



Fermi National Accelerator Laboratory

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Comments About the Use of a Zig-Zag Transformer to Reduce the Neutral Current Created by Unbalanced Nonlinear Loads

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INTRODUCTION

The subject of AC line currents with high harmonic content and the potential for overloaded neutral wires caused by the non-linear loading of electronic power supplies has become one of the most popular and at the same time a very complex topic among electrical engineers. Different solutions are offered for this problem. Some examples are specially designed K-rated AC distribution transformers¹, delta connected primary windings², and L-C tuned filters^{3,4}. All of the above methods have some limitations. For instance, a K-rated transformer does not eliminate harmonics, but transmits them into the feeder. Neutral currents that flow from various loads to the K-rated transformer are still very high. These K-rated transformers are more expensive and are larger in physical size than conventional transformers. The delta connected primary of a power distribution transformer can only eliminate triplen harmonics for balanced loads. Neutral currents caused by the loads are not eliminated. The primary side circuit breaker may also not protect a transformer against overcurrents because the circuit breaker will not see the triplen harmonic current that is circulating in the primary of the transformer⁵. L-C filters can create undesirable resonances, which will lead to an increase in harmonic currents.

Another solution⁶ is to use a number of small Zig-Zag transformers to reduce the neutral current. This is attractive for the following reasons: relatively low cost, simplicity, ease of installation on existing distribution systems, ability to keep neutral currents local thus eliminating the need for larger neutral wires, and the ability to improve the fundamental load current balance as well.

FIELD TEST 1

A site plagued by harmonics, which required investigation, was the 208 V, 3 phase, 60 Hz AC distribution for the second floor of the D0 movable counting house. The counting house has many 5 Vdc and 15 Vdc switch mode power supplies connected to the 120 Vac line. The symptoms were as follows: the 150 KVA (480-208Y/120 V) distribution transformer located on top of the counting house ran very hot. The conduit that contained the transformer secondary wires was also hot. In order to find the cause, we measured phase and neutral currents at the two Panelboards fed by the transformer. The currents were

measured with a BMI PowerScope (the BMI PowerScope plots the current waveforms, analyzes the waveform for harmonic content and charts the spectrum analysis of the first 33 harmonics).

The neutral current value was 215 A RMS with 554.3% of total harmonic distortion (THD). The phase current was about 140 A RMS with a THD of about 70%. All three phase currents were balanced within 20%. The prevailing harmonic was the third harmonic. As a matter of fact, the neutral carried an almost pure third harmonic current (see Fig. 1 and 2). In order to investigate the source of the distortion further we measured the rack currents. Rack M215 was found to be one of the most heavily loaded racks with a neutral current of 32.5 A RMS and a THD of 261%. The phase currents ranged from 24.3 A (phase A) to 22.9 A (phase B) to 10.9A (phase C). The THD of the phase current varied from 69.6% to 82.1% (see Fig. 5 - 8). The rack load was made up mostly of 4 - 1000W and 1 - 500 W switch mode power supplies. This arrangement of supplies per rack made it impossible to balance the load on each branch circuit.

A properly applied Zig-Zag transformer keeps the neutral current local, eliminates triplen harmonics (zero-sequence currents) from the phase currents and improves the overall current balance. We calculated that a Zig-Zag transformer current rating of 15 A per phase would be enough for a typical rack at D0, with the assumption that we would place the transformer as close as possible to the rack. Two transformers were delivered by IPR Systems Inc. in accordance with specification #2262-ES-173136, Rev. 1 shown on Fig. 3. The transformers made by IPR have an E-shaped laminated core and conventional cylindrical coils. The transformer short circuit impedance was not specified .

The first transformer was installed in the branch circuit that fed rack M215 (see Fig. 4). Measurements showed a significant reduction of harmonic current in the branch circuit. The neutral current dropped almost a factor of 3, the RMS current in phase A dropped from 24.3A to 20.0 A, the THD in phase A dropped from 69.6% to 42.9%, and the third harmonic content dropped from 60.0% to 13.5% (see Fig. 5 - 8). Note, that the load currents are the same with or without Zig-Zag transformer.

Later on the transformer was connected to rack M216. The measurements taken at that point showed unexpectedly poor performance of the Zig-Zag transformer despite the fact that rack M216 presented a much smaller load. The neutral RMS current reduction was very small. The current dropped from 22.2 A to 19.8 A, and the THD changed from 280.9% to 266.3%. The third harmonic content changed from 270.7% to 252.7%. Note that the third harmonic current phase shift with respect to the fundamental changed from 327° to 220° . The current wave shape also changed significantly (Fig. 9). The phase currents showed similar behavior (Fig. 10 - 12). The currents in the transformer legs were much larger than would be expected from the third harmonic current reduction (Fig. 13).

LABORATORY TEST

At that time we could not explain the different behavior of the Zig-Zag transformer at rack M215 compared to rack M216 and decided to set up a test to

find the answer. Our test arrangement included the Zig-Zag transformer and a few switch mode power supplies connected to resistive loads. The test set up was made in building NS3, where the AC line is not disturbed by other nonlinear loads. First we checked whether the transformer was wired correctly. We measured the no-load current, swapped the loads between the different phases, but did not find anything wrong. Finally we came to the conclusion that all our troubles were caused by the relatively high Zig-Zag transformer impedance compared to the AC source impedance at D0. According to our measurements and the manufacturer's data, the Zig-Zag transformer's resistance is about 0.12 Ohm per winding or 0.24 Ohm per phase. We performed a shorted secondary test on the Zig-Zag transformer which gave us a transformer impedance of $Z=0.3$ Ohm. From this we calculated the transformer reactance for 60 Hz $X_{60} = 0.186$ Ohm. Thus, the third harmonic current (180 Hz) reactance of the transformer is $X_{180} = 3 \cdot X_{60} = 0.558$ Ohm and the transformer impedance for the third harmonic is $Z_{180} = 0.61$ Ohm. Then, we disconnected the neutral wire between the neutral point of the transformer and the AC line and measured sinusoidal 180 Hz voltage with 11 V peak to peak value between the transformer neutral and ground. This gave us an RMS voltage of 3.9 V applied to each transformer leg. At the same time the load neutral current RMS was 18 A. From this information we calculated a combined phase impedance of Zig-Zag transformer and the AC line of 0.65 Ohm and the AC line impedance of 0.04 Ohm. Fig. 14 shows the equivalent schematic for the third harmonic currents with the nonlinear load represented as the third harmonic voltage source. To calculate the value of the neutral wire impedance we measured the voltage between the transformer neutral point and the ground with the neutral wire in place. The voltage was 1.1 V peak to peak. The neutral current RMS was 11.5A. Similar to what we did above, we calculated a source neutral impedance value of 0.1 Ohm. From this it became apparent, that we should increase the impedance of the source neutral to make it harder for the neutral current to return via the distribution transformer. In order to do so, we installed a choke in the neutral between the AC source and the Zig-Zag transformer thus increasing the AC line impedance for the neutral current. The increased neutral impedance does not affect the phase impedances because the Zig-Zag transformer provides alternate phase current paths with relatively low impedance. For instance instead of the current path: phase A - load - Neutral; the Zig-Zag transformer creates a path via Phase A - load - phases B and C. The neutral impedance of the AC distribution system for third harmonic currents should be increased so that it is about an order of magnitude larger than the Zig-Zag transformer impedance. This will force most of the third harmonic currents to flow through the Zig-Zag transformer. Merely disconnecting the source neutral is not acceptable for safety reasons. A choke with an inductance value of 1 mH, which we had on hand, gives an impedance of 1.13 Ohm for the third harmonic and was used for testing. A design of a small 1 mH choke is described in Appendix 1.

FIELD TEST 2

The combination of the Zig-Zag transformer and the 1 mH choke in the neutral produced much better results for both electronic racks, described above. The neutral current dropped more than a factor of six, the third harmonic current was almost eliminated from the phase currents, and the overall current balance was improved significantly (see Fig. 15 - 18). The harmonics reduction caused by the Zig-Zag transformer combined with the 1 mH choke was very close for both racks.

To find an answer for the previously described unexpected behavior of rack M216, we disconnected the choke and the rack itself from the transformer and measured the unloaded transformer current. The result, shown on Fig. 13, explains the mystery. In the previous test at NS3 the unloaded transformer current was about 0.4 A. The same test in the vicinity of rack M216 showed an unloaded Zig-Zag transformer current of 10.8A. That means that the Zig-Zag transformer provides a relatively low impedance pass for the zero-sequence currents caused by nonlinear loads connected to other branch circuits of the distribution system. Once we understood this we took a second look at M216 rack with the Zig-Zag transformer. As mentioned before, the third harmonic current in the AC line neutral had 110° phase shift with respect to the load neutral third harmonic current. This is caused by the combination of the third harmonic current from rack M216 and other third harmonic currents, attracted from other loads. Adding a choke in the neutral, i.e. introducing a larger impedance for the neutral currents, eliminated the contribution from other loads to a large degree. The choke reduced the transformer no load current at rack M216 from 10.8 A to 1.7A.

CONCLUSION

A Zig-Zag autotransformer in combination with a choke in the neutral and installed close to the load can successfully correct overload problems caused by nonlinear loads, especially in existing installations. The cost of a Zig-Zag transformer with a choke seems to be lower than other retrofits such as the installation of the K-rated transformers, oversized transformers, or tuned L-C filters.

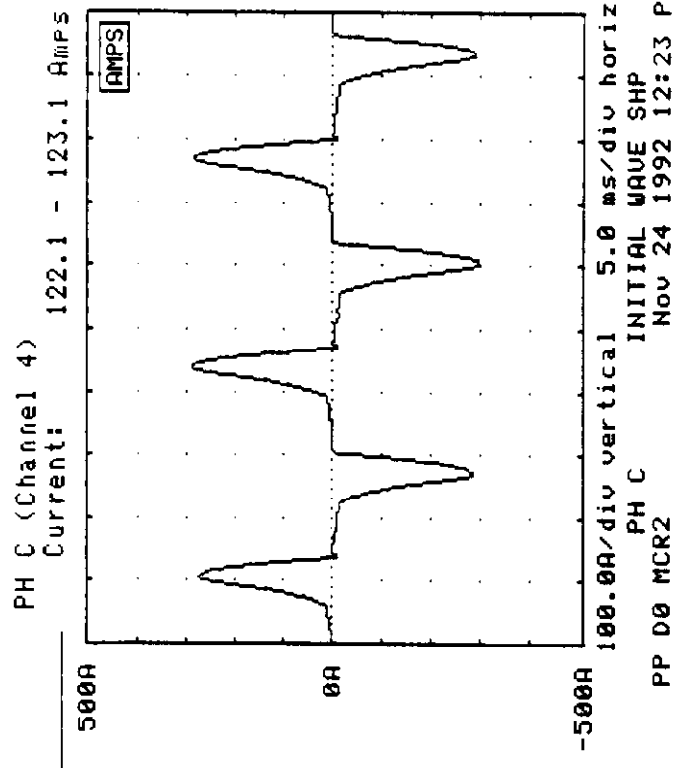
ACKNOWLEDGMENTS

We would like to thank Tim Martin, Julius Lentz, Walt Jaskierny, Steve Morrison, Rick Moore and Demetrius Zafiropoulos, who helped with the tests.

