose is to help repair technicians correctly identify and properly repair machines having these unusual windings.

FIGURE 1: EXAMPLE OF 2-POLE INTERSPERSED WINDING—60 SLOTS



BACKGROUND

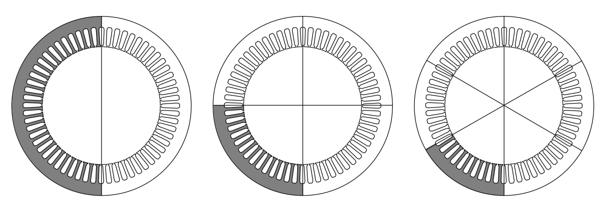
What they are. The interspersed winding gets its name from the way the coils of adjacent groups intermingle. Lay your hands palm-down and overlap your thumbs. That is how the first and last coils of each pole group look in a single-interspersed winding. (See Figure 1.)

What they do. Interspersed windings help solve a significant design problem associated with 2-pole machines. They make it possible to manipulate other design variables (e.g., chord factor and distribution factor) in ways that reduce the adverse effects of harmonic waveforms on the performance of these machines.

To understand how interspersed windings work, it helps to review the design variables that they can affect.

Poles, frequency and speed. The speed of an AC machine is determined by the number of magnetic poles it has and the frequency of supplied power. At 60 Hz, for example, 7200 cycle reverses occur per minute, so the magnetic field of a 2-pole machine rotates at 3600 rpm (7200/2 = 3600 rpm). Similarly, 4-pole machines have a synchronous speed of 1800 rpm (7200/4 = 1800); and 6-pole machines run at 1200 rpm (7200/6 = 1200).

FIGURE 2



Coil pitch. Coil pitch describes the number of stator slots that a coil (or a pole group) spans in a given winding. The shaded areas shown in Figure 2, for example, represent the full coil pitch for 2-, 4- and 6-pole windings.

To find the full coil pitch for a given winding, multiply (1/poles) times the number of stator slots. A 60-slot motor with a 6-pole winding, for instance, would have a full pitch of 10 teeth:

(1/6) x 60 = 10 Teeth (coil sides lie in Slots 1 and 11)

The same 60-slot motor with a 4-pole winding would have a full pitch of 15, with coil sides in Slots 1 and 16. A 2-pole winding, on the other hand, would have full pitch of 30—

i.e., halfway around the stator—with the coil sides in Slots 1 and 31. Winding this could be impossible.

Effective turns per coil. The strength of a winding is determined by the effective turns of each coil. Effective turns, which depend on the coil pitch and the grouping arrangement, equal actual turns only when a full-pitch winding is used. The narrower the coil pitch, the less effective each turn becomes. For a full-pitch winding, the chord factor (K_c, sometimes referred to as K_p) equals 1.

Chord factor. Chord factor is the ratio of the effective turns of a coil to the actual turns. In other words, effective turns equal actual turns times chord factor.

Chord factor (K_c) depends on the relationship of the total slots, poles and coil pitch. The narrower the coil pitch, the lower the chord factor and the less effective each turn becomes. This relationship is described by the formula:

$$\text{Chord factor} = \text{Sin}\left(90 \times \left(\frac{\text{Teeth spanned}}{\text{Slots/Pole}}\right)\right)$$

For a 60-slot, 2-pole motor with a 1 - 20 pitch:

Teeth spanned = 19

$$\text{Chord factor} = \text{Sin}\left(90 \times \left(\frac{19}{30}\right)\right)$$

Sin 57° = .839

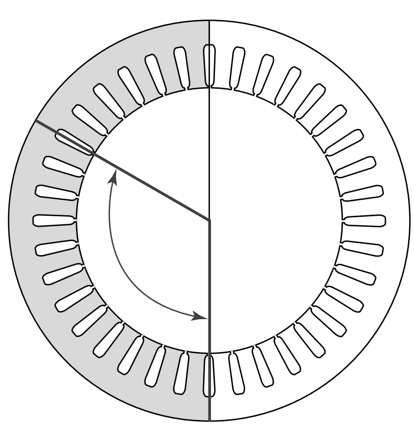
The chord factor remains constant unless the coil pitch is changed.

