THE EFFECT OF UNBALANCED EXCITATION SYSTEM ON THE MMF ANALYSIS OF THE SIX-PHASE WINDING

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Abstract:

The effect of losing one-phase or more of the excitation system on the space MMF harmonics has been investigated for two types of six-phase stator windings ; by means of Goerge's vector diagram. The scope of this work covers the various changes in the resultant MMF waveforms that occur due to one-phase, or two-phase, or three-phase being opened. Consequently, an insight into avoiding the modes of operation which provide an objectional harmonic contents is given.

The results obtained recommend to use the six-phase winding with phase spread, δ , eaual to 60 , in order to improve the overall reliability with one phase being opened ; the most common failures occurred.

1. Introduction:

Sometimes in practice a six-phase machine may have to work under unbalanced supply. So, it is important to study the effect of unbalanced excitation system on the performance of the six-phase machine. The unbalanced operation limiting cases could be happened from one phase, or more phases being opened. These might be occurred in practical if either one or several coils had been burnt out or one-phase or more phases of the six-phase supply had been lost. Such deffects may be found in ac drives, which havesuffered due to their susceptibility to single point or more failures in either the power electronics, control circuits, or dc power supply.

Unbalanced operation of the six-phase machine has given rise to variety of problems. These problems provide considerable local overheating, poor efficiency and regulation, increasing pulsating torques, and an additional losses in the steel and windings. The reason for these problems is that the currents become unbalanced. Thus, the flux distribution in the air-gap is no longer uniform. Therefore, the harmonic analysis of the resultant MMF waveform would provide different magnitudes of the harmonic contents. Accordingly, the determination of the space harmonic magnitudes, under unbalanced operation, is of vital importance in the analysis of the six-phase machine. Investigation can be carried out by means of Goerge's vector diagram, which is based on the actual distribution of the ampere-conductor into the slots, and then accounts for the resultant MMF waveform for the whole winding.

Strictly speaking, the spurpose of this paper is to examine the resultant MMF waveforms of two types of six-phase winding with δ either equal to 30 or 60 electrical degrees. The scope of investigation covers the various changes in the resultant MMF waveforms that occur due to the unbalanced supply and the classification of the higher space harmonic contents. In addition, the investigation would provide an insight into avoiding the modes of operation which provide an objectional harmonic contents.

2. The Limiting Cases of Unbalanced Six-Phase Supply:

It is well-known that a certain degree of imbalance in the supply is expected at the machine terminals. On the other hand, the extreme cases of the six-phase unbalanced excitation system could be considered as follows:

(a) One-phase being opened ; $I_D = 0$
(b) Two-phase being opened ; $I_D = I_E = 0$
(c) Three-phase being opened ; $I_D = I_E = I_F = 0$

3. Consequences of Unbalanced Excitation System:

Before discussing the consequences of unbalanced excitation system, it will be worthwhile to say a few words about the space harmonics of a six-phase machine operating under balanced excitation system. Under the balanced supply, there is set up a rotating magnetic field. The analysis of this magnetic field showed that a six-phase winding with $\delta = 30$ provides higher space harmonic of orders $h = 12\ K \pm 1$, while the space harmonic orders for the six-phase winding with $\delta = 60$, are found to be equal to $h = 6\ K \pm 1$, [1].

With one-phase or more being opened, the machine will have some of the slots partially excited in the case of the six-phase winding with $\delta = 60$. However some of the slots will contain zero ampere-conductor in the case of six-phase winding with $\delta = 30$. Accordingly, the resultant MMF is no longer having the space harmonic orders, h, as resulted from the balanced operation. Therefore, plotting and analysing the resultant MMF waveform of the unbalanced operation become essential to give an insight into avoiding their modes of unbalanced operation which provide an objectional harmonic contents.

4. Determination of The Resultant MMF Waveform Under Unbalanced Excitation System:

In order to achieve data consistency with the actual ampere-conductor distribution for the unbalanced operations given in section 2, the Goerge's vector diagram has been established for these different cases. In addition the balanced operation is given to facilitate the comparison. The current carrying conductors are assumedto be of sinusoidal waveforms.

All phases of a symmetric six-phase machine are identical. The number of turns, wire sizes, etc., are the same for each of the six-phase and follow identical distribution. The six stator phases are labelled A, B, C, D, E, and F. They are evenly displaced in space and excited by the currents having the same displacement in time-phase as the windings have in space-phase. Therefore, two types of windings are considered. The first type is a six-phase winding with $\delta = 30$, while the second one is a six-phase winding with $\delta = 60$. The balanced operation of both types have been investigated recently [1] .

On the other hand, the MMF waveform produced by the unbalanced supply can be analysed by making use of Goerge's vector diagram. Where the resultant MMF is found by summing the actual distribution of the ampere-conductor in each slot. Since the currents flow are of sinusoidal function of time, it can be represented as a vector. The unbalanced supply operation,resulting from one phase or more being opened, could be represented easily by eliminating the corresponding current vectors from the vector current diagram. Therefore, the resultant MMF for each case of unbalance could be easily determined. However, the instantaneous values of the MMF over the different teeth can be found by projecting the vectors P1, P2, P3, ... on the time line. The position of the time line can be chosen arbitrarily, since the magnetic energy in the air-gap is constant. The time line was chosen vertically. Accordingly, the effect of losing one-phase, or more phases could be investigated.