REFERENCES

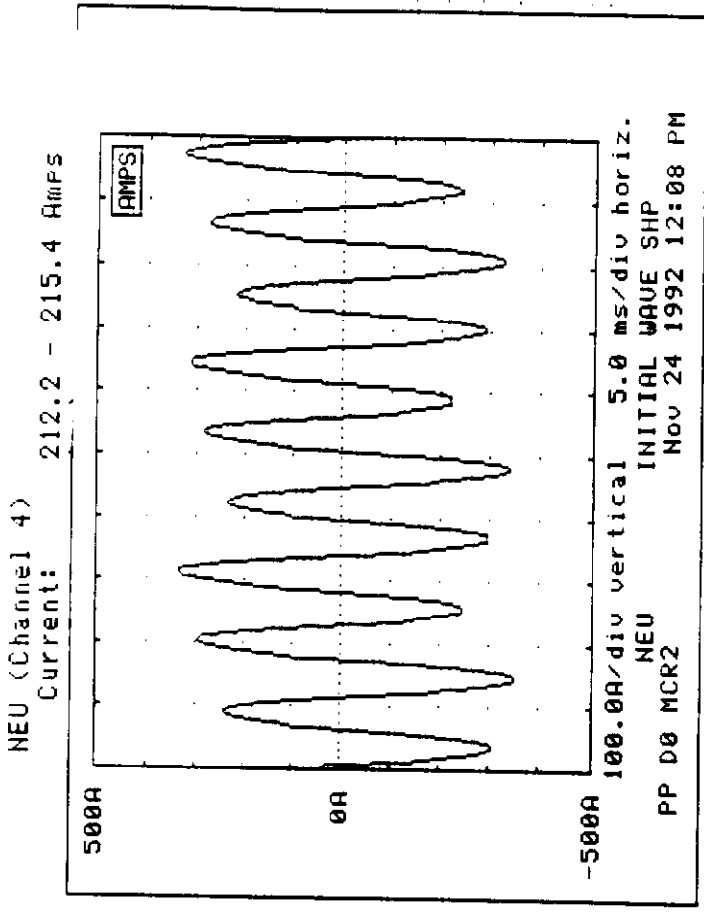
1. John A. DeDad, Coping with phase-to-phase nonlinear loads and harmonics. EC&M, June 1991.
2. A.C. Franklin, D.P. Franklin, The J&P Transformer Book, Butterworth & Co., 1983.

3. Peter Gross, Design and Performance of Harmonic Filters, Power Quality, Premier VI, 1990.
4. Michael Z. Lowenstein, Improving Power Factor in the Presence of Harmonics Using Low-Voltage Tuned Filters, IEEE Transactions on Industry Applications, Vol. 29, No. 3, May/June 1993.
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6. Robert H. Lee, Eliminating Harmonic Currents Using Transformers, Power Quality, September/October, 1991.



Fundamental frequency: 60.0 Hz

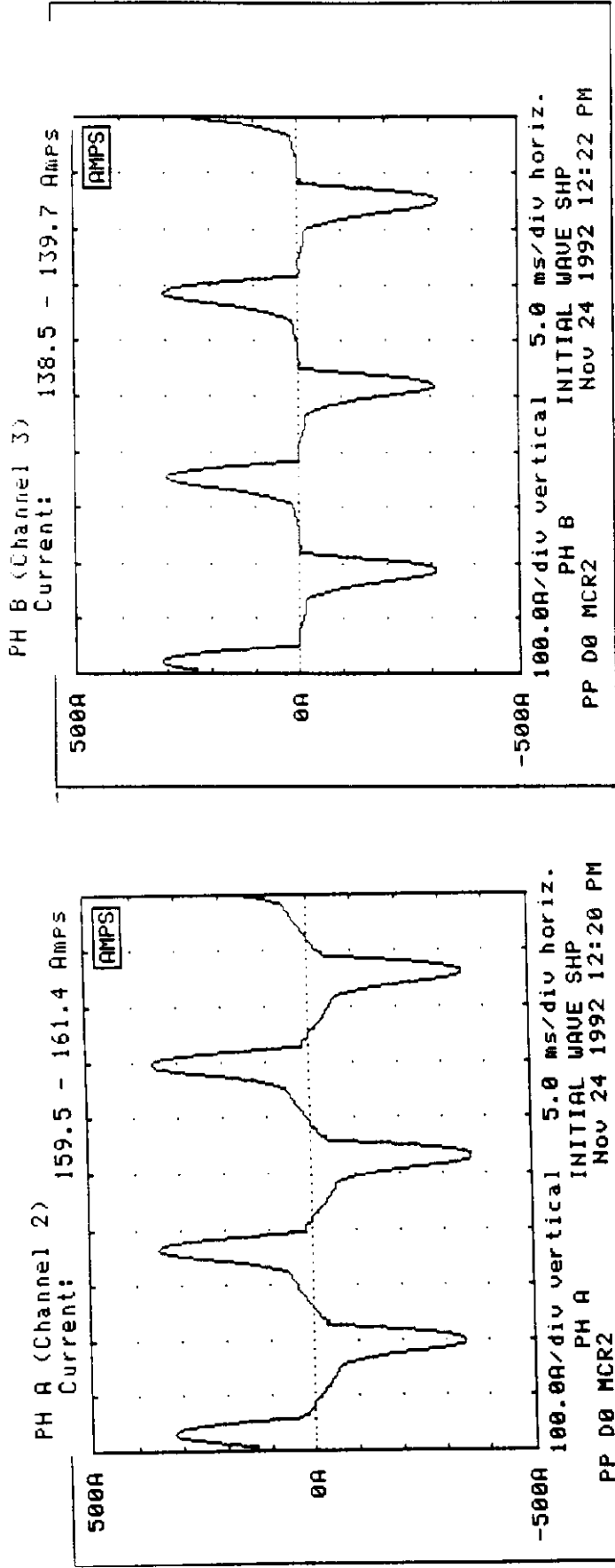
HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0°			
3rd	65.5%	167°	2nd		
5th	30.6%	327°	4th	0.3%	15°
7th	10.6%	97°	6th		
9th	4.4%	207°	8th		
11th	2.6%	267°	10th		
13th	3.5%	30°	12th		
15th	1.7%	156°	14th		
17th	1.1%	245°	16th		
19th	0.9%	325°	18th		
21st	1.0%	77°	20th		
23rd	0.6%	178°	22nd		
25th	0.8%	266°	24th		
27th	0.5%	35°	26th	0.3%	241°
29th	0.4%	119°	28th	0.3%	13°
31st	0.4%	215°	30th	0.4%	106°
33rd	0.5%	318°	32nd	0.4%	209°
ODD	73.3%		EVEN	0.8%	
THD:	73.4%				



Fundamental frequency: 60.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0°			
3rd	552.8%	77°	2nd		
5th	10.5%	138°	4th		
7th	5.4%	236°	6th		
9th	35.2%	274°	8th		
11th	3.2%	260°	10th		
13th	2.1%	349°	12th		
15th	13.1%	52°	14th		
17th	1.7%	327°	16th		
19th	2.0%	159°	18th		
21st	7.6%	162°	20th		
23rd	1.3%	337°	22nd		
25th			24th		
27th	4.2%	276°	26th		
29th			28th	2.5%	293°
31st	1.4%	25°	30th		
33rd	3.5%	22°	32nd		
ODD	554.3%		EVEN	2.5%	
THD:	554.3%				

Fig. 1. Panel #1, phase C and neutral currents.



Fundamental frequency: 60.0 Hz			
HARM	PCT	PHASE	
FUND	100.0%	0°	
3rd	61.5%	168°	
5th	26.5%	325°	
7th	8.3%	85°	
9th	3.4%	176°	
11th	3.6%	254°	
13th	2.9%	31°	
15th	1.3%	111°	
17th	1.5%	218°	
19th	0.9%	321°	
21st	0.7%	46°	
23rd	0.7%	115°	
25th	0.6%	249°	
27th	0.5%	326°	
29th	0.6%	76°	
31st	0.5%	162°	
33rd	0.4%	277°	
			0.3% 252°
			0.2% 69°
			0.3% 69°
			0.4% 186°
ODD	67.8%		
			EVEN 0.6%
THD:	67.8%		

Fig. 2. Panel #1, phase A and B currents.



Specification #2262-ES-173136, Rev. 1

Three Phase Zig-Zag Transformer for Non-linear Loads

Prepared by:
A.T. Visser
A. Kristalinski

1. Application

The transformer will be used to absorb the harmonic currents caused by non-linear loads, connected to a three phase 60 Hz a.c. distribution system. For reference refer to: Power Quality Magazine, September/October 1991, page 33.

2. Transformer Ratings

The transformer shall be rated for service as follows:

2.1	Input source	-	3 phase, 208 V, 60 Hz, 30 A
2.2	kVA	-	5.5
2.3	Neutral current	-	46 Amp, 180 Hz
2.4	Case (enclosure) temperature rise	-	30°C
2.5	Ambient	-	30°C, sea level
2.6	Winding temperature class	-	180°C minimum
2.7	Three pole input circuit breaker at enclosure	-	15A, 300 VAC, 5,000 AIC

3. Transformer Construction

The transformer shall be constructed as follows:

3.1	Enclosure	-	NEMA 1, metal painted
3.2	Enclosure size	-	~12"W, ~12"D, 12" H maximum
3.3	Winding	-	Copper, 3 phase, zig-zag
3.4	Terminal block enclosed	-	Input: 4 wires AWG #10 Output: 4 wires AWG #10 Ground: 2 wires AWG #10
3.5	Nameplate	-	Manufacturer, ratings, weight
3.6	Mounting brackets	-	Install floor mounting brackets

4. Information

Bids shall be supplied with a preliminary outline sketch and delivery schedule.

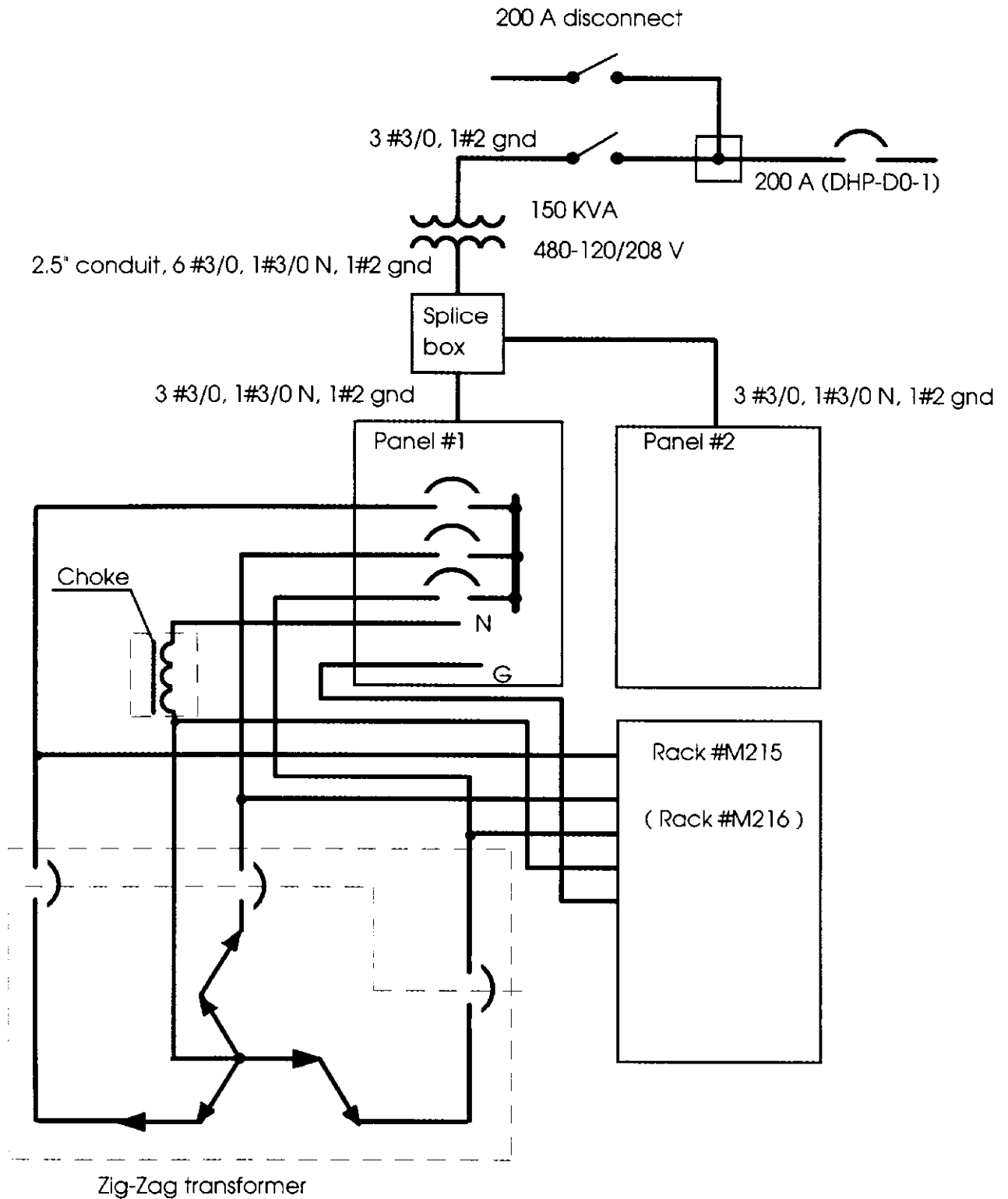
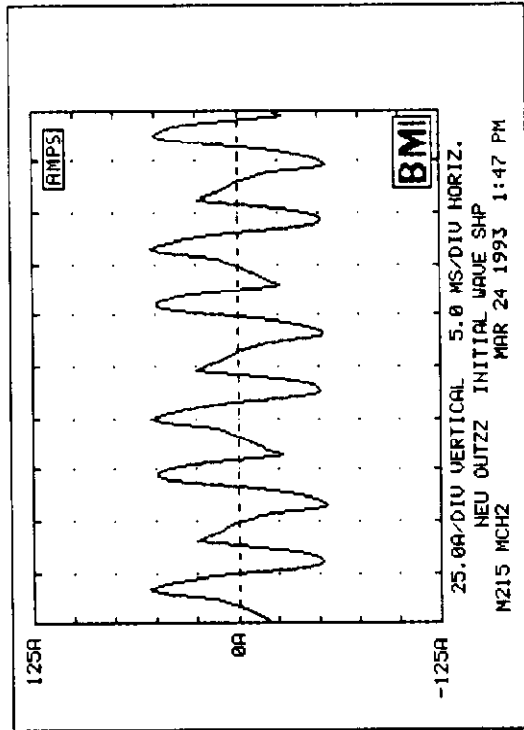


Fig. 4. Single line Distribution Diagram.