In the optimum electric motor, a coil spanned to a chord factor (K_c) of .966 best eliminates the harmonics that distort the normal AC sine wave. This exact pitch is not possible with all slot/pole combinations, so motors with 4 or more poles are usually pitched to a chord factor between .900 and .996.

The 2-pole motor is an exception. Using a 60-slot motor as an example, the desired pitch for a full-strength winding would be between 1 - 27 and 1 - 29. But in that case a cross-section of the coil extension would contain 28 to 30 coils—the sheer bulk of which could make the motor impossible to wind.

To overcome this, most lap-wound 2-pole machines have shorter (narrower) coil pitches, resulting in chord factors between .707 and .866 (see Figure 3). These chord factors fall outside of the desirable range (.900 to .966), so the turns are less effective. Harmonics may also pose problems.

FIGURE 3

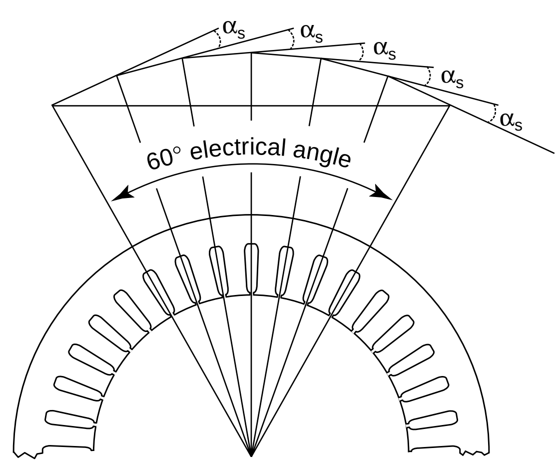


Full pitch for a 2-pole winding would be halfway around the stator bore. For practical reasons, the coil pitch normally used is approximately as shown.

Distribution factor. The distribution factor (K_d) is a mathematical description of the way in which the pole groups and coils are distributed around the stator. It is derived by dividing the sum of the cosines of the electrical angles for each coil in a pole group by the number of coils per group. Consequently, it can be altered by changing the placement of the coils within each group. The interspersed connection offers a way to accomplish this.

$$K_d = \frac{\text{Sum of cosines}}{\text{Coils per group}}$$

FIGURE 4



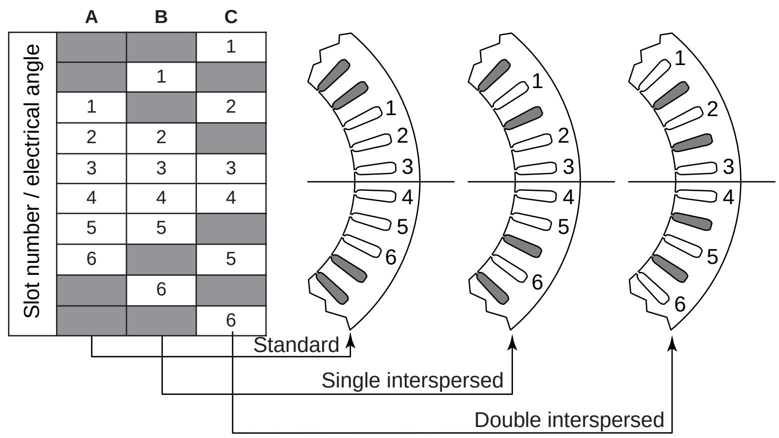
As Figure 4 shows, the electrical angle from the center of a group to the center of each coil within that group increases according to the placement of each coil of the group.

With an interspersed winding, an additional factor comes into play: placement of the interspersed coils of the pole group in slots not immediately adjacent to the rest of the group. This "jump slot" interspersion (represented by your thumbs in the earlier example) means the electrical angle from the center of the pole group to each of the interspersed

FIGURE 5: EXAMPLE OF THE DISTRIBUTION FACTOR FOR A 36-SLOT MOTOR

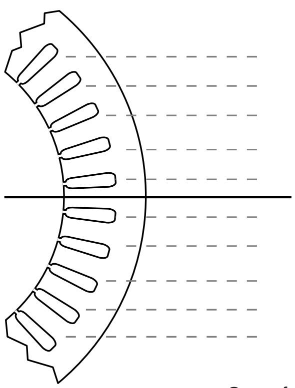
KEY

- Column A shows the coil placement for a standard lap winding.
- Column B shows the coil placement for a group, single-interspersed winding.
- Column C shows the coil placement for a double-interspersed winding.
- Shaded cells indicate slots not occupied by coils of this group. The values in the remaining cells are the cosine of the electrical angle for that coil side.
- To calculate the distribution factor for various harmonics, multiply the ratio of the harmonic times the angle for each coil.