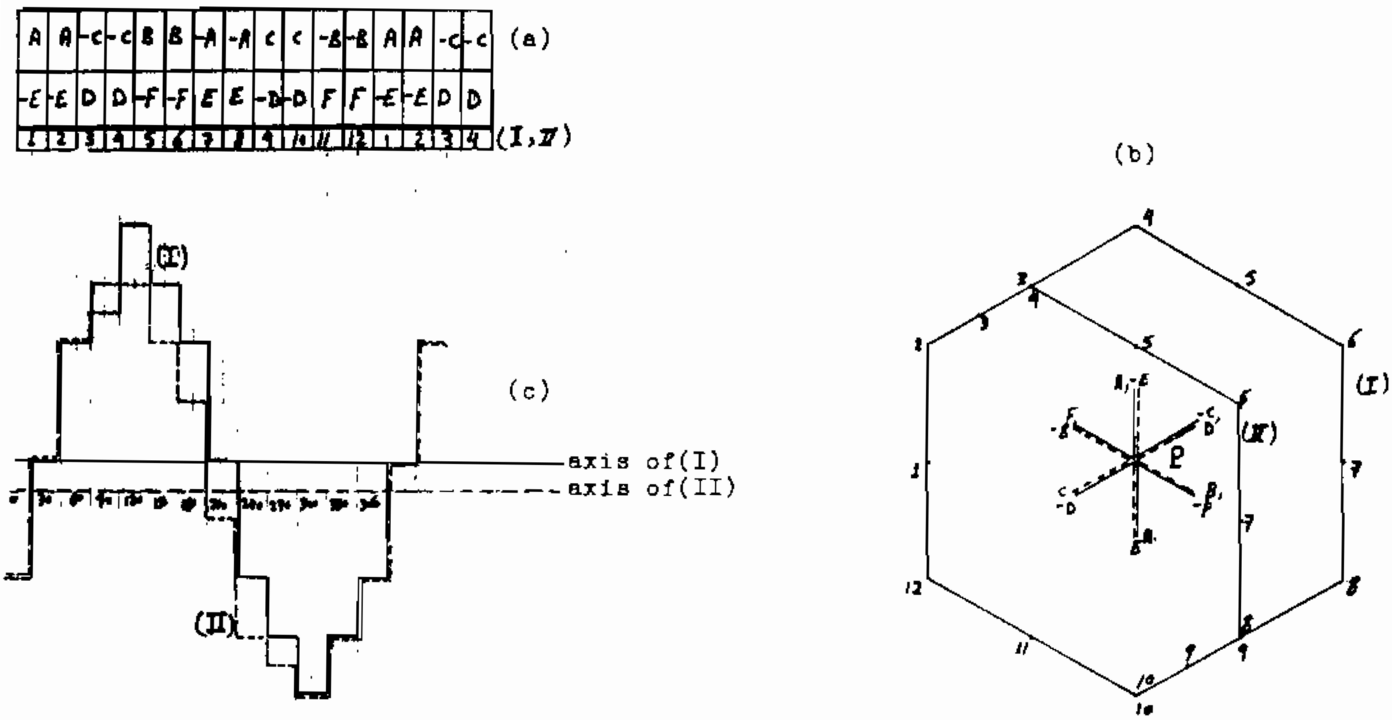
Figures 1 , 2, and 3 illustrate the derivation of the MMF space waveforms, for a two pole, six-phase winding with δ either equal to 60 or 30 electrical degrees, with q = 2 slots for the first type of the winding, while q = 1 or 2 slots for the second type. In order to explain the procedure, Figure 1 representing the case II of the losing of one phase could be considered. It displays this procedure a 12-slot, double pole pitch, six-phase winding with δ = 60 , q = 2, and unity-pitch winding. The upper and the lower layers lie in the same slot belonging to different phases. Figure 1a, case II reveals the distribution of the 12 slots between the layers and phases. So, the layers containing letter D provide zero ampere-conductor as the phase D is assumed to loss its excitation. Figure 1b shows the directions of the currents for the case II at that instant of time, for different slot-groups as well as the Goerge's vector diagram. The polygon II represents the Goerge's vector diagram of losing one-phase ; $I_D = 0$. The shape of the MMF over the different teeth for this case is different from the MMF waveform of the case of the balanced supply, case I, as shown in Figure 1c. In addition, Figure 1c case III and Figure 1c case IV show the various waveforms on losing two phases or three phases , respectively. The instantaneous values of the MMF waveforms are recorded every five electrical degrees and supplied to the computer program as an input data.