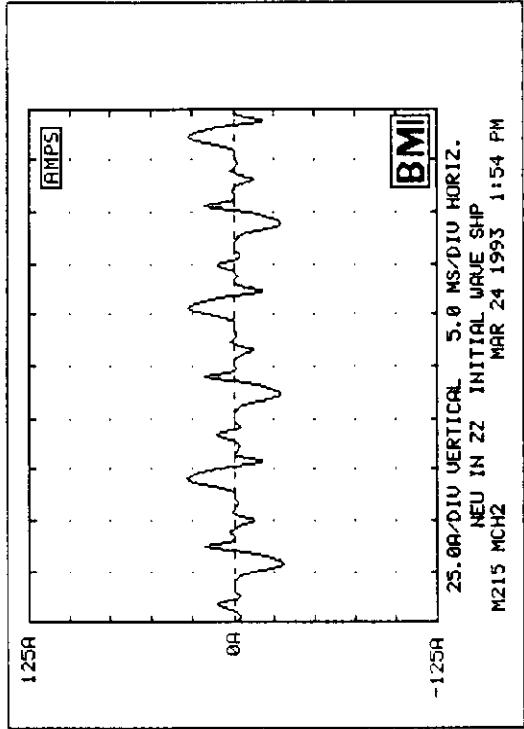
NEU_OUT2Z (Channel 3)
Current: 32.4 - 32.7 Amps

M215 MCH2 Mar 24 1993
NEU_OUT2Z INITIAL WAVE SHP 1:47:29 PM



NEU_IN_ZZ (Channel 3)
Current: 12.3 - 12.5 Amps

M215 MCH2 Mar 24 1993
NEU_IN_ZZ INITIAL WAVE SHP 1:54:39 PM



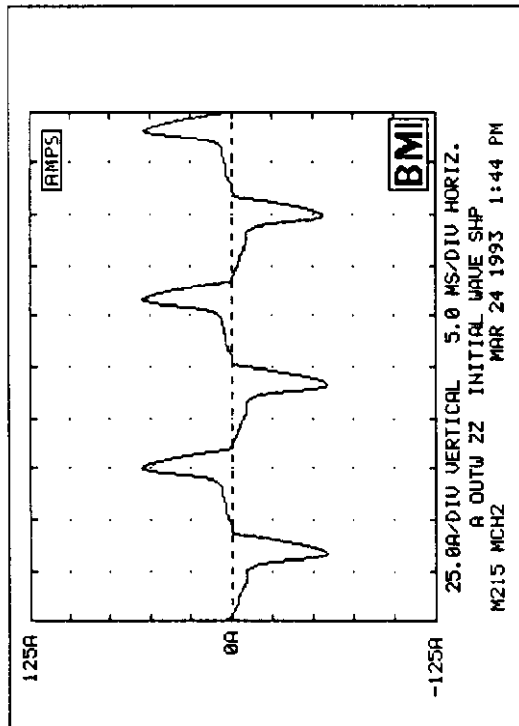
HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0	2nd	1.9%	280
3rd	132.6%	72	4th	1.4%	322
5th	56.2%	265	6th	0.8%	265
7th	28.2%	265	8th		
9th	18.3%	265	10th		
11th	16.8%	213	12th		
13th	1.6%	213	14th		
15th	4.6%	289	16th		
17th	1.1%	43	18th		
19th	2.2%	289	20th		
21st	2.2%	355	22nd		
23rd	2.2%	249	24th		
25th	2.0%	157	26th		
27th			28th		
29th			30th		
31st			32nd		
33rd					
ODD	261.3%		EVEN	2.7%	
THD	261.3%				

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0	2nd	3.6%	218
3rd	128.8%	199	4th	2.1%	111
5th	39.2%	172	6th	1.7%	351
7th	40.6%	293	8th	1.0%	5
9th	32.8%	293	10th	1.1%	316
11th	11.5%	97	12th		
13th	17.8%	196	14th		
15th	8.4%	268	16th	0.5%	198
17th	4.6%	45	18th		
19th	4.9%	149	20th		
21st	2.2%	221	22nd		
23rd	2.2%	33	24th	0.8%	329
25th	1.5%	69	26th	0.8%	126
27th	0.4%	206	28th		
29th	1.8%	145	30th	0.7%	321
31st			32nd	0.6%	172
33rd					
ODD	176.8%		EVEN	5.0%	
THD	176.1%				

Fig 5. Rack # M215, neutral current in the load (left) and in the line (right) with Zig-Zag transformer connected in the parallel to the load.

M215 MCH2 Mar 24 1993
HARMONIC REPORT
A OUTW ZZ (Channel 1)
Current: 24.2 - 24.4 Amps

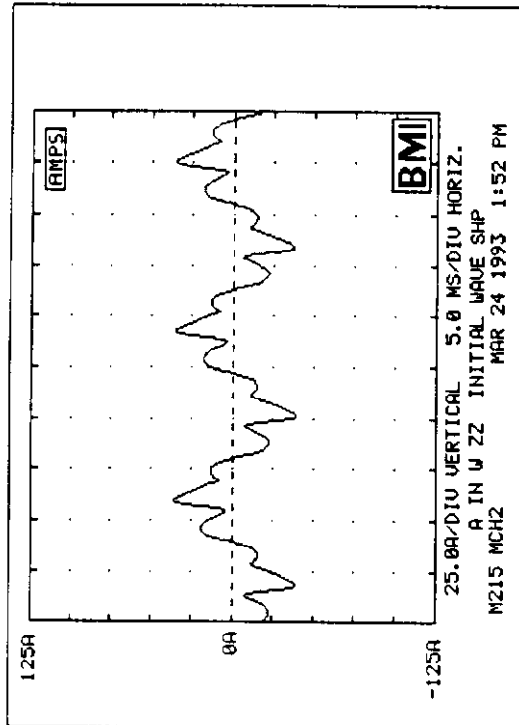
M215 MCH2 Mar 24 1993
A OUTW ZZ INITIAL WAVE SHP 1:44:54 PM



HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0	2nd	0.9%	86
3rd	60.4%	146	4th	0.3%	63
5th	10.2%	114	6th		
7th	5.3%	114	8th		
9th	3.3%	125	10th		
11th	2.3%	125	12th		
13th	1.4%	125	14th		
15th	0.9%	125	16th		
17th	0.8%	125	18th		
19th	0.8%	125	20th		
21st	0.8%	125	22nd		
23rd	0.8%	125	24th		
25th	0.8%	125	26th		
27th	0.8%	125	28th		
29th	0.8%	125	30th		
31st	0.8%	125	32nd		
33rd	0.8%	125			
ODD	69.6%		EVEN	1.1%	
THD:	69.6%				

M215 MCH2 Mar 24 1993
HARMONIC REPORT
A IN W ZZ (Channel 1)
Current: 19.9 - 20.1 Amps

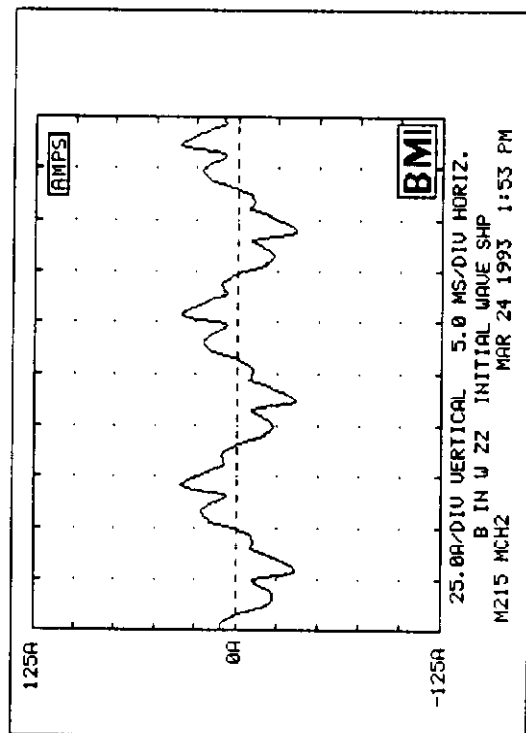
M215 MCH2 Mar 24 1993
A IN W ZZ INITIAL WAVE SHP 1:52:04 PM



HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0	2nd	1.4%	176
3rd	13.5%	321	4th	0.3%	110
5th	9.8%	137	6th	0.2%	163
7th	8.2%	137	8th	0.2%	193
9th	7.6%	217	10th		
11th	7.6%	217	12th		
13th	7.6%	217	14th		
15th	7.6%	217	16th		
17th	7.6%	217	18th		
19th	7.6%	217	20th		
21st	7.6%	217	22nd		
23rd	7.6%	217	24th		
25th	7.6%	217	26th		
27th	7.6%	217	28th		
29th	7.6%	217	30th		
31st	7.6%	217	32nd		
33rd	7.6%	217			
ODD	42.8%		EVEN	1.5%	
THD:	42.9%				

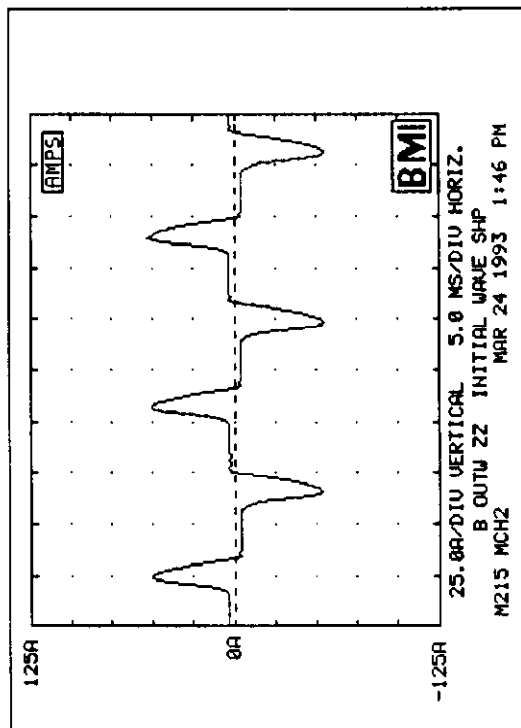
Fig. 6. Rack # M215, phase A current in the load (left) and in the line (right) with Zig-Zag transformer connected in the parallel to the load.