The distribution factor (K_d) for the coil group = $\dfrac{\text{Sum of the cosines of the group of coils}}{\text{Coils per group}}$

36 SLOTS — 6 COILS PER GROUP



Fundamental

	A	B	C
45			0.707
35		0.819	
25	0.909		0.909
15	0.966	0.966	
5	0.996	0.996	0.996
5	0.996	0.996	0.996
15	0.966	0.966	
25	0.909		0.909
35		0.819	
45			0.773
Sum of cosines	5.736	5.562	5.218
Distribution factor	0.956	0.927	0.870

5th harmonic

	A	B	C
225			-0.707
175		-0.996	
125	-0.574		-0.574
75	0.259	0.259	
25	0.906	0.906	0.906
25	0.906	0.906	0.906
75	0.259	0.259	
125	-0.574		-0.574
175		-0.996	
225			-0.707
Sum of cosines	1.182	0.388	0.750
Distribution factor	0.197	0.056	0.125

7th harmonic

	A	B	C
315			0.707
245		-0.423	
175	-0.996		-0.996
105	-0.259	-0.259	
35	0.819	0.819	0.819
35	0.819	0.819	0.819
105	-0.259	-0.259	
175	-0.996		-0.996
245		-0.423	
315			0.707
Sum of cosines	0.872	0.274	1.060
Distribution factor	0.145	0.046	0.177

coils is greater than that of the corresponding coil in a standard winding.

Because the distribution factor is derived from the cosines of these angles, it will change if the layout of the interspersed coils changes. Figure 5 compares the cosine angles and resulting distribution factors for a 36-slot motor with standard grouping with those of single- and double-interspersed schemes. (See the Appendix for comparison of other slot numbers.)

The distribution factor is lower for the interspersed schemes, so each turn is less effective. Consequently, more actual turns are needed for an interspersed winding than for a standard winding.

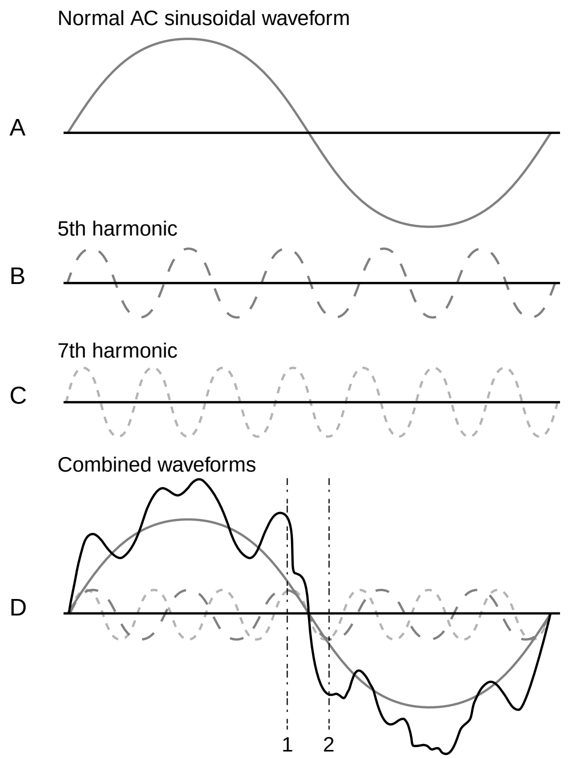
$$\text{Actual turns} = \frac{\text{Effective turns}}{(K_d \times K_c)}$$

Although the chord factor for a 2-pole motor may be as low as .707, the slightly lower distribution factor requires only a small increase in turns per coil. At the same time, the dramatic reduction in the 5th and 7th harmonics means that the intersperse can significantly improve motor performance.

HARMONICS

Harmonics are multiples of the fundamental (or line) electrical frequency. In the case of 60 Hz power, for example, the fundamental frequency completes 60 cycles per sec-

FIGURE 6: WAVEFORMS



ond, producing the normal AC sinusoidal waveform (see Figure 6A).

