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THE INFLUENCE OF INTERSPERSED A SIX-PHASE STATOR WINDING ON THE MMF HARMONIC ANALYSIS

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Abstract:

The influence of interspersed a six-phase winding by one slot on the space MMF harmonic analysis has been investigated, by means of Goerge's vector diagram. Two types of six-phase windings with δ either equal to 30 or 60 electrical degrees are considered. These two types of windings are likely to be existed in practice. The scope of investigation covers the double-layer winding, two-pole, q=3 slots or 6 slots, either for interspersed arrangement or conventional arrangement.

The principles of interspersed the six-phase windings are described and compared with the conventional arrangement in terms of harmonic analysis. From which, it is shown that, controlling the lower belt harmonics of six-phase winding with δ = 60 and q = 6 slots may be achieved with insignificant reduction in the fundamental harmonic magnitude. Moreover, this type of six-phase winding should, therefore, find useful application in the systems, which suffer from their susceptibility to single point or more failures [2].

1. Introduction:

An important consideration in the design of stator windings for AC machines is that harmonic effects should be minimised, while the useful fundamental MMF is made as large as possible. Such improvement can be obtained from a six-phase winding with δ = 30, as the existed harmonic orders is given by the equation, $h = 12k \pm 1$; while a six-phase winding with δ = 60 electrical degrees produce harmonic orders of $h = 6k \pm 1$ [1]. From which, the winding with δ = 30 electrical degrees of six-phase winding was recommended to provide less space harmonic orders under balanced excitation systems. On the other hand, this winding under unbalanced operation was found to produce 3-rd, 5-th, 7-th, and 9-th harmonics of greater amplitude than that produced by the six-phase winding with δ = 60 electrical degrees [2]. However, the 5-th and 7-th harmonic magnitudes, for the six-phase winding with δ = 60, are found to be independent of the modes of operation. Therefore, this feature, of the six-phase winding with δ = 60, encourage the author to seek method of reducing the harmonic magnitudes; other than old methods such as choice of coil pitch or using a fractional slot winding. As they are used to eliminate one of chosen harmonic or a compromise reduction of a number of low-order harmonic.

Therefore, this paper aims for using the interspersed technique, which has been used previously with the three-phase windings, to reduce the effect of lower belt harmonics, such as 5-th and 7-th harmonics [3]. This technique is considered to be used with a six-phase winding with δ either equal to 30 or 60 electrical degrees, which they are likely to be found in practice. The scope of investigation covers the number of slots per phase per pole, q, equal three slots for both windings. Moreover, the six-phase winding with δ = 60 for q = 6 slots is investigated in order to compare the harmonic analysis of the two types of windings for the same number of slots per double pole pitch; S = 36 slots.

2. Description Of Interspersed Technique:

This technique has been used with the conventional three-phase winding to reduce the magnitude of the winding factors of the belt harmonic orders, such as 5-th and 7-th harmonics[3] .

For the purpose of this paper, it is important to note that the origin of the MMF harmonics is due to the actual distribution of the coils between the phases. Therefore, a Goerge's vector diagram was used. From which, the resultant MMF waveform of six-phase windings are seen to be basically dependent on the physical distribution of each phase winding. Moreover, the refinement of the basic winding arrangement is necessary if the space harmonics are to be controlled at their source. This is achieved with the interspersed winding by effectively altering the distribution of each phase belt to shape the MMF waveform of each phase and so to reduce the largest harmonics. The technique consists in interchanging each end coil side of one phase group with the corresponding coil side from the adjacent phase group and repeating this cyclic interchange throughout the winding, so that as a result all the phase groups are interleaved.

Figures 1 and 2 show the 36-slot, six-phase winding arrangement for two-pole, unity-pitch, with δ either equal 30 or 60 electrical degrees. On the other hand, Figure 3 shows the derivation of the space MMF waveform for S = 18 slots, q = 3 slots with δ = 60, in order to compare the analysis of this resultant waveform with that obtained from Figure 1 on the basis of constant q for both windings. However, in these Figures case I, represents the conventional six-phase winding, while case II, represents the interspersed six-phase winding.