MM215 MCH2 Mar 24 1993
B IN W ZZ INITIAL WAVE SHP 1:53:22 PM



HARM	PCT	PHASE	HARM	PCT	PHASE
FOUND	100.0%	0	FOUND	100.0%	0
1	100.0%	1	1	100.0%	1
2	100.0%	2	2	100.0%	2
3	100.0%	3	3	100.0%	3
4	100.0%	4	4	100.0%	4
5	100.0%	5	5	100.0%	5
6	100.0%	6	6	100.0%	6
7	100.0%	7	7	100.0%	7
8	100.0%	8	8	100.0%	8
9	100.0%	9	9	100.0%	9
10	100.0%	10	10	100.0%	10
11	100.0%	11	11	100.0%	11
12	100.0%	12	12	100.0%	12
13	100.0%	13	13	100.0%	13
14	100.0%	14	14	100.0%	14
15	100.0%	15	15	100.0%	15
16	100.0%	16	16	100.0%	16
17	100.0%	17	17	100.0%	17
18	100.0%	18	18	100.0%	18
19	100.0%	19	19	100.0%	19
20	100.0%	20	20	100.0%	20
21	100.0%	21	21	100.0%	21
22	100.0%	22	22	100.0%	22
23	100.0%	23	23	100.0%	23
24	100.0%	24	24	100.0%	24
25	100.0%	25	25	100.0%	25
26	100.0%	26	26	100.0%	26
27	100.0%	27	27	100.0%	27
28	100.0%	28	28	100.0%	28
29	100.0%	29	29	100.0%	29
30	100.0%	30	30	100.0%	30
31	100.0%	31	31	100.0%	31
32	100.0%	32	32	100.0%	32
33	100.0%	33	33	100.0%	33
34	100.0%	34	34	100.0%	34
35	100.0%	35	35	100.0%	35
36	100.0%	36	36	100.0%	36
37	100.0%	37	37	100.0%	37
38	100.0%	38	38	100.0%	38
39	100.0%	39	39	100.0%	39
40	100.0%	40	40	100.0%	40
41	100.0%	41	41	100.0%	41
42	100.0%	42	42	100.0%	42
43	100.0%	43	43	100.0%	43
44	100.0%	44	44	100.0%	44
45	100.0%	45	45	100.0%	45
46	100.0%	46	46	100.0%	46
47	100.0%	47	47	100.0%	47
48	100.0%	48	48	100.0%	48
49	100.0%	49	49	100.0%	49
50	100.0%	50	50	100.0%	50
51	100.0%	51	51	100.0%	51
52	100.0%	52	52	100.0%	52
53	100.0%	53	53	100.0%	53
54	100.0%	54	54	100.0%	54
55	100.0%	55	55	100.0%	55
56	100.0%	56	56	100.0%	56
57	100.0%	57	57	100.0%	57
58	100.0%	58	58	100.0%	58
59	100.0%	59	59	100.0%	59
60	100.0%	60	60	100.0%	60
61	100.0%	61	61	100.0%	61
62	100.0%	62	62	100.0%	62
63	100.0%	63	63	100.0%	63
64	100.0%	64	64	100.0%	64
65	100.0%	65	65	100.0%	65
66	100.0%	66	66	100.0%	66
67	100.0%	67	67	100.0%	67
68	100.0%	68	68	100.0%	68
69	100.0%	69	69	100.0%	69
70	100.0%	70	70	100.0%	70
71	100.0%	71	71	100.0%	71
72	100.0%	72	72	100.0%	72
73	100.0%	73	73	100.0%	73
74	100.0%	74	74	100.0%	74
75	100.0%	75	75	100.0%	75
76	100.0%	76	76	100.0%	76
77	100.0%	77	77	100.0%	77
78	100.0%	78	78	100.0%	78
79	100.0%	79	79	100.0%	79
80	100.0%	80	80	100.0%	80
81	100.0%	81	81	100.0%	81
82	100.0%	82	82	100.0%	82
83	100.0%	83	83	100.0%	83
84	100.0%	84	84	100.0%	84
85	100.0%	85	85	100.0%	85
86	100.0%	86	86	100.0%	86
87	100.0%	87	87	100.0%	87
88	100.0%	88	88	100.0%	88
89	100.0%	89	89	100.0%	89
90	100.0%	90	90	100.0%	90
91	100.0%	91	91	100.0%	91
92	100.0%	92	92	100.0%	92
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94	100.0%	94	94	100.0%	94
95	100.0%	95	95	100.0%	95
96	100.0%	96	96	100.0%	96
97	100.0%	97	97	100.0%	97
98	100.0%	98	98	100.0%	98
99	100.0%	99	99	100.0%	99
100	100.0%	100	100	100.0%	100
101	100.0%	101	101	100.0%	101
102	100.0%	102	102	100.0%	102
103	100.0%	103	103	100.0%	103
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109	100.0%	109	109	100.0%	109
110	100.0%	110	110	100.0%	110
111	100.0%	111	111	100.0%	111
112	100.0%	112	112	100.0%	112
113	100.0%	113	113	100.0%	113
114	100.0%	114	114	100.0%	114
115	100.0%	115	115	100.0%	115
116	100.0%	116	116	100.0%	116
117	100.0%	117	117	100.0%	117
118	100.0%	118	118	100.0%	118
119	100.0%	119	119	100.0%	119
120	100.0%	120	120	100.0%	120
121	100.0%	121	121	100.0%	121
122	100.0%	122	122	100.0%	122
123	100.0%	123	123	100.0%	123
124	100.0%	124	124	100.0%	124
125	100.0%	125	125	100.0%	125
126	100.0%	126	126	100.0%	126
127	100.0%	127	127	100.0%	127
128	100.0%	128	128	100.0%	128
129	100.0%	129	129	100.0%	129
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131	100.0%	131	131	100.0%	131
132	100.0%	132	132	100.0%	132
133	100.0%	133	133	100.0%	133
134	100.0%	134	134	100.0%	134
135	100.0%	135	135	100.0%	135
136	100.0%	136	136	100.0%	136
137	100.0%	137	137	100.0%	137
138	100.0%	138	138	100.0%	138
139	100.0%	139	139	100.0%	139
140	100.0%	140	140	100.0%	140
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142	100.0%	142	142	100.0%	142
143	100.0%	143	143	100.0%	143
144	100.0%	144	144	100.0%	144
145	100.0%	145	145	100.0%	145
146	100.0%	146	146	100.0%	146
147	100.0%	147	147	100.0%	147
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163	100.0%	163	163	100.0%	163
164	100.0%	164	164	100.0%	164
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166	100.0%	166	166	100.0%	166
167	100.0%	167	167	100.0%	167
168	100.0%	168	168	100.0%	168
169	100.0%	169	169	100.0%	169
170	100.0%	170	170	100.0%	170
171	100.0%	171	171	100.0%	171
172	100.0%	172	172	100.0%	172
173	100.0%	173	173	100.0%	173
174	100.0%	174	174	100.0%	174
175	100.0%	175	175	100.0%	175
176	100.0%	176	176	100.0%	176
177	100.0%	177	177	100.0%	177
178	100.0%	178	178	100.0%	178
179	100.0%	179	179	100.0%	179
180	100.0%	180	180	100.0%	180
181	100.0%	181	181	100.0%	181
182	100.0%	182	182	100.0%	182
183	100.0%	183	183	100.0%	183
184	100.0%	184	184	100.0%	184
185	100.0%	185	185	100.0%	185
186	100.0%	186	186	100.0%	186
187	100.0%	187	187	100.0%	187
188	100.0%	188	188	100.0%	188
189	100.0%	189	189	100.0%	189
190	100.0%	190	190	100.0%	190
191	100.0%	191	191	100.0%	191
192	100.0%	192	192	100.0%	192
193	100.0%	193	193	100.0%	193
194	100.0%	194	194	100.0%	194
195	100.0%	195	195	100.0%	195
196	100.0%	196	196	100.0%	196
197	100.0%	197	197	100.0%	197
198	100.0%	198	198	100.0%	198
199	100.0%	199	199	100.0%	199
200	100.0%	200	200	100.0%	200
201	100.0%	201	201	100.0%	201
202	100.0%	202	202	100.0%	202
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221	100.0%	221	221	100.0%	221
222	100.0%	222	222	100.0%	222
223	100.0%	223	223	100.0%	223
224	100.0%	224	224	100.0%	224
225	100.0%	225	225	100.0%	225
226	100.0%	226	226	100.0%	226
227	100.0%	227	227	100.0%	227
228					

MM215 MCH2 Mar 24 1993
B OUTW ZZ INITIAL WAVE SHP 1:46:10 PM

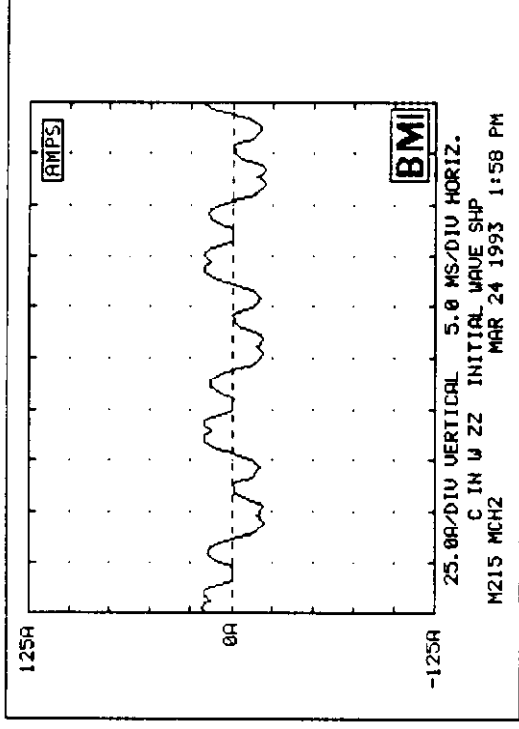


HARM	PCT	PHASE	HARM	PCT	PHASE
1000	79.2%	THO	2nd	1.2%	70
1000	79.2%	THO	1st	0.6%	158
1000	79.2%	THO	1st	0.6%	302
1000	79.2%	THO	1st	0.4%	19
1000	79.2%	THO	1st	0.3%	208
1000	79.2%	THO	1st	0.2%	153
1000	79.2%	THO	1st	0.3%	242
1000	79.2%	THO	EVEN	1.7%	

Fig. 7. Rack # M215, phase B current in the load (left) and in the line (right) with Zig-Zag transformer connected in the parallel to the load.

M215 MCH2 Mar 24 1993
 HARMONIC REPORT 1:58 PM
 C IN W Z2 (Channel 1)
 Current: 12.5 - 12.5 Amps

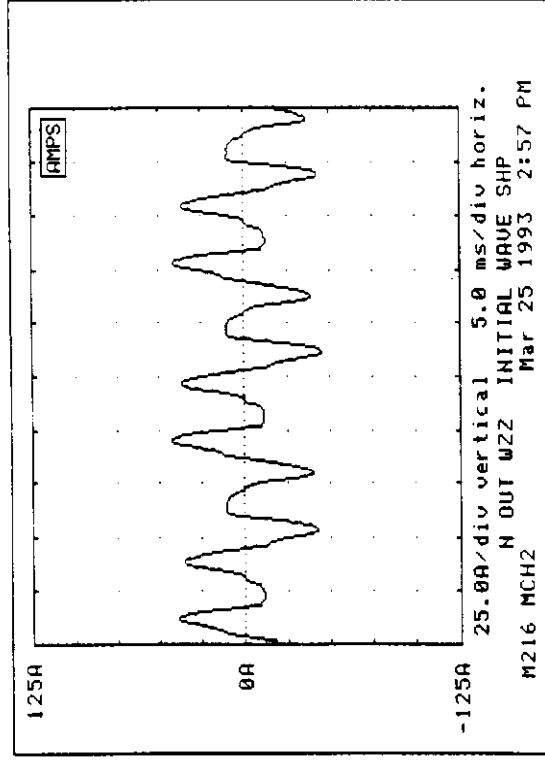
M215 MCH2 Mar 24 1993
 C IN W Z2 INITIAL WAVE SHP 1:58:58 PM