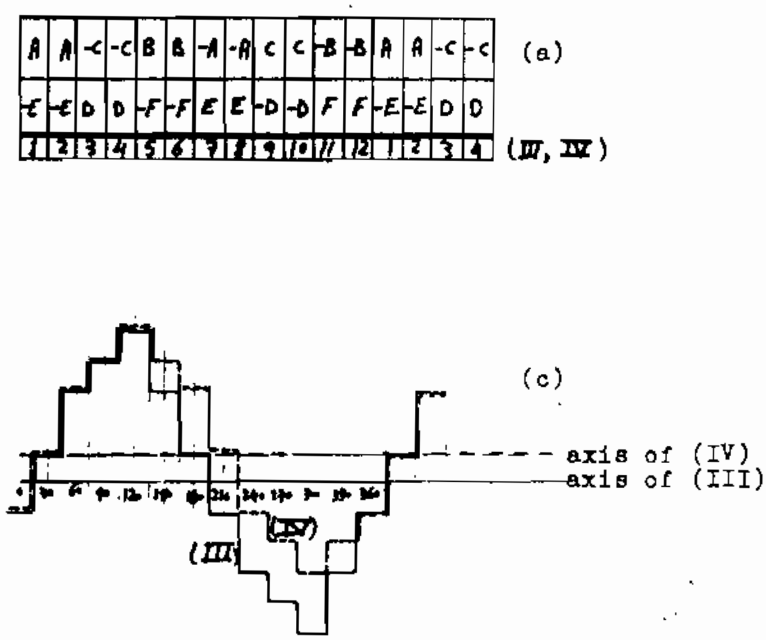
The resultant MMF waveforms of the cases of unbalanced excitation shown in Figures 1, 2, and 3 are analysed by the computer program. The aim is to determine the magnitude of the belt and slot harmonics, and to facilitate the comparison between the balanced and unbalanced excitation systems for six-phase winding with a displacement angle δ of 60 or 30 electrical degrees.

5. Computer Results And Discussion:

By means of a computer program using the step by step technique, some of six-phase windings have been investigated under the unbalanced excitation system. The results are tabulated in Tables 1 to 14. Table 3 can serve as a check on the computer program validity. It contains the harmonic analysis for a 12-slot, double layer, unity-pitch, six-phase winding with δ = 60 , for q = 2. The obtained harmonic contents show a consistency with the previously published results [1] , and [2] . Tables 3 to 14 illustrate the fundamental and the higher space harmonic magnitudes as relative values YN1%, of the maximum height of the stepped waveform ; YMAX, and also as a percentage of the fundamental harmonic : YN2%.

The 12-slot windings of double-pole pitch is wound for six-phase winding with δ either equal 60 or 30 electrical degrees, for unity pitch, as shown in Figures 1 and 2 , consequently : for different cases of unbalanced excitation. The results are given in Tables 3 to 10. On the other hand, the effect of increasing the number of slots per pole per phase ; q = 2 for six-phase winding with δ = 30 is shown in Figure 3. The harmonic analyses are given in Tables 11 to 14. The computed per





(I) Balanced excitation system.
(II) One-phase open ; $I_D = 0$.
(III) Two-phase open ; $I_D = I_E = 0$.
(IV) Three-phase open ; $I_D = I_E = I_F = 0$

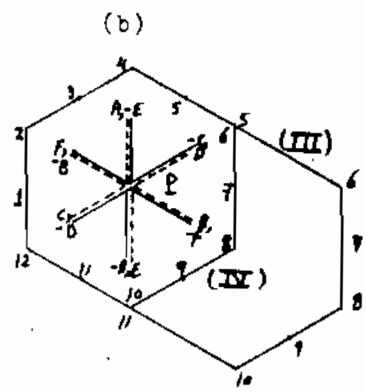


Fig. (1) Derivation of space MMF for, a six-phase winding with $\delta = 60°$, unity-pitch, q = 2 under unbalanced excitation system, of different cases I, II, III, IV.
(a) Stator-coil currents for double pole pitch.
(b) Goerge's vector diagram.
(c) The space MMF waveform.