In order to explain the procedure, Figure 1 case I and Figure 1 case II could be considered as an example. Figure 1 case I represents the conventional six-phase winding with δ= 30 for q = 3 slots. While Figure 1 case II represents the interspersed winding with δ = 30 for q = 3 slots, which may conveniently be described as 1-1-1 interspersed winding. The comparison between case I and case II of the same Figures shows the interspersed effect on the Goerge's vector diagram as well as on the resultant MMF waveform. The effect on the resultant MMF waveform may be regarded as a shaping operation , splitting up the MMF steps within the phase belt. The harmonic analysis results of the resultant MMF of the six-phase windings under investigation have been listed in Tables 3 to 8 .

3.Harmonic Analysis Of The Resultant MMF Of The Six-Phase Windings:

Since a large number of different six-phase winding arrangements are to be investigated, a computer program was prepared to calculate the magnitudes of harmonic orders, using input data specifying the physical distribution of the coils. These data were obtained every five electrical degree from the resultant MMF waveform, which these waveforms have been derived by using Goerge's vector diagram. The calculation are performed for harmonic orders up to including the 35-th harmonic, in order to include the first slot harmonic order for S = 36 slots of double pole-pitch.

Typical results are given in Tables 3 and 4 for the six-phase winding with $\delta = 30^\circ$, q = 3, S = 36 slots, of conventional and interspersed windings, consequently. Moreover, Tables 5 to 8 include the harmonic analysis for the six-phase winding with $\delta = 60^\circ$ for conventional and interspersed windings with q = 6 slots and q = 3 slots.

4. Discussion Of The Computer Results:

By means of a computer program using the step by step technique, some of six-phase winding with δ either equal 30 or 60 electrical degrees have been investigated. These windings have been considered conventionally wound and interspersed wound, in order to ease the comparison. The harmonic analysis results are included in Tables 3 to 8. However, Table 1 include the fundamental harmonic magnitudes of different windings under investigation. Moreover, Table 2 include the 5-th, 7-th, 11-th, and 13-th harmonic magnitudes for the same windings under investigation. Therefore, it is easy to study the effect of interspersed the windings by one slot on the MMF waveforms. In Table 1, the relative fundamental harmonic magnitude of the maximum height of the stepped waveform have been recalculated as a percentage of the fundamental harmonic of its conventional six-phase winding. Accordingly, the fundamental harmonic magnitude, of the interspersed six-phase winding with $\delta = 30^\circ$ and S =36 slots, is found to be reduced by about 4% of the fundamental harmonic of its conventional arrangement. However, for the same number of slots, S = 36 slots, with $\delta = 60$, the reduction is 1.2% of the fundamental harmonic of its conventional arrangement. On the other hand, for the same number of slots per pole per phase, q = 3, with $\delta = 60^\circ$ the fundamental harmonic magnitude, of the interspersed six-phase winding shows reduction about 14% of the fundamental harmonic of its conventional arrangement.

The magnitude of the fundamental harmonic is important since this is a measure of the useful output obtainable from the machine. In general, from the foregoing discussion, the use of the interspersed arrangement results in a reduction in the fundamental harmonic magnitude of its conventional arrangement. This reduction is found to be very small with the six-phase winding of q = 6 slots, and $\delta = 60$ electrical degrees.

The influence of interspersed the winding by one slot on the higher space harmonic magnitudes is given in Table 2. From which, we noticed that, the fifth and seventh harmonics are reduced for the six-phase winding with $\delta = 60^\circ$ and q = 6 slots. On the other hand, these two harmonics are increased for the same type of winding but with q = 3 slots. Moreover, these two harmonics could be considered very small with the six-phase winding with $\delta = 30^\circ$ either for interspersed or conventional winding. Nevertheless, the interspersed effect on the 11-th and 13-th harmonics is not so favourable, resulting in increased magnitudes for all the six-phase windings under investigation, but the effects produced by these harmonics are not often significant because of their higher order.

For more investigation, Tables 3 to 8 include the harmonic analysis of the resultant MMF up to 35-th harmonic order, for the six-phase winding being considered.