Fundamental frequency: 60.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0	2nd	2.3%	28
3rd	17.5%	29	4th	0.5%	28
5th	2.8%	31	6th	0.3%	28
7th	1.0%	31	8th	0.3%	28
9th	0.6%	31	10th	0.4%	51
11th	0.3%	31	12th	0.3%	38
13th	0.3%	31	14th	0.3%	167
15th	0.3%	31	16th	0.3%	274
17th	0.3%	31	18th	0.3%	61
19th	0.3%	31	20th	0.3%	38
21st	0.3%	31	22nd	0.3%	167
23rd	0.3%	31	24th	0.3%	274
25th	0.3%	31	26th	0.3%	61
27th	0.3%	31	28th	0.3%	38
29th	0.3%	31	30th	0.3%	167
31st	0.3%	31	32nd	0.3%	274
33rd	0.3%	31	34th	0.3%	61
35th	0.3%	31	36th	0.3%	38
37th	0.3%	31	38th	0.3%	167
39th	0.3%	31	40th	0.3%	274
41st	0.3%	31	42nd	0.3%	61
43rd	0.3%	31	44th	0.3%	38
45th	0.3%	31	46th	0.3%	167
47th	0.3%	31	48th	0.3%	274
49th	0.3%	31	50th	0.3%	61
51st	0.3%	31	52nd	0.3%	38
53rd	0.3%	31	54th	0.3%	167
55th	0.3%	31	56th	0.3%	274
57th	0.3%	31	58th	0.3%	61
59th	0.3%	31	60th	0.3%	38
61st	0.3%	31	62nd	0.3%	167
63rd	0.3%	31	64th	0.3%	274
65th	0.3%	31	66th	0.3%	61
67th	0.3%	31	68th	0.3%	38
69th	0.3%	31	70th	0.3%	167
71st	0.3%	31	72nd	0.3%	274
73rd	0.3%	31	74th	0.3%	61
75th	0.3%	31	76th	0.3%	38
77th	0.3%	31	78th	0.3%	167
79th	0.3%	31	80th	0.3%	274
81st	0.3%	31	82nd	0.3%	61
83rd	0.3%	31	84th	0.3%	38
85th	0.3%	31	86th	0.3%	167
87th	0.3%	31	88th	0.3%	274
89th	0.3%	31	90th	0.3%	61
91st	0.3%	31	92nd	0.3%	38
93rd	0.3%	31	94th	0.3%	167
95th	0.3%	31	96th	0.3%	274
97th	0.3%	31	98th	0.3%	61
99th	0.3%	31	100th	0.3%	38
101st	0.3%	31	102nd	0.3%	167
103rd	0.3%	31	104th	0.3%	274
105th	0.3%	31	106th	0.3%	61
107th	0.3%	31	108th	0.3%	38
109th	0.3%	31	110th	0.3%	167
111th	0.3%	31	112th	0.3%	274
113th	0.3%	31	114th	0.3%	61
115th	0.3%	31	116th	0.3%	38
117th	0.3%	31	118th	0.3%	167
119th	0.3%	31	120th	0.3%	274
121st	0.3%	31	122nd	0.3%	61
123rd	0.3%	31	124th	0.3%	38
125th	0.3%	31	126th	0.3%	167
127th	0.3%	31	128th	0.3%	274
129th	0.3%	31	130th	0.3%	61
131st	0.3%	31	132nd	0.3%	38
133rd	0.3%	31	134th	0.3%	167
135th	0.3%	31	136th	0.3%	274
137th	0.3%	31	138th	0.3%	61
139th	0.3%	31	140th	0.3%	38
141st	0.3%	31	142nd	0.3%	167
143rd	0.3%	31	144th	0.3%	274
145th	0.3%	31	146th	0.3%	61
147th	0.3%	31	148th	0.3%	38
149th	0.3%	31	150th	0.3%	167
151st	0.3%	31	152nd	0.3%	274
153rd	0.3%	31	154th	0.3%	61
155th	0.3%	31	156th	0.3%	38
157th	0.3%	31	158th	0.3%	167
159th	0.3%	31	160th	0.3%	274
161st	0.3%	31	162nd	0.3%	61
163rd	0.3%	31	164th	0.3%	38
165th	0.3%	31	166th	0.3%	167
167th	0.3%	31	168th	0.3%	274
169th	0.3%	31	170th	0.3%	61
171st	0.3%	31	172nd	0.3%	38
173rd	0.3%	31	174th	0.3%	167
175th	0.3%	31	176th	0.3%	274
177th	0.3%	31	178th	0.3%	61
179th	0.3%	31	180th	0.3%	38
181st	0.3%	31	182nd	0.3%	167
183rd	0.3%	31	184th	0.3%	274
185th	0.3%	31	186th	0.3%	61
187th	0.3%	31	188th	0.3%	38
189th	0.3%	31	190th	0.3%	167
191st	0.3%	31	192nd	0.3%	274
193rd	0.3%	31	194th	0.3%	61
195th	0.3%	31	196th	0.3%	38
197th	0.3%	31	198th	0.3%	167
199th	0.3%	31	200th	0.3%	274
201st	0.3%	31	202nd	0.3%	61
203rd	0.3%	31	204th	0.3%	38
205th	0.3%	31	206th	0.3%	167
207th	0.3%	31	208th	0.3%	274
209th	0.3%	31	210th	0.3%	61
211st	0.3%	31	212nd	0.3%	38
213rd	0.3%	31	214th	0.3%	167
215th	0.3%	31	216th	0.3%	274
217th	0.3%	31	218th	0.3%	61
219th	0.3%	31	220th	0.3%	38
221st	0.3%	31	222nd	0.3%	167
223rd	0.3%	31	224th	0.3%	274
225th	0.3%	31	226th	0.3%	61
227th	0.3%	31	228th	0.3%	38
229th	0.3%	31	230th	0.3%	167
231st	0.3%	31	232nd	0.3%	274
233rd	0.3%	31	234th	0.3%	61
235th	0.3%	31	236th	0.3%	38
237th	0.3%	31	238th	0.3%	167
239th	0.3%	31	240th	0.3%	274
241st	0.3%	31	242nd	0.3%	61
243rd	0.3%	31	244th	0.3%	38
245th	0.3%	31	246th	0.3%	167
247th	0.3%	31	248th	0.3%	274
249th	0.3%	31	250th	0.3%	61
251st	0.3%	31	252nd	0.3%	38
253rd	0.3%	31	254th	0.3%	167
255th	0.3%	31	256th	0.3%	274
257th	0.3%	31	258th	0.3%	61
259th	0.3%	31	260th	0.3%	38
261st	0.3%	31	262nd	0.3%	167
263rd	0.3%	31	264th	0.3%	274
265th	0.3%	31	266th	0.3%	61
267th	0.3%	31	268th	0.3%	38
269th	0.3%	31	270th	0.3%	167
271st	0.3%	31	272nd	0.3%	274
273rd	0.3%	31	274th	0.3%	61
275th	0.3%	31	276th	0.3%	38
277th	0.3%	31	278th	0.3%	167
279th	0.3%	31	280th	0.3%	274
281st	0.3%	31	282nd	0.3%	61
283rd	0.3%	31	284th	0.3%	38
285th	0.3%	31	286th	0.3%	167
287th	0.3%	31	288th	0.3%	274
289th	0.3%	31	290th	0.3%	61
291st	0.3%	31	292nd	0.3%	38
293rd	0.3%	31	294th	0.3%	167
295th	0.3%	31	296th	0.3%	274
297th	0.3%	31	298th	0.3%	61
299th	0.3%	31	300th	0.3%	38
301st	0.3%	31	302nd	0.3%	167
303rd	0.3%	31	304th	0.3%	274
305th	0.3%	31	306th	0.3%	61
307th	0.3%	31	308th	0.3%	38
309th	0.3%	31	310th	0.3%	167
311st	0.3%	31	312nd	0.3%	274
313rd	0.3%	31	314th	0.3%	61
315th	0.3%	31	316th	0.3%	38
317th	0.3%	31	318th	0.3%	167
319th	0.3%	31	320th	0.3%	274
321st	0.3%	31	322nd	0.3%	61
323rd	0.3%	31	324th	0.3%	38
325th	0.3%	31	326th	0.3%	167
327th	0.3%	31	328th	0.3%	274
329th	0.3%	31	330th	0.3%	61
331st	0.3%	31	332nd	0.3%	38
333rd	0.3%	31	334th	0.3%	167
335th	0.3%	31	336th	0.3%	274
337th	0.3%	31	338th	0.3%	61
339th	0.3%	31	340th	0.3%	38
341st	0.3%	31	342nd	0.3%	167
343rd	0.3%	31	344th	0.3%	274
345th	0.3%	31	346th	0.3%	61
347th	0.3%	31	348th	0.3%	38
349th	0.3%	31	350th	0.3%	167
351st	0.3%	31	352nd	0.3%	274
353rd	0.3%	31	354th	0.3%	61
355th	0.3%	31	356th	0.3%	38
357th	0.3%	31	358th	0.3%	167
359th	0.3%	31	360th	0.3%	274
361st	0.3%	31	362nd	0.3%	61
363rd	0.3%	31	364th	0.3%	38
365th	0.3%	31	366th	0.3%	167
367th	0.3%	31	368th	0.3%	274
369th	0.3%	31	370th	0.3%	61
371st	0.3%	31	372nd	0.3%	38
373rd	0.3%	31	374th	0.3%	167
375th	0.3%	31	376th	0.3%	274
377th	0.3%	31	378th	0.3%	61
379th	0.3%	31	380th	0.3%	38
381st	0.3%	31	382nd	0.3%	167
383rd	0.3%	31	384th	0.3%	274
385th	0.3%	31	386th	0.3%	61
387th	0.3%	31	388th	0.3%	38
389th	0.3%	31	390th	0.3%	167
391st	0.3%	31	392nd	0.3%	274

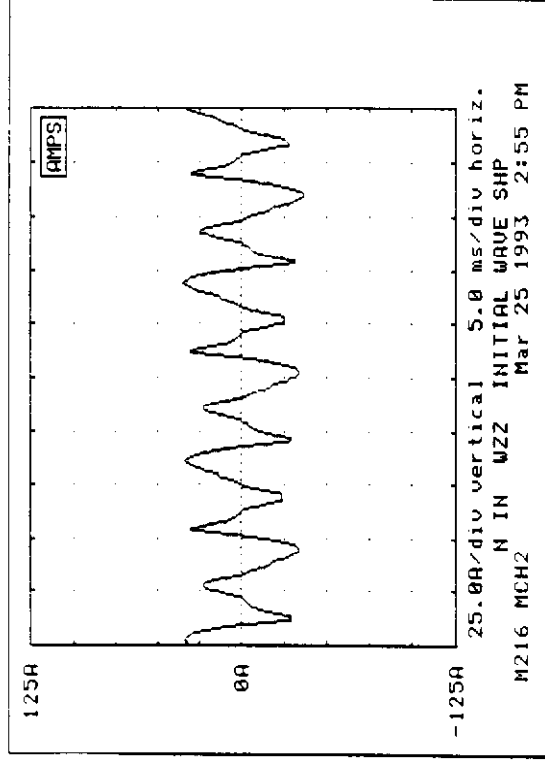
N OUT WZZ (Channel 3)
Current: 22.1 - 22.4 AmPS



Fundamental frequency: 60.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0°			
3rd	270.7%	327°	2nd		
5th	45.5%	277°	4th	2.7%	169°
7th	52.1%	71°	6th	2.0%	65°
9th	20.5%	10°	8th	0.5%	264°
11th	13.1%	203°	10th	0.6%	189°
13th	11.3%	297°	12th		
15th	9.3%	268°	14th		
17th	4.1%	133°	16th		
19th	1.8%	271°	18th		
21st	2.8%	146°	20th		
23rd	1.7%	80°	22nd		
25th	1.7%	223°	24th		
27th	2.3%	69°	26th		
29th	1.0%	47°	28th	0.8%	240°
31st	0.7%	8°	30th	0.5%	77°
33rd	1.4%	327°	32nd		
ODD	280.9%		EVEN	3.6%	
THD:	280.9%				