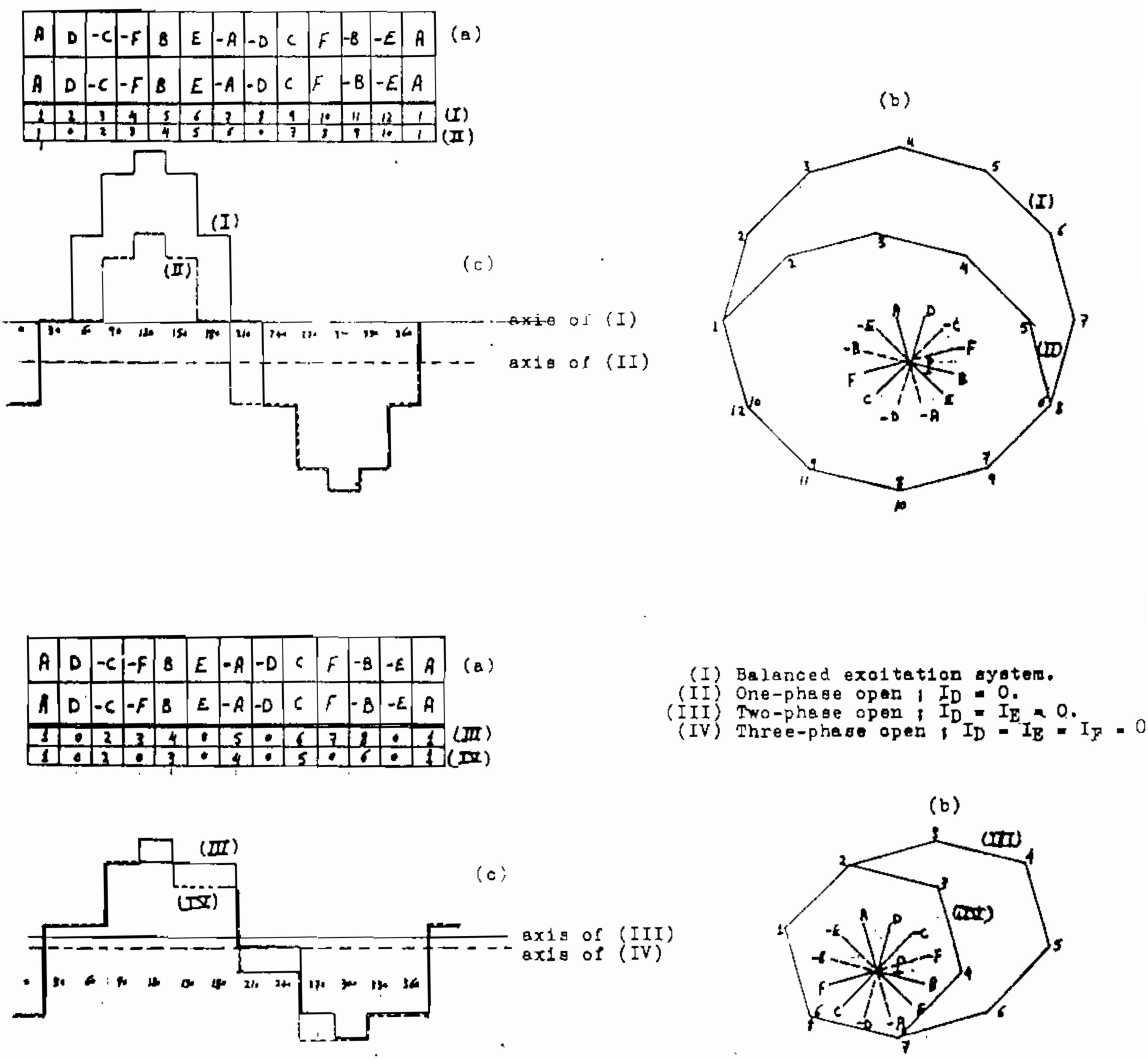
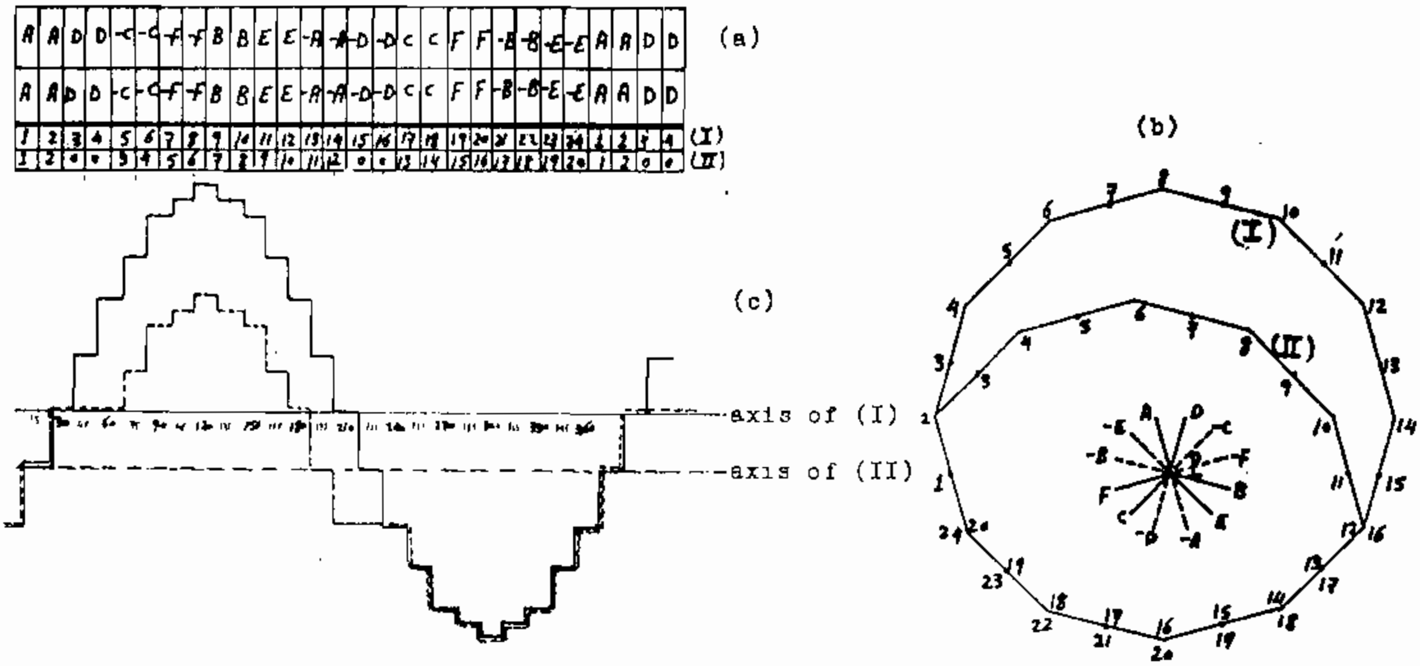
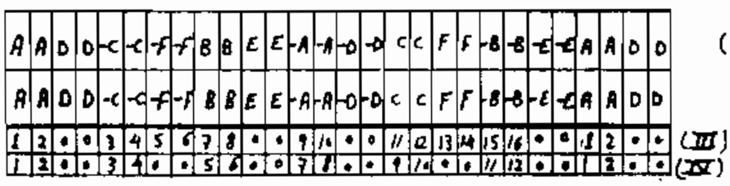


Fig. (2) Derivation of space MMF for, a six-phase winding with $\delta = 30°$, unity-pitch, q = 1 under unbalanced excitation system, of different cases I, II, III, IV
(a) Stator-coil currents for double pole pitch.
(b) Goerge's vector diagram.
(c) The space MMF waveform.