5. Conclusion:

This investigation demonstrate that, the use of the interspersed arrangement results in a reduction in the fundamental harmonic magnitude in comparison with the fundamental harmonics of their conventional arrangement. The reduction varies from 14% with q = 3 slots to 1.2% with q = 6 slots for the six - phase winding with δ = 6o electrical degrees. However, this reduction reach 4% with q = 3 for the six-phase winding with δ = 30 electrical degrees.

On the other hand, in Table 2 the analysis shows that, the fifth and seventh harmonics are reduced with q = 6 slots and $\delta = 60^\circ$ in comparison with q = 3 slots of the same winding. Moreover, the effect on the 11-th and 13-th harmonics is not so favourable, resulting in increased magnitudes for all the six-phase windings under investigation.

References:

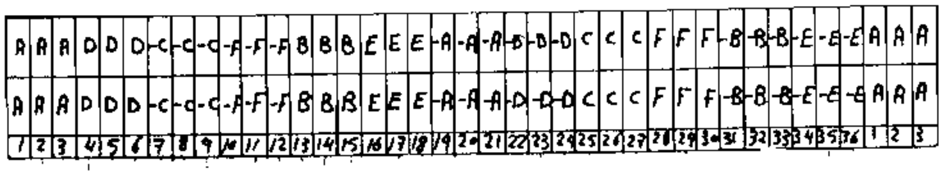
(1) A.R.A. Amin: "Evaluation Of The Air-Gap MMF Distribution And Harmonic Contents Of The Six-phase Stator Winding", Faculty of Engineering Bulletin, Mansoura University, June 1985.

(2) A.R.A. Amin: " The Effect Of Unbalanced Excitation System On The MMF Analysis Of The Six-Phase Winding", Faculty of Engineering Bulletin, Mansoura University, December 1985.

(3) B.J. Chalmers: "A.C. Machine Windings With Reduced Harmonic Content", Proc. IEE, vol 111, No. 11, November 1964.

List Of Symbols:

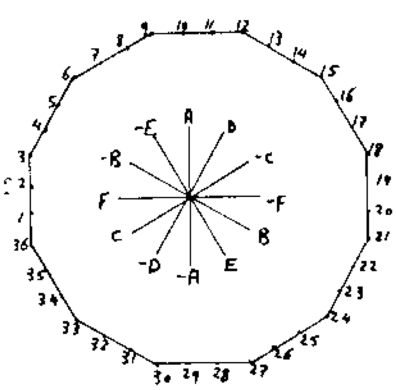
h Space harmonic order.
q The number of slot per pole per phase.
S The number of slots per double pole pitch.
δ The displacement angle between similar phases in space.



(a)

Case (I) Conventional winding arrangement.

(b)



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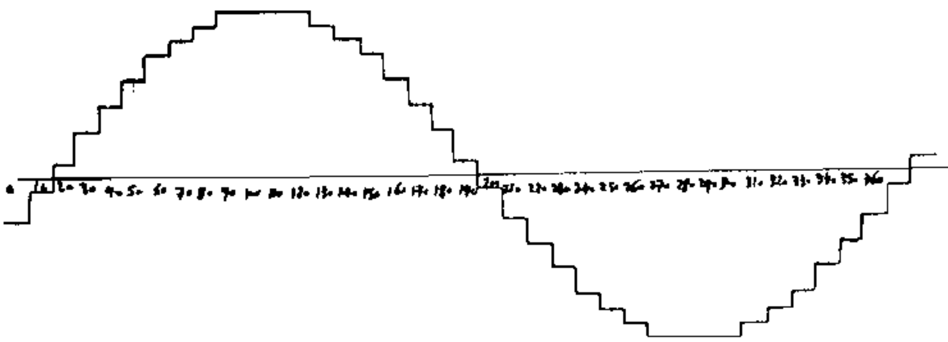
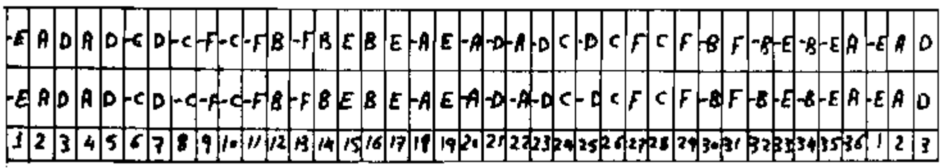


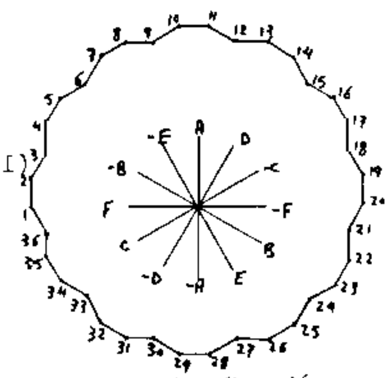
axis of (I)



(a)

Case (II) interspersed winding arrangement.