If harmonic frequencies were present, they would simultaneously (though independently) complete their own cycles, each with its own waveform. The 5th harmonic, for instance, would complete 300 cycles per second, while the 7th harmonic would cycle 420 times (see Figures 6B and 6C). Other harmonics exist as well, but the 5th and 7th impact the operation of three-phase electric motors the most.

The effect of each unique harmonic depends on its magnitude and on the shape of the resulting waveform when it combines with the fundamental waveform.

As Figure 6D shows, the 5th and 7th harmonics affect the fundamental frequency most when the sum total is at the greatest deviation from zero (near points 1 and 2). That is because the different waveform values are additive at each point in time (represented by the horizontal axis). The dark line shows how the combined effects of the 5th and 7th harmonics distort the fundamental AC sinusoidal waveform.

HOW DO HARMONICS AFFECT THE OPERATION OF A MOTOR?

Negative torque. One problem introduced by harmonics is that alternate odd harmonics (except for multiples of 3) "buck" the line frequency waveform, producing a negative torque when rotor speed is above the synchronous speed for that harmonic. These negative-sequence harmonics (including the 5th, 11th and 17th) try to rotate the induction motor in the opposite direction (see Table 1). The negative torque has a subtractive effect on output torque.

TABLE 1. HARMONIC FREQUENCIES AND THEIR RESPECTIVE SEQUENCES (+ OR -)

Harmonic	1	3	5	7	9	11	13	15	17
Sequence	+	0	-	+	0	-	+	0	-
Frequency	60	180	300	420	540	660	780	900	1020

Eddy current losses. Another concern with harmonics has to do with eddy current losses. Since they are a function of the square of the frequency, eddy current losses associated with the 5th harmonic on 60 Hz power theoretically could be 25 times those of the fundamental frequency, while those for the 7th harmonic could be 49 times as great. (This would only be true if the magnitudes of the fundamental and harmonic frequencies were the same.) Fortunately, the magnitude of harmonics is determined by this equation:

1/n x K_pK_d x Fundamental frequency

Where:

n = Harmonic order

K_c = Coil pitch

K_d = Distribution factor for the harmonic

On motors with 4 or more poles, spanning a winding to a chord factor of .900 to .996 minimizes the effects of negative torque and eddy current losses due to 5th and 7th harmonics. The smaller span needed for lap-wound 2-pole, however, may permit harmonics of sufficient magnitude to reduce net torque drastically. One solution is to strengthen the design enough to overcome the negative torque, so that net torque is sufficient to meet demand.

WHAT THE INTERSPERSE DOES

The interspersed connection changes the distribution factor of each pole group. It also affects each frequency differently—i.e., the line frequency and the various harmonic frequencies. Variables include the number of coils per group, the number of stator slots, coil pitch and the interspersion scheme used (single or double). By selecting the interspersion scheme that best reduces the effects of disruptive harmonics, it is possible to improve motor performance.

HOW INTERSPERSION HELPS

The line frequency distribution factor for each interspersed scheme is slightly lower than that of the standard grouping, but for the 5th and 7th harmonics it is dramatically lower. A slight decrease in the effective turns is more than offset by the reduction in harmonic distortion.

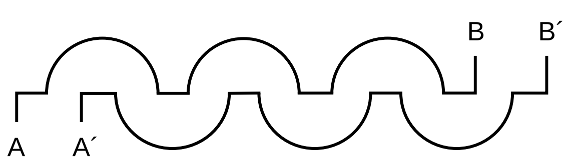
Note also that the benefits of the interspersion depend on the number of coils per pole group, or (since these are unique to 2-poles) the number of stator slots. For groups of 6 coils (36 slots), the single interspersion yields a lower distribution factor for both the 5th and 7th harmonics. With a 54-slot winding (9 coils/group), the benefit of the double-interspersed scheme is considerably greater than that of the single-interspersed (see the Appendix).

Other considerations include copper savings resulting from the narrower coil pitch. For a manufacturer producing thousands of 2-pole machines annually, the savings may be significant. Offsetting this is the additional complexity of the connection. With a random-wound stator, the additional connection time may offset the savings on materials.