(I) Balanced excitation system.
(II) One-phase open ; $I_D = 0$.
(III) Two-phase open ; $I_D = I_E = 0$.
(IV) Three-phase open ; $I_D = I_E = I_F = 0$.

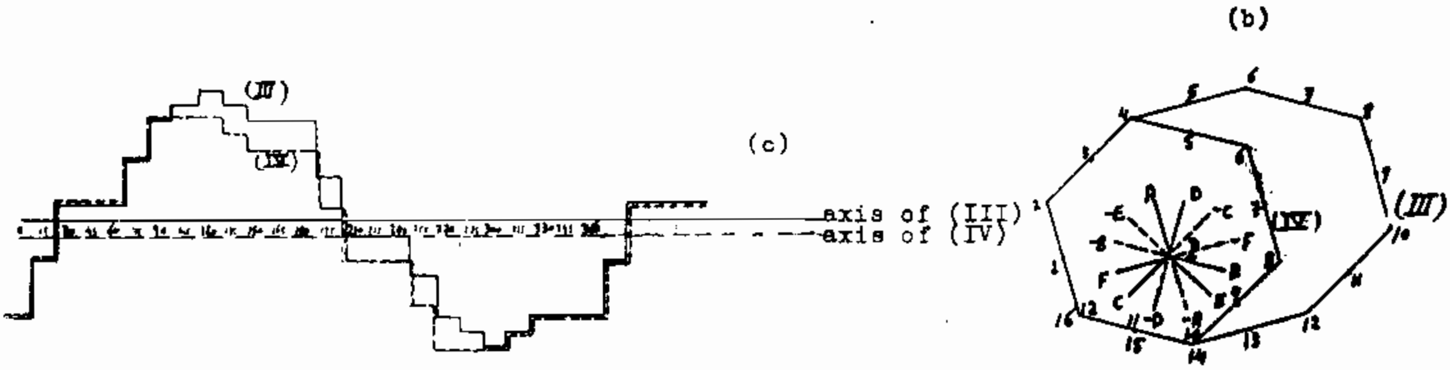


Fig. (3) Derivation of space MMF for, a six-phase winding with $\delta = 30°$, unity-pitch, q = 2 under unbalanced excitation system, of different cases I, II, III, IV.
(a) Stator-coil currents for double pole pitch.
(b) Goerge's vector diagram.
(c) The space MMF waveform.

TABLE 1

The comparison between the fundamental harmonic magnitudes for different cases of unbalanced excitation system.

Types of winding	Types of excitation	YN1%	YMAX (p.u.)	YN (p.u.)	YN% of its balanced excitation.
Six-phase, $q=2$, $\delta = 60°$ $S=12$	balanced	92.268	4.0	3.69	100.0
	one-phase open	97.853	3.5	3.425	92.82
	two-phase open	88.714	2.5	2.22	60.16
	three-phase open	92.268	2.0	1.845	50.0
Six-phase, $q=1$, $\delta = 30°$ $S=12$	balanced	98.684	3.82	3.77	100.0
	one-phase open	90.676	2.9	2.63	69.76
	two-phase open	91.083	2.2	2.0	53.05
	three-phase open	98.447	1.93	1.9	50.4
Six-phase $q=2$, $\delta = 30$ $S=24$	balanced	98.824	3.8	3.76	100.0
	one-phase open	90.539	2.9	2.63	69.95
	two-phase open	92.476	2.2	2.03	53.99
	three-phase open	97.226	1.98	1.925	51.2

TABLE 2

The comparison between the belt harmonic magnitudes as a percent of its fundamental for different cases of unbalanced excitation.

Types of winding	Types of excitation	Third harmonic	Fifth harmonic	Seventh harmonic	Ninth harmonic
Six-phase, $q = 2$, $\delta = 60°$, $S = 12$	balanced	0.0	5.4	3.887	0.0
	one-phase open	4.394	5.4	3.887	1.499
	two-phase open	6.785	5.4	3.887	2.314
	three-phase open	0.0	5.4	3.887	0.0
Six-phase $q = 1$, $\delta = 30°$, $S = 12$	balanced	0.16	0.028	0.02	0.054
	one-phase open	15.787	9.195	6.618	5.385
	two-phase open	5.957	18.368	13.221	2.032
	three-phase open	0.672	20.153	14.506	0.229
Six-phase, $q = 2$, $\delta = 30°$ $S = 24$	balanced	0.127	0.233	0.049	0.61
	one-phase open	14.732	7.565	4.456	1.653
	two-phase open	5.187	14.556	8.196	0.674
	three-phase open	1.643	16.369	8.764	0.27

TABLE 3

Space MMF harmonic analysis for 6-phase, $\delta = 60°$, unity-pitch, q = 2, for balanced excitation system.