(b)



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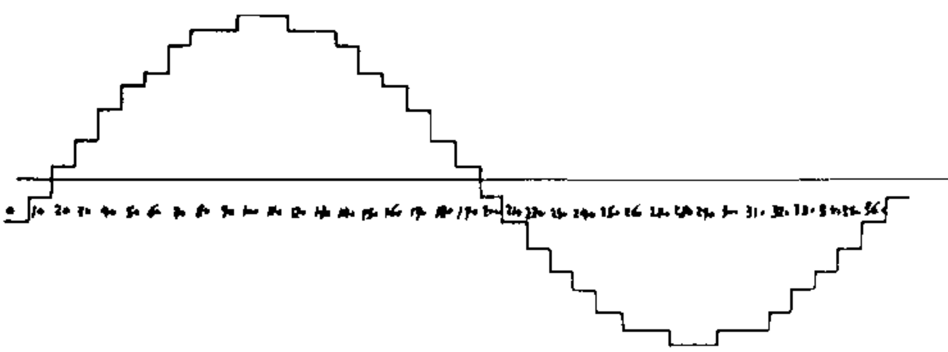


axis of (II)

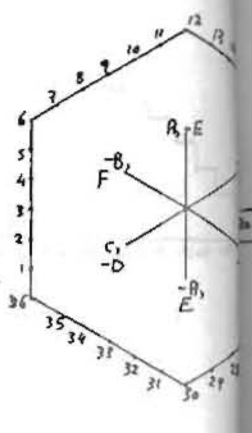
Fig. (1) Derivation of space MMF for, a six-phase winding with δ = [illegible], unity-pitch, S = 36, q = 3 slots for two cases I, and II.
(a) Stator-coil currents for double pole pitch.
(b) Goerge's vector diagram.
(c) The space MMF waveform.

A	A	A	A	A	A	-C	-C	-C	-C	-C	-C	B	B	B	B	B	B	-A	-A	-A	-A	-A	-A	C	C	C	C	C	C	-B	-B	-B	-B	-B	-B
-E	-E	-E	-E	-E	-E	D	D	D	D	D	D	-F	-F	-F	-F	-F	-F	E	E	E	E	E	E	-D	-D	-D	-D	-D	-D	F	F	F	F	F	F
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

(a)

Case (I) Conventi
winding arrangeme

(b)



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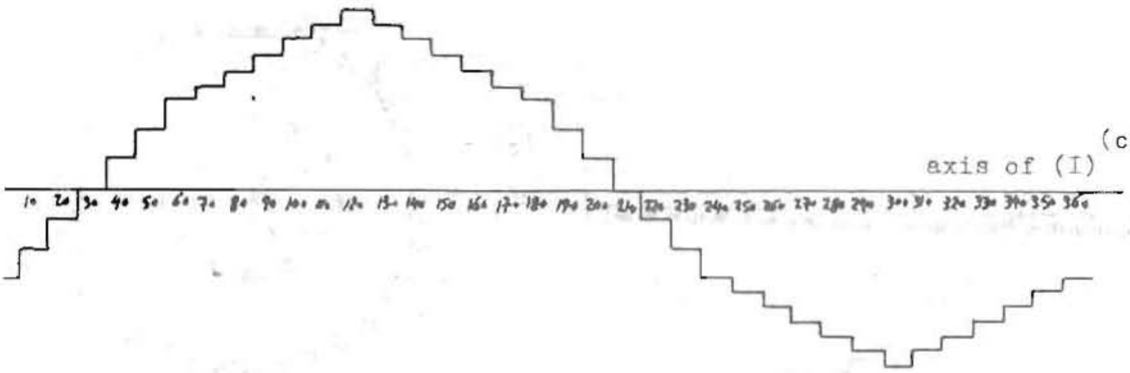
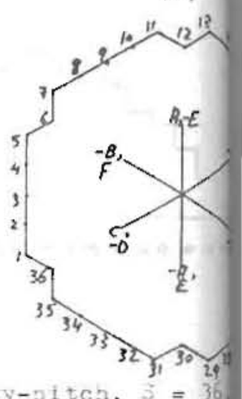