INTERLEAVED COILS

An unusual aspect of some interspersed windings is interleaved coils. With this design, each pole group is divided to form two parallel paths. The two parallel paths within each group allow use of a 4-circuit connection on a 2-pole motor. The electrical angle of each coil in the group—and therefore the distribution factor of the group—does not change. Interleaving the coils is a means of doubling the circuits. When a random-wound motor has the interleaved connection shown in Figure 7, it is best to wind the coils individually and essential to duplicate the connection exactly.

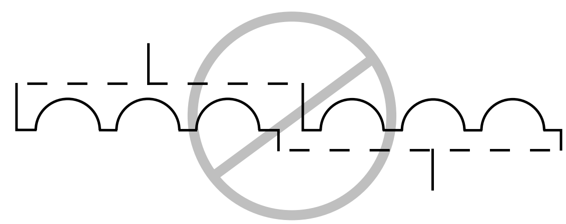
FIGURE 7: CORRECT METHOD OF INTERLEAVING AND INTERSPERSING COILS



Method of Interleaving and Interspersing coils. Looping individual coils is usually the best way to accomplish this, although it is possible to extend the crossovers when looping the coils in order to save labor (see Figure 7).

When rewinding a motor that has a large number of parallel wires and very few turns, it may help to double the number of circuits. To use twice the normal maximum circuits, the interleave method shown in Figure 7 must be used. Attempting to simplify this by splitting the group in two and paralleling them results in the two halves being out of phase by 32.36° (see Figure 8). This would produce harmful circulating currents.

FIGURE 8: INCORRECT METHOD OF INTERLEAVING AND INTERSPERSING COILS



CONCLUSION

The role of the interspersed connection is to reduce distortion of the sinusoidal waveform of 2-pole machines. Electric motors originally designed with an interspersed connection should have the intersperse duplicated when repairs include a stator rewind. A motor designed with an intersperse will lose a significant amount of torque if the intersperse connection is ignored. The intersperse also offers a means of improving the efficiency of a 2-pole motor, by reducing the counter-torque that results from the use of less effective coil pitches necessary for 2-pole windings.

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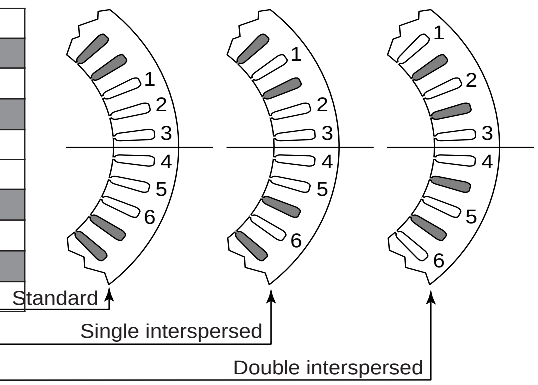
Note: This article was originally published in December 2000.

APPENDIX—DISTRIBUTION FACTORS

KEY

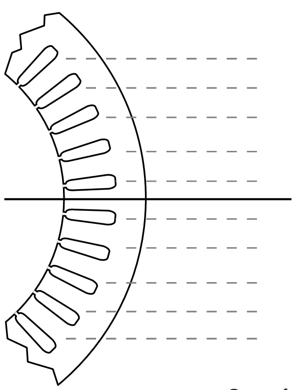
- Column A shows the coil placement for a standard lap winding.
- Column B shows the coil placement for a group, single-interspersed winding.
- Column C shows the coil placement for a double-interspersed winding.
- Shaded cells indicate slots not occupied by coils of this group. The values in the remaining cells are the cosine of the electrical angle for that coil side.
- To calculate the distribution factor for various harmonics, multiply the ratio of the harmonic times the angle for each coil.

Slot number / electrical angle	A	B	C
			1
		1	
	1		2
	2	2	
	3	3	3
	4	4	4
	5	5	
	6		5
		6	
			6



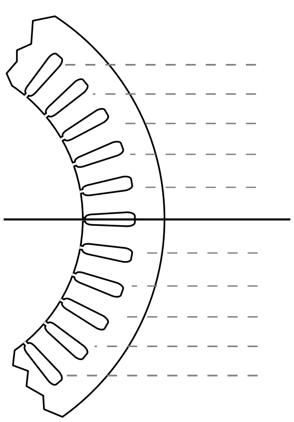
$$\text{The distribution factor } (K_d) \text{ for the coil group} = \frac{\text{Sum of the cosines of the group of coils}}{\text{Coils per group}}$$