PHASE = 6.0 DELTA = 60.0 ID = 1 IE = 1 IF = 1
Q= 2.0 SLOT= 12.0 CHORDING = .0 YMAX = 4.00

HARMONIC ORDER	ALPHAN	YN1I	YN2I
1	-27.500	92.268	100.000
2	60.341	.000	.000
3	.0	.000	.000
4	4.764	000	.000
5	42.500	4.983	5.400
6	-51.512	000	.000
7	-12.500	3.586	3.887
8	74.476	000	.000
9	77.376	.000	.000
10	-5.631	.000	.000
11	57.500	8.716	9.447
12	-25.284	.000	.000
13	2.500	7.491	8.118
14	82.761	.000	.000
15	5.124	.000	.000
16	-11.165	000	.000
17	72.500	1.596	1.730
18	-85.920	.000	.000
19	17.500	463	1.585
20	-86.368	.000	.000
21	13.522	.000	.000
22	15.755	.000	.000
22	87.500	4.772	5.172
24	-85.840	.000	.000
25	32.500	4.537	4.918
26	-32.491	.000	.000
27	-83.740	.000	.000
28	28.893	.000	.000
29	-77.498	1.131	1.225
30	-35.281	.000	.000

TABLE 4

Space MMF harmonic analysis for 6-phase, $\delta = 60°$, unity-pitch, q = 2, with one-phase open ; $I_D = 0$.

PHASE = 6.0 DELTA = 60.0 ID = 0 IE = 1 IF = 1
Q= 2.0 SLOT= 12.0 CHORDING = .0 YMAX = 3.50

HARMONIC ORDER	ALPHAN	YN1I	YN2I
1	-18.552	97.853	100.000
2	57.995	.000	.000
3	-82.500	4.299	4.394
4	30.964	.000	.000
5	33.552	5.284	5.400
6	-52.404	.000	.000
7	-3.552	3.803	3.887
8	76.651	.000	.000
9	-67.500	1.466	1.499
10	-4.863	.000	.000
11	48.552	9.244	9.447
12	-20.702	.000	.000
13	11.448	7.944	8.118
14	81.998	.000	.000
15	-52.503	.922	.942
16	-10.450	.000	.000
17	63.552	1.693	1.730
18	-88.564	.000	.000
19	26.448	1.551	1.585
20	-84.549	.000	.000
21	-37.505	.707	.723
22	13.285	.000	.000
23	78.552	5.061	5.172
24	-87.781	.000	.000
25	41.448	4.812	4.918
26	-32.071	.000	.000
27	-22.496	.607	.621
28	31.117	.000	.000
29	-44.446	1.199	1.225
30	-59.389	.000	.000

TABLE 5

Space MMF harmonic analysis for 6-phase, $\delta = 60°$, unity-pitch, q = 2, with two-phase open ; $I_D = I_E = 0$.

PHASE = 6.0 DELTA = 60.0 ID = 0 IE = 0 IF = 1
Q= 2.0 SLOT= 12.0 CHORDING = .0 YMAX = 2.50

HARMONIC ORDER	ALPHAN	YN1I	YN2I
1	13.602	88.714	100.000
2	-8.366	.000	.000
3	82.500	6.019	6.785
4	81.833	.000	.000
5	28.602	4.793	5.400
6	-41.785	.000	.000
7	1.398	3.448	3.887
8	77.375	000	.000
9	-67.500	2.053	2.314
10	-8.013	000	.000
11	43.602	8.380	9.447
12	-6.782	.000	.000
13	16.398	7.202	8.118
14	82.226	.000	.000
15	52.498	1.291	1.455
16	-9.589	.000	.000
17	58.603	1.535	1.730
18	-84.215	.000	.000
19	31.397	1.406	1.585
20	87.069	000	.000
21	37.497	990	1.116
22	8.962	000	.000
23	73.603	4.588	5.172
24	89.887	.000	.000
25	46.398	4.363	4.918
26	21.353	.000	.000
27	-27.503	850	.959
28	34.875	.000	.000
29	88.605	1.087	1.225
30	-57.195	.000	.000

TABLE 6

Space MMF harmonic analysis for 6-phase, $\delta = 60°$, unity-pitch, q = 2, with three-phase open; $I_D = I_E = I_F = 0$.

PHASE = 6.0 DELTA = 60.0 ID = 0 IE = 0 IF = 0
Q= 2.0 SLOT= 12.0 CHORDING = .0 YMAX = 2.00

HARMONIC ORDER	ALPHAN	YN1I	YN2I
1	-27.500	92.268	100.000
2	60.341	.000	.000
3	.0	.500	.000
4	-4.764	.000	.000
5	42.500	4.983	5.400
6	-51.512	.000	.000
7	-12.500	3.586	3.887
8	74.476	.000	.000
9	-77.374	.000	.000
10	-5.631	.000	.000
11	57.500	8.716	9.447
12	-25.284	.000	.000
13	2.500	7.491	3.118
14	82.761	.000	.000
15	-5.124	.000	.000
16	-11.165	.000	.000
17	72.500	1.596	1.730
18	-85.920	.000	.000
19	17.500	1.463	1.585
20	-86.368	.000	.000
21	13.522	.000	.000
22	15.755	.000	.000
23	87.500	4.772	5.172
24	-85.840	.000	.000
25	32.500	4.537	4.918
26	-32.491	.000	.000
27	-83.740	.000	.000
28	28.893	.000	.000
29	-77.498	1.131	1.225
30	-35.281	.000	.000

TABLE 7

Space MMF harmonic analysis for 6-phase, $\delta = 30°$, unity-pitch, q = 1, for balanced excitation system.