B	A	A	A	A	-C	A	-C	-C	-C	-C	B	-C	B	B	B	B	-A	B	-A	-A	-A	-A	C	-A	C	C	C	C	-B	C	-B	-B	-B	-B	A
F	-E	-E	-E	-E	D	-E	D	D	D	D	-F	D	-F	-F	-F	-F	E	-F	E	E	E	E	-D	E	-D	-D	-D	-D	F	-D	F	F	F	F	-E
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36

(a)

Case (II) Interspe
winding arrangement

(b)



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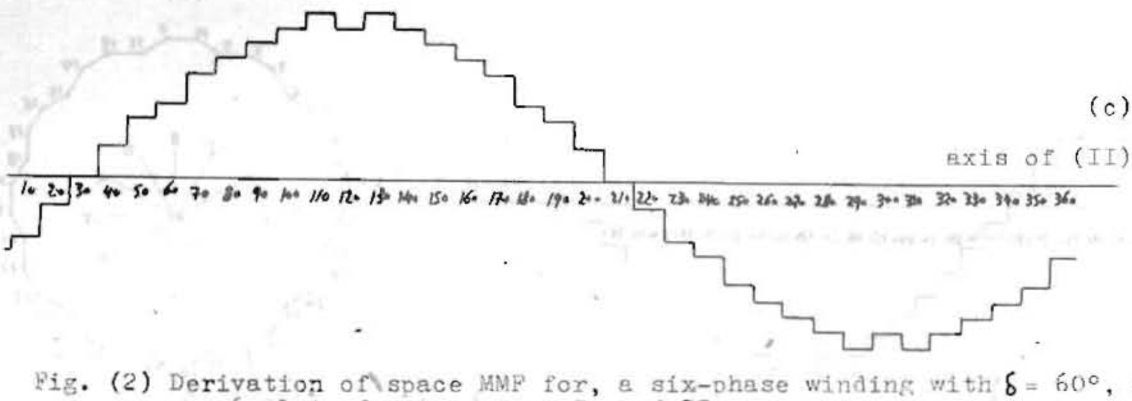


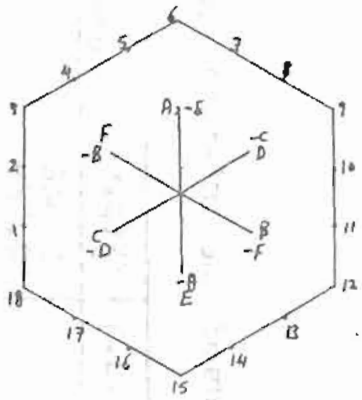
Fig. (2) Derivation of space MMF for, a six-phase winding with $\delta = 60°$, unity-pitch, S = 36,
q = 6 slots for two cases I, and II.
(a) Stator-coil currents for double pole pitch.
(b) Goerge's vector diagram.
(c) The space MMF waveform.

(a)

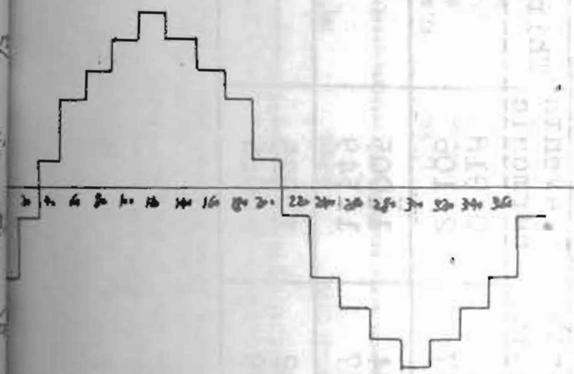
A	A	A	-C	-C	-C	B	B	B	-A	-A	-A	C	C	C	-B	-B	-B	A	A
-E	-E	-E	D	D	D	-F	-F	-F	E	E	E	-D	-D	-D	F	F	F	-E	-E
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	1	2

Case (I) Conventional winding arrangement.