N IH WZZ (Channel 2)
Current: 19.7 - 19.9 AmPS

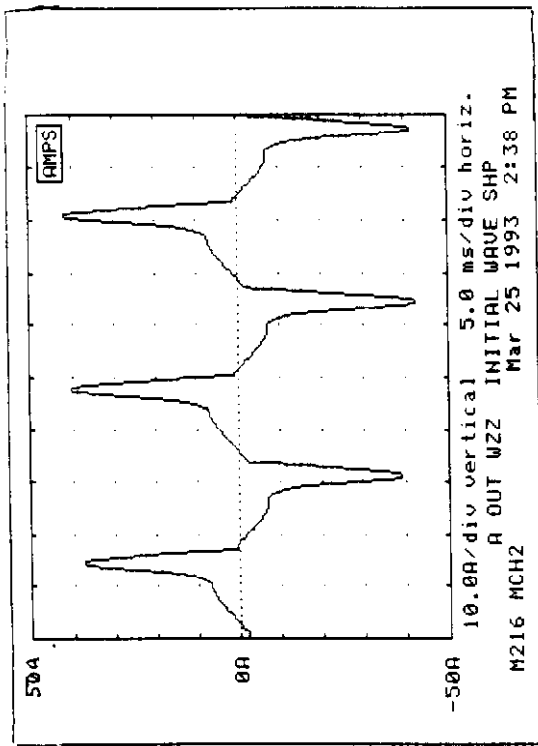


Fundamental frequency: 60.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0°			
3rd	252.7%	220°	2nd	4.4%	238°
5th	51.5%	325°	4th	1.9%	24°
7th	53.0%	138°	6th	2.7%	307°
9th	33.6%	188°	8th		
11th	14.3%	302°	10th		
13th	11.5%	57°	12th	0.5%	266°
15th	5.2%	145°	14th		
17th	5.8%	275°	16th		
19th	0.9%	42°	18th		
21st	4.6%	105°	20th		
23rd	0.8%	52°	22nd		
25th	0.7%	40°	24th		
27th	2.6%	73°	26th	0.5%	82°
29th	0.5%	53°	28th	1.8%	146°
31st			30th		
33rd	2.1%	16°	32nd	0.7%	64°
ODD	266.2%		EVEN	5.8%	
THD:	266.3%				

Fig. 9. Rack # M216; neutral current in the load (left) and in the line (right) with Zig-Zag transformer connected in the parallel to the load.

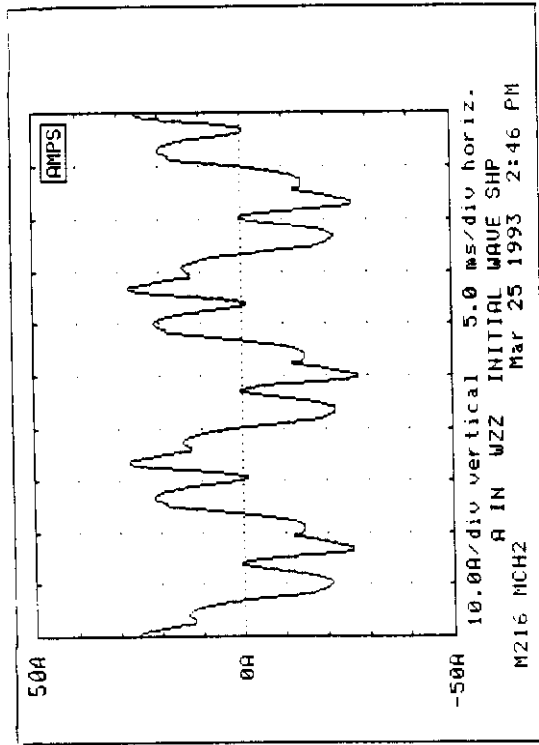
A OUT W22 (Channel 4)
Current: 16.2 - 16.4 Amps



Fundamental frequency: 60.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0°	2nd	1.7%	294°
3rd	55.6%	134°	4th	0.9%	100°
5th	36.2%	279°	6th		
7th	18.3%	59°	8th	0.2%	74°
9th	6.5%	191°	10th	0.3%	244°
11th	0.8%	282°	12th		
13th	1.9%	277°	14th		
15th	2.2%	42°	16th		
17th	1.4%	154°	18th		
19th	0.9%	214°	20th		
21st	1.0%	306°	22nd		
23rd	1.1%	55°	24th		
25th	0.9%	160°	26th	0.3%	100°
27th	0.7%	257°	28th	0.3%	183°
29th	0.5%	338°	30th	0.3%	263°
31st	0.4%	62°	32nd	0.4%	1°
33rd	0.4%	154°			
EVEN			2.1%		
THD:			69.2%		

A IN W22 (Channel 4)
Current: 15.5 - 15.7 Amps

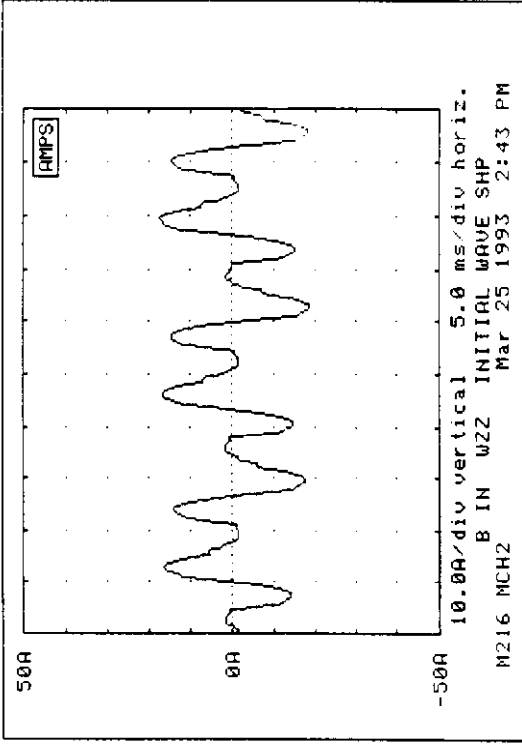


Fundamental frequency: 60.0 Hz

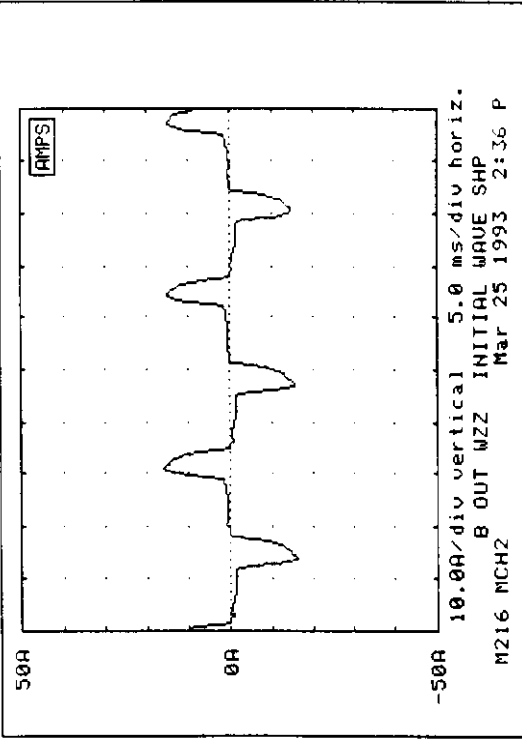
HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0°	2nd	1.4%	262°
3rd	51.0%	27°	4th	0.6%	311°
5th	37.6%	280°	6th	0.8%	93°
7th	18.8%	61°	8th	0.5%	229°
9th	6.1%	257°	10th		
11th	0.8%	290°	12th		
13th	1.9%	282°	14th		
15th	0.7%	333°	16th		
17th	1.8%	150°	18th		
19th	0.6%	213°	20th		
21st	0.4%	47°	22nd		
23rd	1.1%	45°	24th		
25th	0.8%	150°	26th	0.3%	280°
27th	0.6%	331°	28th	0.3%	305°
29th	0.6%	320°	30th	0.2%	61°
31st	0.3%	80°	32nd	0.4%	229°
33rd	0.4%	231°			
EVEN			1.9%		
THD:			66.5%		

Fig. 10. Rack # M216, phase A current in the load (left) and in the line (right) with Zig-Zag transformer connected in the parallel to the load.

B IN WZZ (Channel 2)
Current: 10.0 - 10.1 Amps



B OUT WZZ (Channel 2)
Current: 6.7 - 6.9 Amps



Fundamental frequency: 60.0 Hz

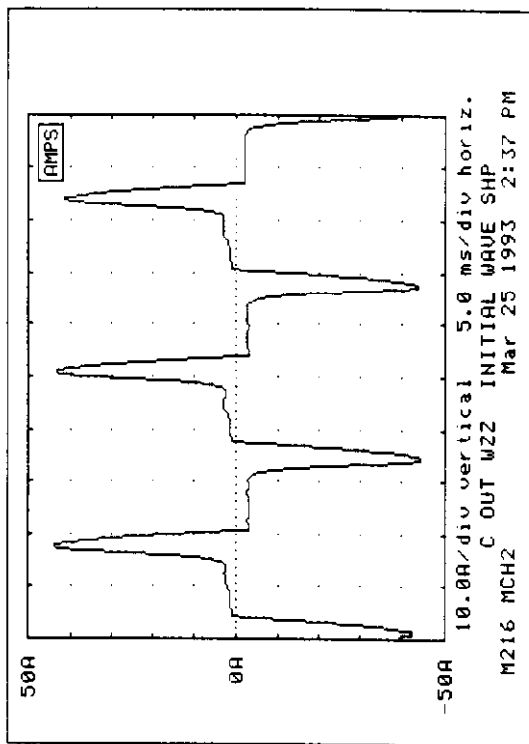
HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0°	2nd	5.3%	195°
3rd	66.9%	156°	4th	1.9%	5°
5th	32.8%	319°	6th	2.5%	186°
7th	5.0%	156°	8th	1.1%	21°
9th	10.8%	80°	10th	1.3%	228°
11th	10.9%	246°	12th	1.1%	78°
13th	3.8%	52°	14th	0.7%	266°
15th	2.0%	91°	16th		
17th	3.8%	180°	18th		
19th	1.7%	359°	20th		
21st	1.3%	344°	22nd		
23rd	2.3%	122°	24th		
25th	1.4%	269°	26th		
27th	0.8%	232°	28th		
29th	1.2%	56°	30th		
31st	0.4%	102°	32nd	0.6%	202°
33rd	0.5%	209°			
ODD	76.6%		EVEN	6.5%	
THD:	76.9%				

Fundamental frequency: 60.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0°	2nd	2.5%	211°
3rd	141.3%	309°	4th	1.9%	134°
5th	30.4%	305°	6th	0.9%	290°
7th	2.8%	138°	8th	0.9%	126°
9th	6.8%	190°	10th		
11th	10.5%	214°	12th	0.5%	215°
13th	3.4%	19°	14th		
15th	4.9%	37°	16th		
17th	4.3%	121°	18th	0.3%	163°
19th	1.3%	293°	20th	0.3%	85°
21st	3.9%	242°	22nd		
23rd	2.1%	56°	24th		
25th	1.0%	208°	26th		
27th	1.6%	106°	28th	0.8%	282°
29th	1.2%	354°	30th	0.4%	34°
31st	0.6%	87°	32nd	0.8%	136°
33rd	0.6%	254°			
ODD	145.4%		EVEN	3.7%	
THD:	145.5%				

Fig. 11. Rack # M216, phase B current in the load (left) and in the line (right) with Zig-Zag transformer connected in the parallel to the load.