36 SLOTS — 6 COILS PER GROUP



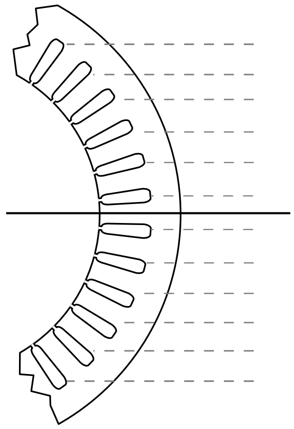
Fundamental	A	B	C	5th harmonic	A	B	C	7th harmonic	A	B	C
45			0.707	225			-0.707	315			0.707
35		0.819		175		-0.996		245		-0.423	
25	0.909		0.909	125	-0.574		-0.574	175	-0.996		-0.996
15	0.966	0.966		75	0.259	0.259		105	-0.259	-0.259	
5	0.996	0.996	0.996	25	0.906	0.906	0.906	35	0.819	0.819	0.819
5	0.996	0.996	0.996	25	0.906	0.906	0.906	35	0.819	0.819	0.819
15	0.966	0.966		75	0.259	0.259		105	-0.259	-0.259	
25	0.909		0.909	125	-0.574		-0.574	175	-0.996		-0.996
35		0.819		175		-0.996		245		-0.423	
45			0.773	225			-0.707	315			0.707
Sum of cosines	5.736	5.562	5.218		1.182	0.388	0.750		0.872	0.274	1.060
Distribution factor	0.956	0.927	0.870		0.197	0.056	0.125		0.145	0.046	0.177

42 SLOTS — 7 COILS PER GROUP



Fundamental	A	B	C	5th harmonic	A	B	C	7th harmonic	A	B	C
42.85			0.733	214			-0.829	300			0.500
34.28		0.826		171		-0.988		240		-0.500	
25.71	0.901		0.901	129	-0.629		-0.629	180	-1.000		-1.000
17.14	0.956	0.956		86	0.070	0.070		120	-0.500	-0.500	
8.57	0.989	0.989	0.989	43	0.731	0.731	0.731	60	0.500	0.500	0.500
0	1.000	1.000	1.000	0	1.000	1.000	1.000	0	1.000	1.000	1.000
8.57	0.989	0.989	0.989	43	0.731	0.731	0.731	60	0.500	0.500	0.500
17.14	0.956	0.956		86	0.070	0.070		120	-0.500	-0.500	
25.71	0.901		0.901	129	-0.629		-0.629	180	-1.000		-1.000
34.28		0.826		171		-0.988		240		-0.500	
42.85			0.733	214			-0.829	300			0.500
Sum of cosines	6.692	6.542	6.246		1.134	0.626	0.454		1.000	0.000	1.000
Distribution factor	0.956	0.935	0.892		0.192	0.089	0.065		0.143	0.000	0.143

48 SLOTS — 8 COILS PER GROUP



Fundamental

41.25			0.752
33.75		0.832	
26.25	0.897		0.897
18.75	0.947	0.947	
11.25	0.981	0.981	0.981
3.75	0.998	0.998	0.998
3.75	0.998	0.998	0.998
11.25	0.981	0.981	0.981
18.75	0.947	0.947	
26.25	0.897		0.897
33.75		0.832	
41.25			0.752
Sum of cosines	7.646	7.516	7.256
Distribution factor	0.956	0.940	0.907

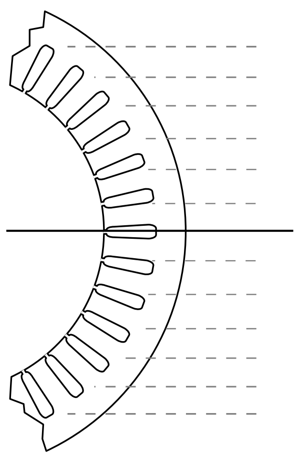
5th harmonic

206			-0.899
169		-0.982	
131	-0.656		-0.656
94	-0.070	-0.070	
56	0.559	0.559	0.559
19	0.946	0.946	0.946
19	0.946	0.946	0.946
56	0.559	0.559	0.559
94	-0.070	-0.070	
131	-0.656		-0.656
169		-0.982	
206			-0.899
	1.588	0.906	0.100
	0.1948	0.113	0.0125