(b)



(c)



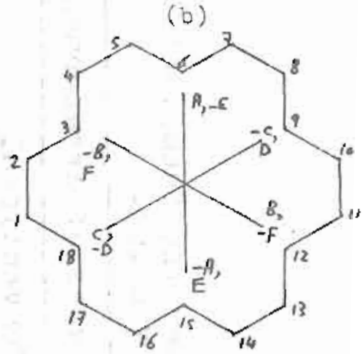
(c) axis of (I)

(a)

-B	A	-C	A	-C	B	-C	B	-A	B	-A	C	-A	C	-B	C	-B	A	-B	A
F	-E	D	-E	D	-F	D	-F	E	-F	E	-D	E	-D	F	-D	F	-E	F	-E
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	1	2

Case (II) Interspersed winding arrangement.

(b)



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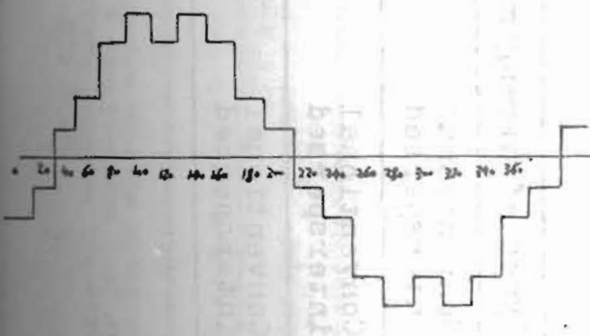

axis of (II)

Fig. (3) Derivation of space MMF for, a six-phase winding with δ = 60°, unity-pitch, S = 18, Q = 3 slots for two cases I, and II.
(a) Stator-coil currents for double pole pitch.
(b) Goerge's vector diagram.
(c) The space MMF waveform.

TABLE (1)

The comparison between the fundamental harmonic magnitudes of the interspersed and conventional six-phase winding.

Types of winding	Types of arrangement	YN1%	YMAX(p.u.)	YN(p.u.)	YN% of its Conventional arrangement
Six-phase, q = 3, δ=30°, S=36.	Conventional interspersed	101.654 97.488	2.8 2.8	2.846 2.729	100.000 95.889
Six-phase, q = 6, δ= 60°, S=36	Conventional interspersed	91.334 96.704	3.0 2.8	2.74 2.708	100.000 98.830
Six-phase, q = 3, δ= 60°, S=18°	Conventional interspersed	91.830 96.733	3.0 2.45	2.755 2.37	100.000 86.025

TABLE (2)

The comparison between the lower belt harmonic magnitudes as a percent of its fundamental harmonic magnitude.

Types of winding	Types of arrangement	Fifth harmonic	Seventh harmonic	Eleventh harmonic	Thirteenth harmonic
Six-phase, q = 3, δ= 30°, S=36	Conventional interspersed	0.065 0.620	0.35 0.067	0.918 2.106	1.456 1.946
Six-phase, q = 6 δ= 60°, S=36	Conventional interspersed	4.156 1.036	2.204 0.677	1.005 1.549	0.781 1.925
Six-phase, q = 3, δ= 60°, S=18	Conventional interspersed	4.704 6.634	2.802 7.809	1.825 5.086	1.895 2.673

Table (3)

Space MMF harmonic analysis for 6-ph, δ= 30°, unity-pitch, q = 3, for conventional winding arrangement.