PHASE = 6.0 DELTA = 30.0 ID = 1 IE = 1 IF = 1
Q= 1.0 SLOT= 12.0 CHORDING = .0 YMAX = 3.02

HARMONIC ORDER	ALPHAN	YN1%	YN2%
1	-27.500	98.684	100.000
2	33.690	.000	.000
3	-82.500	.158	.160
4	67.620	.000	.000
5	42.520	.027	.028
6	-62.049	.000	.000
7	-12.469	.020	.020
8	75.492	.000	.000
9	-67.504	.054	.054
10	2.090	.000	.000
11	57.500	9.322	9.447
12	-20.835	.000	.000
13	2.500	8.011	8.118
14	81.987	.000	.000
15	-52.380	.034	.034
16	12.087	.000	.000
17	72.441	.009	.009
18	-30.115	.000	.000
19	17.480	.008	.008
20	84.720	.000	.000
21	-37.356	.026	.026
22	14.748	.000	.000
23	87.500	5.104	5.172
24	38.214	.000	.000
25	32.500	4.853	4.918
26	-48.051	.000	.000
27	-22.572	.022	.023
28	29.474	.000	.000
29	-77.060	.006	.006
30	-31.301	.000	.000

TABLE 8

Space MMF harmonic analysis for 6-phase, $\delta = 30°$, unity-pitch, q = 1, with one-phase open ; $I_D = 0$.

PHASE = 6.0 DELTA = 30.0 ID = 0 IE = 1 IF = 1
Q= 1.0 SLOT= 12.0 CHORDING = .0 YMAX = 2.90

HARMONIC ORDER	ALPHAN	YN1%	YN2%
1	-20.660	90.676	100.000
2	-75.069	.000	.000
3	53.969	14.315	15.787
4	39.638	.000	.000
5	-34.443	8.338	9.195
6	-26.565	.000	.000
7	64.443	6.001	6.618
8	79.143	.000	.000
9	-23.969	4.882	5.385
10	-2.048	.000	.000
11	50.660	8.566	9.447
12	-6.653	.000	.000
13	9.340	7.361	8.118
14	79.688	.000	.000
15	83.970	3.069	3.385
16	-9.508	.000	.000
17	-4.445	2.671	2.946
18	-88.608	.000	.000
19	-85.556	2.448	2.699
20	-85.455	.000	.000
21	6.032	2.355	2.597
22	1.606	.000	.000
23	80.661	4.690	5.172
24	-85.695	.000	.000
25	39.340	4.459	4.918
26	-42.955	.000	.000
27	-66.031	2.022	2.230
28	79.788	.000	.000
29	25.556	1.892	2.087
30	-4.390	.000	.000

TABLE 9

Space MMF harmonic analysis for 6-phase, $\delta = 30°$, unity-pitch, q = 1, with two-phase open, $I_D = I_E = 0$.

PHASE = 6.0 DELTA = 30.0 ID = 0 IE = 0 IF = 1
Q= 1.0 SLOT= 12.0 CHORDING = .0 YMAX = 2.20

HARMONIC ORDER	ALPHAN	YN1%	YN2%
1	-37.145	91.083	100.000
2	-82.405	.000	.000
3	63.810	5.426	5.957
4	45.401	.000	.000
5	-58.259	16.700	18.368
6	37.611	.000	.000
7	38.259	12.042	13.221
8	49.336	.000	.000
9	-73.811	1.851	2.032
10	2.855	.000	.000
11	[illegible]	8.604	9.447
12	69.114	.000	.000
13	7.145	7.394	8.118
14	81.294	.000	.000
15	-86.185	1.163	1.277
16	-9.782	.000	.000
17	-28.260	5.360	5.885
18	-85.913	.000	.000
19	-61.741	4.911	5.392
20	-84.220	.000	.000
21	-3.807	.893	.980
22	26.021	.000	.000
23	-82.855	4.711	5.172
24	-78.137	.000	.000
25	22.855	4.479	4.918
26	-35.978	.000	.000
27	-56.189	.767	.842
28	25.944	.000	.000
29	1.741	3.797	4.168
30	-10.840	.000	.000

TABLE 10

Space MMF harmonic analysis for 6-phase, $\delta = 30°$, unity-pitch, q = 1, with three-phase open, $I_D = I_E = I_F = 0$.

PHASE = 6.0 DELTA = 30.0 ID = 0 IE = 0 IF = 0
Q= 1.0 SLOT= 12.0 CHORDING = .0 YMAX = 1.93

HARMONIC ORDER	ALPHAN	YN1%	YN2%
1	-27.643	98.447	100.000
2	-41.634	.000	.000
3	-37.499	.662	.672
4	64.885	.000	.000
5	-47.357	19.840	20.153
6	-65.772	.000	.000
7	77.357	14.280	14.506
8	72.437	.000	.000
9	67.503	.226	.229
10	3.775	.000	.000
11	57.643	9.300	9.447
12	-57.179	.000	.000
13	2.357	7.992	8.118
14	80.216	.000	.000
15	-7.492	.142	.144
16	-4.574	.000	.000
17	-17.358	6.356	6.456
18	-84.820	.000	.000
19	-72.643	5.824	5.916
20	-79.649	.000	.000
21	-82.454	.109	.111
22	32.481	.000	.000
23	87.644	5.092	5.172
24	-79.744	.000	.000
25	32.357	4.841	4.918
26	-38.373	.000	.000
27	22.481	.093	.095
28	30.445	.000	.000
29	12.643	4.503	4.574
30	-24.414	.000	.000

TABLE 11

Space MMF harmonic analysis for 6-phase, $\delta = 30°$, unity-pitch, q = 2, for balanced excitation system.