7th harmonic

289			0.326
236		-0.559	
184	-0.998		-0.998
131	-0.656	-0.656	
79	0.191	0.191	0.191
26	0.899	0.899	0.899
26	0.899	0.899	0.899
79	0.191	0.191	0.191
131	-0.656	-0.656	
184	-0.998		-0.998
236		-0.559	
289			0.326
	1.128	0.250	0.836
	0.141	0.0313	0.1045

54 SLOTS — 9 COILS PER GROUP



Fundamental

40			0.766
33		0.835	
26	0.894		0.894
20	0.940	0.940	
13	0.973	0.973	0.973
6.7	0.993	0.993	0.993
0	1.000	1.000	1.000
6.7	0.993	0.993	0.993
13	0.973	0.973	0.973
20	0.940	0.940	
26	0.894		0.894
33		0.835	
40			0.766
Sum of cosines	8.600	8.482	8.252
Distribution factor	0.956	0.942	0.917

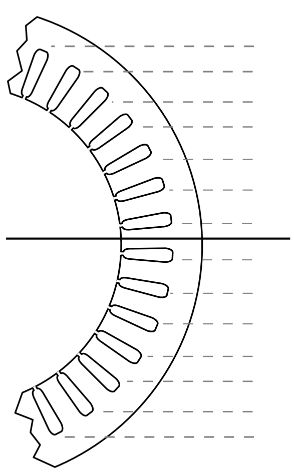
5th harmonic

200			-0.940
167		-0.974	
133	-0.682		-0.682
100	-0.174	-0.174	
67	0.391	0.391	0.391
33	0.839	0.839	0.839
0	1.000	1.000	1.000
33	0.839	0.839	0.839
67	0.391	0.391	0.391
100	-0.174	-0.174	
133	-0.682		-0.682
167		-0.974	
200			-0.940
	1.748	1.164	0.216
	0.1942	0.129	0.024

7th harmonic

280			0.174
233		-0.602	
187	-0.993		-0.993
140	-0.766	-0.766	
93	-0.052	-0.052	-0.052
47	0.682	0.682	0.682
0	1.000	1.000	1.000
47	0.682	0.682	0.682
93	-0.052	-0.052	-0.052
140	-0.766	-0.766	
187	-0.993		-0.993
233		-0.602	
280			0.174
	1.258	0.476	0.622
	0.140	0.0529	0.0691

60 SLOTS — 10 COILS PER GROUP



Fundamental

39			0.777
33		0.839	
27	0.891		0.891
21	0.934	0.934	
15	0.966	0.966	0.966
9	0.988	0.988	0.988
3	0.999	0.999	0.999
3	0.999	0.999	0.999
9	0.988	0.988	0.988
15	0.966	0.966	0.966
21	0.934	0.934	
27	0.891		0.891
33		0.839	
39			0.777
Sum of cosines	9.566	9.452	9.242
Distribution factor	0.956	0.945	0.924

5th harmonic

195			-0.966
165		-0.966	
135	-0.707		-0.707
105	-0.259	-0.259	
75	0.259	0.259	0.259
45	0.707	0.707	0.707
15	0.966	0.966	0.966
15	0.966	0.966	0.966
45	0.707	0.707	0.707
75	0.259	0.259	0.259
105	-0.174	-0.174	
135	-0.707		-0.707
165		-0.966	
195			-0.966
	1.932	1.414	0.518
	0.193	0.141	0.052

7th harmonic

273			0.052
231		-0.629	
189	-0.988		-0.988
147	-0.839	-0.839	
105	-0.259	-0.259	-0.259
63	0.454	0.454	0.454
21	0.934	0.934	0.934
21	0.934	0.934	0.934
63	0.454	0.454	0.454
105	-0.259	-0.259	-0.259
147	-0.839	-0.839	
189	-0.988		-0.988
231		-0.629	
273			0.052
	1.396	0.678	0.386
	0.140	0.068	0.039

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Electrical Apparatus Service Association, Inc.
1331 Baur Boulevard • St. Louis, MO 63132 U.S.A. • (314) 993-2220 • Fax (314) 993-1269 • www.easa.com

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