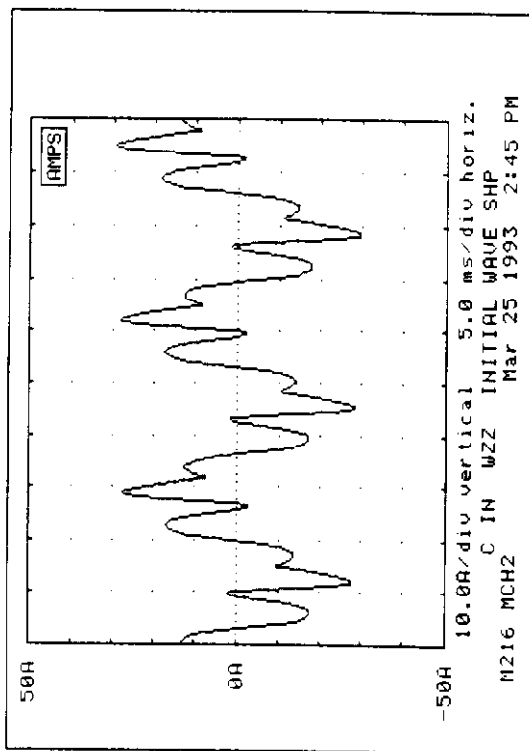
C OUT WZZ (Channel 3)
Current: 16.8 - 17.0 Amps



Fundamental frequency: 60.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0°	2nd	1.8%	353°
3rd	76.7%	153°	4th	0.7%	274°
5th	48.1%	311°	6th	0.3%	261°
7th	21.0%	110°	8th		
9th	3.7%	286°	10th		
11th	4.4%	208°	12th		
13th	5.1%	359°	14th		
15th	3.1%	138°	16th		
17th	0.8%	247°	18th		
19th	1.1%	273°	20th		
21st	1.2%	35°	22nd		
23rd	0.7%	142°	24th	0.2%	184°
25th	0.6%	22°	26th	0.2%	8°
27th	0.7%	336°	28th	0.3%	45°
29th	0.7%	66°	30th	0.3%	158°
31st	0.4%	178°	32nd		
33rd	0.3%	237°			
ODD	93.3%		EVEN	2.0%	
THD:	93.3%				

C IN WZZ (Channel 3)
Current: 15.2 - 15.3 Amps

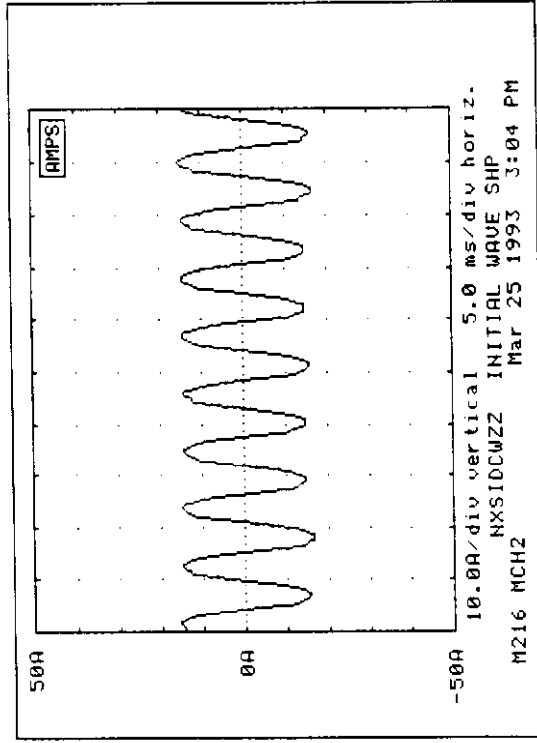


Fundamental frequency: 60.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0°	2nd	1.2%	348°
3rd	36.1%	56°	4th	0.6%	336°
5th	47.3%	321°	6th	0.2%	129°
7th	19.8%	123°	8th	0.4%	294°
9th	9.9%	343°	10th		
11th	4.3%	227°	12th		
13th	4.8%	22°	14th		
15th	1.9%	213°	16th		
17th	0.4%	272°	18th		
19th	1.2%	303°	20th		
21st	1.0%	145°	22nd		
23rd	0.7%	212°	24th		
25th	0.7%	265°	26th		
27th	0.5%	108°	28th	0.3%	319°
29th	0.5%	129°	30th	0.3%	111°
31st	0.4%	224°	32nd	0.2%	238°
33rd	0.4%	38°			
ODD	63.9%		EVEN	1.5%	
THD:	63.9%				

Fig. 12. Rack # M216, phase C current in the load (left) and in the line (right) with Zig-Zag transformer connected in the parallel to the load.

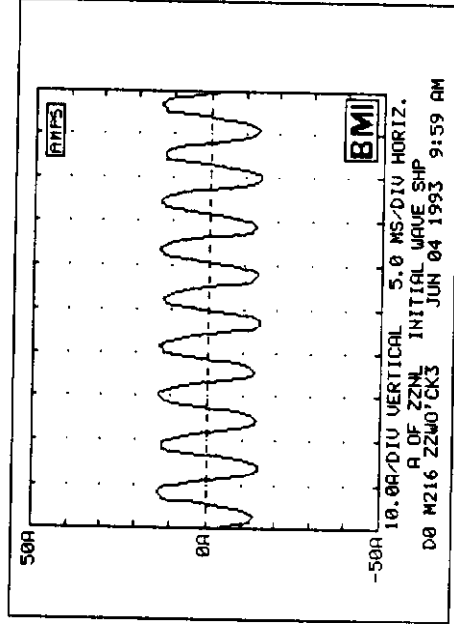
HXSIDCWZZ (Channel 3)
Current: 11.8 - 11.8 Amps



Fundamental frequency: 180.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0°	2nd	0.3%	264°
3rd	7.4%	355°	4th		
5th	2.5%	289°	6th		
7th	1.3%	195°	8th		
9th	0.9%	119°	10th		
11th	0.6%	39°			
ODD	8.0%		EVEN	0.3%	
THD:	8.0%				

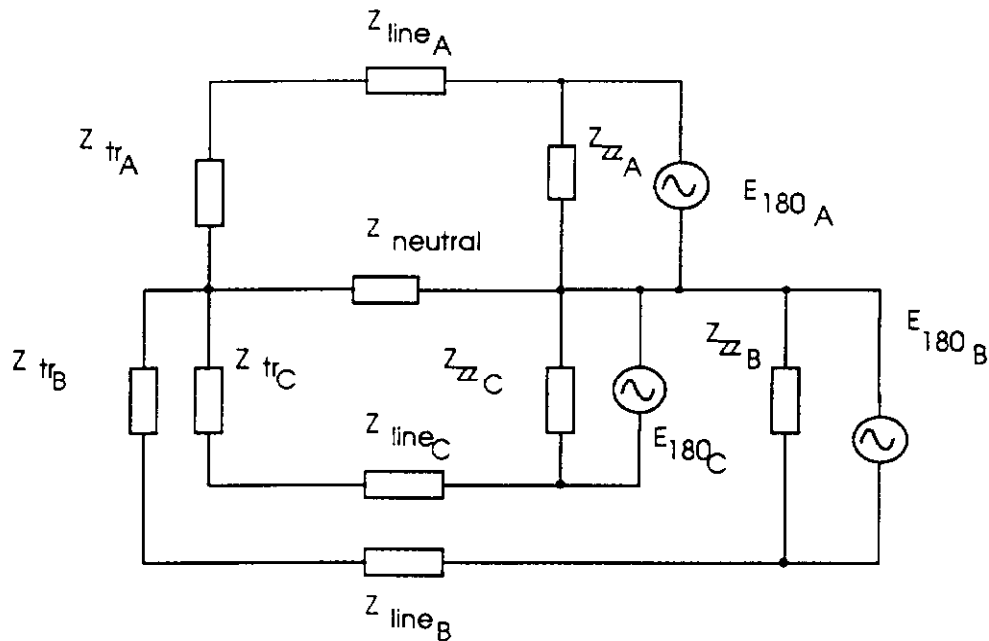
D0 M216 ZZW0'CK3 Jun 04 1993
HARMONIC REPORT
A OF ZZNL (Channel 1)
Current: 10.8 - 10.8 Amps
D0 M216 ZZW0'CK3 Jun 04 1993
A OF ZZNL INITIAL WAVE SHP 9:59:22 AM



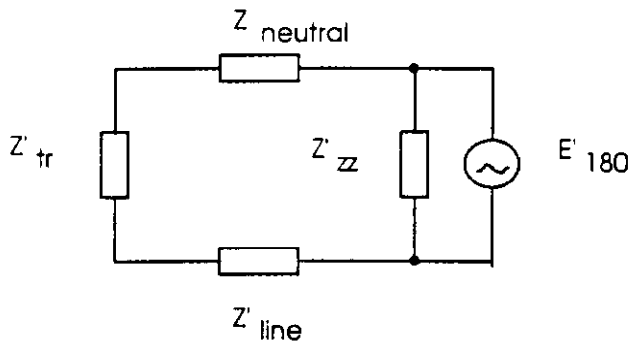
Fundamental frequency: 180.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0	2nd	0.4%	72
3rd	8.9%	348	4th		
5th	2.5%	277	6th		
7th	1.4%	164	8th		
9th	0.7%	95	10th		
11th	0.5%	346			
ODD	9.4%		EVEN	0.4%	
THD:	9.4%				

Fig. 13. Rack # M216, Zig-Zag transformer leg (phase) current (left); the point in the distribution system, where rack # M216 is connected, Zig-Zag transformer leg (phase) current (right).



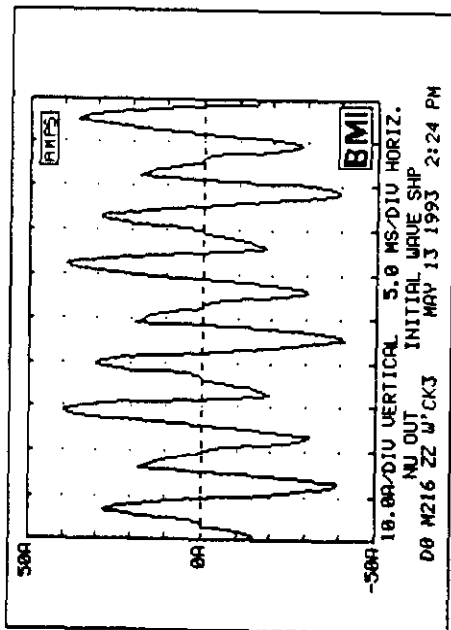
Each phase is represented as combination of three impedances: Zig-Zag transformer (Z_{zz}), line (Z_{line}) and distribution transformer (Z_{tr}). The load is represented by three third harmonic voltage sources (E_{180}). Third harmonic voltages in all phases are in phase and we can substitute three voltage sources by the single source and derive the schematic below:



Because all three phases are symmetrical: $Z'_{tr} = Z_{tr} / 3$; $Z'_{zz} = Z_{zz} / 3$; $Z'_{line} = Z_{line} / 3$; $E'_{180} = E_{180} / 3$.

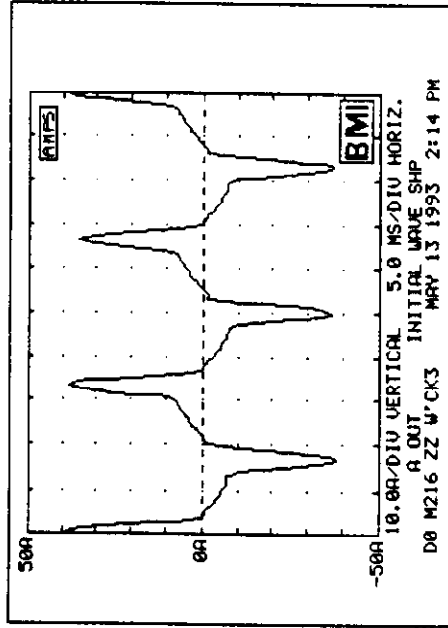
Fig. 14. Equivalent schematic of the distribution system, load and Zig-Zag transformer for the third harmonic current.