PHASE = 6.0 DELTA = 30.0 ID = 1 IE = 1 IF = 1
Q= 2.0 SLOT= 24.0 CHORDING = .0 YMAX = 3.80

HARMONIC ORDER	ALPHAN	YN1I	YN2I
1	-30.000	98.824	100.000
2	-84.785	.000	.000
3	89.999	.126	.127
4	-38.199	.000	.000
5	30.002	.230	.233
6	-59.172	.000	.000
7	-29.979	.048	.049
8	74.802	.000	.000
9	90.000	.603	.610
10	6.158	.000	.000
11	30.000	1.075	1.088
12	-46.933	.000	.000
13	-30.001	.924	.935
14	76.634	.000	.000
15	-89.985	.379	.383
16	-10.995	.000	.000
17	29.855	.021	.022
18	-81.743	.000	.000
19	-30.028	.068	.068
20	-79.773	.000	.000
21	-89.795	.021	.021
22	.226	.000	.000
23	29.999	5.111	5.172
24	-86.926	.000	.000
25	-29.999	4.860	4.918
26	-67.430	.000	.000
27	-89.880	.018	.018
28	34.857	.000	.000
29	29.990	.052	.053
30	-26.020	.000	.000

TABLE 12

Space MMF harmonic analysis for 6-phase, $\delta = 30°$, unity-pitch, q = 2, with one-phase open, $I_D = 0$.

PHASE = 6.0 DELTA = 30.0 ID = 0 IE = 1 IF = 1
Q= 2.0 SLOT= 24.0 CHORDING = .0 YMAX = 2.90

HARMONIC ORDER	ALPHAN	YN1I	YN2I
1	-23.367	90.539	100.000
2	53.616	.000	.000
3	46.930	13.339	14.732
4	42.274	.000	.000
5	-47.110	6.849	7.565
6	-65.469	.000	.000
7	39.445	4.034	4.456
8	64.489	.000	.000
9	-30.685	1.496	1.653
10	-6.607	.000	.000
11	31.667	1.546	1.707
12	-41.550	.000	.000
13	-31.668	1.328	1.467
14	71.826	.000	.000
15	30.601	.941	1.039
16	-8.602	.000	.000
17	-39.443	1.796	1.983
18	-81.692	.000	.000
19	47.109	2.011	2.221
20	-80.697	.000	.000
21	-46.932	2.194	2.424
22	-8.621	.000	.000
23	23.366	4.683	5.172
24	-87.680	.000	.000
25	-23.367	4.452	4.918
26	-68.293	.000	.000
27	46.929	1.884	[illegible]
28	32.817	.000	.000
29	-47.111	1.554	1.717
30	-13.951	.000	.000

TABLE 13

Space MMF harmonic analysis for 6-phase, $\delta = 30°$, unity-pitch, q = 2, with two-phase open, $I_D = I_E = 0$.

PHASE = 6.0 DELTA = 30.0 ID = 0 IE = 0 IF = 1
Q= 2.0 SLOT= 24.0 CHORDING = .0 YMAX = 2.20

HARMONIC ORDER	ALPHAN	YN1I	YN2I
1	-39.147	92.476	100.000
2	87.834	.000	.000
3	46.402	4.797	5.187
4	21.606	.000	.000
5	-68.533	13.461	14.556
6	-42.916	.000	.000
7	70.867	7.579	8.196
8	67.843	.000	.000
9	-18.284	.599	.647
10	-2.413	.000	.000
11	65.204	.810	.876
12	-87.647	.000	.000
13	-65.204	.696	.753
14	73.123	.000	.000
15	18.276	.376	.407
16	-10.418	.000	.000
17	-70.865	3.373	3.648
18	-82.635	.000	.000
19	68.532	3.952	4.273
20	-71.565	.000	.000
21	-46.408	.789	.853
22	-10.337	.000	.000
23	39.146	4.783	5.172
24	-80.131	.000	.000
25	-39.146	4.548	4.918
26	-53.477	.000	.000
27	46.377	.678	.733
28	27.803	.000	.000
29	-68.533	3.055	3.303
30	-9.801	.000	.000

TABLE 14

Space MMF harmonic analysis for 6-phase, $\delta = 30°$, unity-pitch, q = 2, with three-phase open; $I_D = I_E = I_F = 0$.

PHASE = 6.0 DELTA = 30.0 ID = 0 IE = 0 IF = 0
Q= 2.0 SLOT= 24.0 CHORDING = .0 YMAX = 1.98

HARMONIC ORDER	ALPHAN	YN1I	YN2I
1	-31.063	97.226	100.000
2	66.457	.000	.000
3	-39.088	1.597	1.643
4	43.531	.000	.000
5	-56.217	15.915	16.369
6	-37.093	.000	.000
7	62.595	8.520	8.764
8	74.612	.000	.000
9	76.115	.262	.270
10	.909	.000	.000
11	31.364	1.443	1.484
12	-71.917	.000	.000
13	-31.365	1.240	1.275
14	71.479	.000	.000
15	-76.144	.165	.169
16	-10.470	.000	.000
17	-62.594	3.792	3.901
18	-82.017	.000	.000
19	56.217	4.672	4.805
20	-69.619	.000	.000
21	39.085	.263	.270
22	-11.364	.000	.000
23	31.062	5.028	5.172
24	-79.114	.000	.000
25	-31.062	4.781	4.918
26	-53.263	.000	.000
27	-39.086	.226	.232
28	27.660	.000	.000
29	-56.217	3.612	3.715
30	-16.974	.000	.000