PHASE =6.0 DELTA =30.0 Q =3.0 SL OT=36.0 SPERSED = .0 YMAX =2.80

HARMONIC ORDER	ALPHAN	YN1%	YN2%
1	-12.500	101.654	100.000
2	-85.663	.000	.000
3	-37.501	.577	.567
4	51.072	.000	.000
5	-62.502	.066	.065
6	-77.196	.000	.000
7	-87.503	.356	.350
8	82.688	.000	.000
9	67.498	.259	.255
10	-5.375	.000	.000
11	42.501	.933	.918
12	-29.006	.000	.000
13	17.501	1.480	1.456
14	77.777	.000	.000
15	-7.503	.384	.378
16	-9.496	.000	.000
17	-32.482	.206	.202
18	-63.941	.000	.000
19	-57.511	.188	.185
20	-81.474	.000	.000
21	-82.484	.295	.290
22	-.462	.000	.000
23	72.496	.943	.927
24	89.374	.000	.000
25	47.501	.486	.478
26	-62.236	.000	.000
27	22.524	.107	.106
28	35.810	.000	.000
29	-2.506	.112	.110
30	-56.779	.000	.000
31	-27.593	.015	.014
32	41.569	.000	.000
33	-52.465	.076	.075
34	-13.884	.000	.000
35	-77.500	4.438	4.366

Table (4)

Space MMF harmonic analysis for 6-ph, δ= 30°, unity-pitch, q = 3, for Interspersed winding arrangement.

PHASE =6.0 DELTA =30.0 Q =3.0 SL OT=36.0 SPERSED =1.0 YMAX =2.80

HARMONIC ORDER	ALPHAN	YN1%	YN2%
1	-12.500	97.488	100.000
2	-58.868	.000	.000
3	-37.499	.187	.192
4	28.673	.000	.000
5	-62.500	.604	.620
6	68.490	.000	.000
7	-87.482	.066	.067
8	81.273	.000	.000
9	67.503	.207	.213
10	-4.392	.000	.000
11	42.500	2.053	2.106
12	-22.272	.000	.000
13	17.499	1.897	1.946
14	77.476	.000	.000
15	-7.488	.073	.075
16	-11.358	.000	.000
17	-32.551	.073	.075
18	-86.354	.000	.000
19	-57.467	.067	.069
20	-79.974	.000	.000
21	-82.588	.056	.057
22	.941	.000	.000
23	72.503	1.209	1.240
24	87.911	.000	.000
25	47.500	1.069	1.096
26	-66.954	.000	.000
27	22.469	.086	.088
28	35.969	.000	.000
29	-2.486	.021	.021
30	-62.379	.000	.000
31	-27.490	.134	.137
32	37.107	.000	.000
33	-52.604	.025	.025
34	-15.429	.000	.000
35	-77.500	4.256	4.366

Table (5)

Space MMF harmonic analysis for 6-ph, $\delta = 60°$, unity-pitch, q = 6, for conventional winding arrangement.

PHASE =6.0 DELTA =60.0 Q =6.0 SL OT=36.0 SPERSED = .0 YMAX =3.00

HARMONIC ORDER	ALPHAN	YN1Z	YN2Z
1	-27.500	91.334	100.000
2	13.092	.000	.000
3	48.221	.000	.000
4	3.180	.000	.000
5	42.500	3.796	4.156
6	-60.542	.000	.000
7	-12.500	2.013	2.204
8	77.078	.000	.000
9	-82.164	.000	.000
10	-9.242	.000	.000
11	57.501	.918	1.005
12	-44.698	.000	.000
13	2.501	.713	.781
14	78.344	.000	.000
15	-9.838	.000	.000
16	-11.498	.000	.000
17	72.501	.516	.565
18	-83.320	.000	.000
19	17.501	.473	.518
20	-82.989	.000	.000
21	14.736	.000	.000
22	5.628	.000	.000
23	87.496	.454	.497
24	-84.626	.000	.000
25	32.500	.478	.523
26	-57.609	.000	.000
27	-58.499	.000	.000
28	31.597	.000	.000
29	-77.497	.635	.695
30	-27.535	.000	.000
31	47.498	.842	921
32	34.864	.000	.000
33	-35.175	.000	.000
34	-15.258	.000	.000
35	-62.500	3.988	4.366

Table (6)

Space MMF harmonic analysis for 6-ph, $\delta = 60°$, unity-pitch, q = 6, for Interspersed winding arrangement.

PHASE =6.0 DELTA =60.0 Q =6.0 SL OT=36.0 SPERSED =1.0 YMAX =2.80

HARMONIC ORDER	ALPHAN	YN1Z	YN2Z
1	-27.500	96.704	100.000
2	-55.101	.000	.000
3	-82.502	.118	.122
4	3.270	.000	.000
5	42.501	1.001	1.036
6	-71.686	.000	.000
7	-12.501	.655	.677
8	75.727	.000	.000
9	-75.964	.000	.000
10	-4.128	.000	.000
11	57.499	1.498	1.549
12	-30.375	.000	.000
13	2.500	1.861	1.925
14	78.167	.000	.000
15	-52.462	.095	.098
16	-10.547	.000	.000
17	72.500	1.687	1.745
18	-84.695	.000	.000
19	17.500	1.546	1.599
20	-81.612	.000	.000
21	-37.449	.073	.075
22	6.446	.000	.000
23	87.502	1.186	1.226
24	-87.196	.000	.000
25	32.500	.780	.806
26	-66.562	.000	.000
27	-56.695	.000	.000
28	32.307	.000	.000
29	-77.511	.206	.213
30	-34.282	.000	.000
31	47.491	.222	.230
32	32.508	.000	.000
33	-7.749	.016	.016
34	-20.680	.000	.000
35	-62.500	4.222	4.366

Table (7)

Space MMF harmonic analysis for 6-ph, $\delta = 60°$, unity-pitch, q = 3, for conventional winding arrangement.

PHASE =6.0 DELTA =60.0 Q =3.0 SL OT=18.0 SPERSED = .0 YMAX =3.00

HARMONIC ORDER	ALPHAN	YN1%	YN2%
1	-27.500	91.830	100.000
2	-85.043	.000	.000
3	-82.501	.284	.309
4	-3.540	.500	.000
5	42.500	4.319	4.704
6	-41.496	.000	.000
7	-12.500	2.573	2.802
8	80.580	.000	.000
9	-67.499	.194	.211
10	-10.142	.000	.000
11	57.500	1.676	1.825
12	-53.915	.000	.000
13	2.500	1.740	1.895
14	75.296	.000	.000
15	-52.448	.061	.066
16	-15.035	.000	.000
17	72.500	5.929	6.456
18	-84.817	.000	.000
19	17.500	5.433	5.916
20	-81.926	.000	.000
21	-37.574	.047	.051
22	-3.540	.000	.000
23	87.502	1.109	1.207
24	-81.040	.000	.000
25	32.500	.872	.950
26	-59.679	.000	.000
27	-22.517	.080	.087
28	28.472	.000	.000
29	-77.502	.811	.884
30	-23.560	.000	.000
31	47.501	.958	1.043
32	30.759	.000	.000
33	-7.403	.037	.041
34	-23.459	.000	.000
35	-62.500	4.009	4.366

Table (8)

Space MMF harmonic analysis for 6-ph, $\delta = 60°$, unity-pitch, q = 3, for Interspersed winding arrangement.

PHASE =6.0 DELTA =60.0 Q =3.0 SL OT=18.0 SPERSED =1.0 YMAX =2.45

HARMONIC ORDER	ALPHAN	YN1%	YN2%
1	-27.500	96.733	100.000
2	-83.548	.000	.000
3	-82.501	.434	.449
4	16.314	.000	.000
5	42.500	6.418	6.634
6	-73.088	.000	.000
7	-12.500	7.554	7.809
8	75.192	.000	.000
9	-67.500	.296	.306
10	-2.393	.000	.000
11	57.500	4.920	5.086
12	-15.744	.000	.000
13	2.500	2.585	2.673
14	75.919	.000	.000
15	-52.462	.093	.096
16	-15.742	.000	.000
17	72.500	6.245	6.456
18	-84.919	.000	.000
19	17.500	5.723	5.916
20	-77.347	.000	.000
21	-37.554	.071	.074
22	-10.918	.000	.000
23	87.499	1.647	1.702
24	-83.164	.000	.000
25	32.500	2.561	2.647
26	-60.735	.000	.000
27	-22.507	.123	.127
28	32.671	.000	.000
29	-77.499	2.382	2.462
30	-9.595	.000	.000
31	47.499	1.423	1.471
32	38.757	.000	.000
33	-7.424	.057	.059
34	-25.921	.000	.000
35	-62.500	4.223	4.366