NU OUT (Channel 3)
Current 20.8 - 21.2 Amps
D0 M216 Z2 W'CK3 May 13 1993
NU OUT INITIAL WAVE SHP 21:24:22 PM



Fundamental frequency: 60.0 Hz					
HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0	2nd	1.8%	117
3rd	1.8%	287	4th	1.6%	112
5th	0.9%	287	6th	0.9%	287
7th	0.6%	112	8th	0.6%	112
9th	0.6%	112	10th	0.6%	112
11th	0.6%	112	12th	0.6%	112
13th	0.6%	112	14th	0.6%	112
15th	0.6%	112	16th	0.6%	112
17th	0.6%	112	18th	0.6%	112
19th	0.6%	112	20th	0.6%	112
21st	0.6%	112	22nd	0.6%	112
23rd	0.6%	112	24th	0.6%	112
25th	0.6%	112	26th	0.6%	112
27th	0.6%	112	28th	0.6%	112
29th	0.6%	112	30th	0.6%	112
31st	0.6%	112	32nd	0.6%	112
33rd	0.6%	112	34th	0.6%	112
35th	0.6%	112	36th	0.6%	112
37th	0.6%	112	38th	0.6%	112
39th	0.6%	112	40th	0.6%	112
41st	0.6%	112	42nd	0.6%	112
43rd	0.6%	112	44th	0.6%	112
45th	0.6%	112	46th	0.6%	112
47th	0.6%	112	48th	0.6%	112
49th	0.6%	112	50th	0.6%	112
51st	0.6%	112	52nd	0.6%	112
53rd	0.6%	112	54th	0.6%	112
55th	0.6%	112	56th	0.6%	112
57th	0.6%	112	58th	0.6%	112
59th	0.6%	112	60th	0.6%	112
61st	0.6%	112	62nd	0.6%	112
63rd	0.6%	112	64th	0.6%	112
65th	0.6%	112	66th	0.6%	112
67th	0.6%	112	68th	0.6%	112
69th	0.6%	112	70th	0.6%	112
71st	0.6%	112	72nd	0.6%	112
73rd	0.6%	112	74th	0.6%	112
75th	0.6%	112	76th	0.6%	112
77th	0.6%	112	78th	0.6%	112
79th	0.6%	112	80th	0.6%	112
81st	0.6%	112	82nd	0.6%	112
83rd	0.6%	112	84th	0.6%	112
85th	0.6%	112	86th	0.6%	112
87th	0.6%	112	88th	0.6%	112
89th	0.6%	112	90th	0.6%	112
91st	0.6%	112	92nd	0.6%	112
93rd	0.6%	112	94th	0.6%	112
95th	0.6%	112	96th	0.6%	112
97th	0.6%	112	98th	0.6%	112
99th	0.6%	112	100th	0.6%	112
101st	0.6%	112	102nd	0.6%	112
103rd	0.6%	112	104th	0.6%	112
105th	0.6%	112	106th	0.6%	112
107th	0.6%	112	108th	0.6%	112
109th	0.6%	112	110th	0.6%	112
111th	0.6%	112	112th	0.6%	112
113th	0.6%	112	114th	0.6%	112
115th	0.6%	112	116th	0.6%	112
117th	0.6%	112	118th	0.6%	112
119th	0.6%	112	120th	0.6%	112
121st	0.6%	112	122nd	0.6%	112
123rd	0.6%	112	124th	0.6%	112
125th	0.6%	112	126th	0.6%	112
127th	0.6%	112	128th	0.6%	112
129th	0.6%	112	130th	0.6%	112
131st	0.6%	112	132nd	0.6%	112
133rd	0.6%	112	134th	0.6%	112
135th	0.6%	112	136th	0.6%	112
137th	0.6%	112	138th	0.6%	112
139th	0.6%	112	140th	0.6%	112
141st	0.6%	112	142nd	0.6%	112
143rd	0.6%	112	144th	0.6%	112
145th	0.6%	112	146th	0.6%	112
147th	0.6%	112	148th	0.6%	112
149th	0.6%	112	150th	0.6%	112
151st	0.6%	112	152nd	0.6%	112
153rd	0.6%	112	154th	0.6%	112
155th	0.6%	112	156th	0.6%	112
157th	0.6%	112	158th	0.6%	112
159th	0.6%	112	160th	0.6%	112
161st	0.6%	112	162nd	0.6%	112
163rd	0.6%	112	164th	0.6%	112
165th	0.6%	112	166th	0.6%	112
167th	0.6%	112	168th	0.6%	112
169th	0.6%	112	170th	0.6%	112
171st	0.6%	112	172nd	0.6%	112
173rd	0.6%	112	174th	0.6%	112
175th	0.6%	112	176th	0.6%	112
177th	0.6%	112	178th	0.6%	112
179th	0.6%	112	180th	0.6%	112
181st	0.6%	112	182nd	0.6%	112
183rd	0.6%	112	184th	0.6%	112
185th	0.6%	112	186th	0.6%	112
187th	0.6%	112	188th	0.6%	112
189th	0.6%	112	190th	0.6%	112
191st	0.6%	112	192nd	0.6%	112
193rd	0.6%	112	194th	0.6%	112
195th	0.6%	112	196th	0.6%	112
197th	0.6%	112	198th	0.6%	112
199th	0.6%	112	200th	0.6%	112
201st	0.6%	112	202nd	0.6%	112
203rd	0.6%	112	204th	0.6%	112
205th	0.6%	112	206th	0.6%	112
207th	0.6%	112	208th	0.6%	112
209th	0.6%	112	210th	0.6%	112
211st	0.6%	112	212nd	0.6%	112
213rd	0.6%	112	214th	0.6%	112
215th	0.6%	112	216th	0.6%	112
217th	0.6%	112	218th	0.6%	112
219th	0.6%	112	220th	0.6%	112
221st	0.6%	112	222nd	0.6%	112
223rd	0.6%	112	224th	0.6%	112
225th	0.6%	112	226th	0.6%	112
227th	0.6%	112	228th	0.6%	112
229th	0.6%	112	230th	0.6%	112
231st	0.6%	112	232nd	0.6%	112
233rd	0.6%	112	234th	0.6%	112
235th	0.6%	112	236th	0.6%	112
237th	0.6%	112	238th	0.6%	112
239th	0.6%	112	240th	0.6%	112
241st	0.6%	112	242nd	0.6%	112
243rd	0.6%	112	244th	0.6%	112
245th	0.6%	112	246th	0.6%	112
247th	0.6%	112	248th	0.6%	112
249th	0.6%	112	250th	0.6%	112
251st	0.6%	112	252nd	0.6%	112
253rd	0.6%	112	254th	0.6%	112
255th	0.6%	112	256th	0.6%	112
257th	0.6%	112	258th	0.6%	112
259th	0.6%	112	260th	0.6%	112
261st	0.6%	112	262nd	0.6%	112
263rd	0.6%	112	264th	0.6%	112
265th	0.6%	112	266th	0.6%	112
267th	0.6%	112	268th	0.6%	112
269th	0.6%	112	270th	0.6%	112
271st	0.6%	112	272nd	0.6%	112
273rd	0.6%	112	274th	0.6%	112
275th	0.6%	112	276th	0.6%	112
277th	0.6%	112	278th	0.6%	112
279th	0.6%	112	280th	0.6%	112
281st	0.6%	112	282nd	0.6%	112
283rd	0.6%	112	284th	0.6%	112
285th	0.6%	112	286th	0.6%	112
287th	0.6%	112	288th	0.6%	112
289th	0.6%	112	290th	0.6%	112
291st	0.6%	112	292nd	0.6%	112
293rd	0.6%	112	294th	0.6%	112
295th	0.6%	112	296th	0.6%	112
297th	0.6%	112	298th	0.6%	112
299th	0.6%	112	300th	0.6%	112
301st	0.6%	112	302nd	0.6%	112
303rd	0.6%	112	304th	0.6%	112
305th	0.6%	112	306th	0.6%	112
307th	0.6%	112	308th	0.6%	112
309th	0.6%	112	310th	0.6%	112
311st	0.6%	112	312nd	0.6%	112
313rd	0.6%	112	314th	0.6%	112
315th	0.6%	112	316th	0.6%	112
317th	0.6%	112	318th	0.6%	112
319th	0.6%	112	320th	0.6%	112
321st	0.6%	112	322nd	0.6%	112
323rd	0.6%	112	324th	0.6%	112
325th	0.6%	112	326th	0.6%	112
327th	0.6%	112	328th	0.6%	112
329th	0.6%	112	330th	0.6%	112
331st	0.6%	112	332nd	0.6%	112
333rd	0.6%	112	334th	0.6%	112
335th	0.6%	112	336th	0.6%	112
337th	0.6%	112	338th	0.6%	112
339th	0.6%	112	340th	0.6%	112
341st	0.6%	112	342nd	0.6%	112
343rd	0.6%	112	344th	0.6%	112
345th	0.6%	112	346th	0.6%	112
347th	0.6%	112	348th	0.6%	112
349th	0.6%	112	350th	0.6%	112
351st	0.6%	112	352nd	0.6%	112
353rd	0.6%	112	354th	0.6%	112
355th	0.6%	112	356th	0.6%	112
357th	0.6%	112	358th	0.6%	112
359th	0.6%	112	360th	0.6%	112
361st	0.6%	112	362nd	0.6%	112
363rd	0.6%	112	364th	0.6%	112
365th	0.6%	112	366th	0.6%	112
367th	0.6%	112	368th	0.6%	112
369th	0.6%	112	370th	0.6%	112
371st	0.6%	112	372nd	0.6%	112
373rd	0.6%	112	374th	0.6%	112
375th	0.6%	112	376th	0.6%	112
377th	0.6%	112	378th	0.6%	112
379th	0.6%	112	380th	0.6%	112
381st	0.6%	112	382nd	0.6%	112
383rd	0.6%	112	384th	0.6%	112
385th	0.6%	112	386th	0.6%	112
3			EVEN	2.6%	

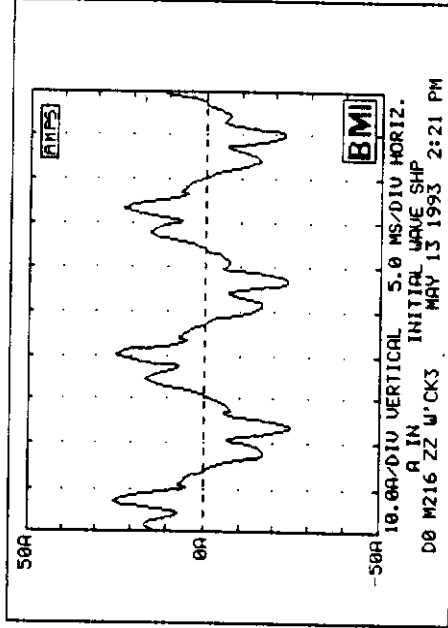
D0 M216 ZZ W'CK3 May 13 1993
 HARMONIC REPORT 2:14 PM
 A OUT (Channel 1) 16.7 - 16.9 Amps
 D0 M216 ZZ W'CK3 May 13 1993
 A OUT INITIAL WAVE SHP 2:14:33 PM



Fundamental frequency: 60.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0	2nd	1.0%	281
3rd	0.5%	96	3rd	0.2%	62
4th	0.2%	62	4th	0.2%	275
5th	0.2%	275	5th	0.3%	30
6th	0.3%	30	6th	0.4%	225
7th	0.4%	225	7th	2.1%	
8th	2.1%		EVEN		
9th					
10th					
11th					
12th					
13th					
14th					
15th					
16th					
17th					
18th					
19th					
20th					
21st					
ODD	65.0%				
THD:	65.0%				

D0 M216 ZZ W'CK3 May 13 1993
 HARMONIC REPORT 2:21 PM
 A IN (Channel 1) 12.9 - 13.1 Amps
 D0 M216 ZZ W'CK3 May 13 1993
 A IN INITIAL WAVE SHP 2:21:48 PM

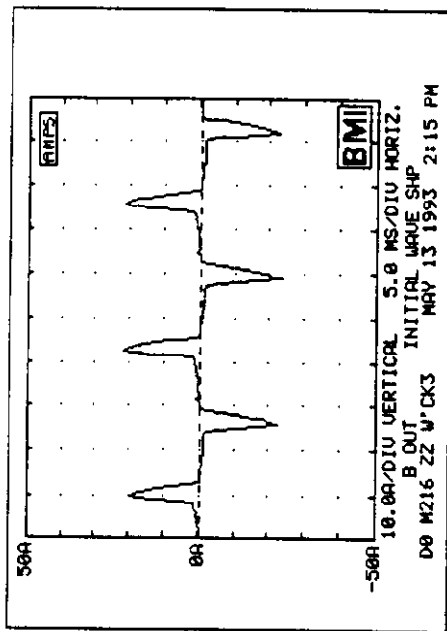


Fundamental frequency: 60.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0	2nd	2.0%	248
3rd	0.4%	248	3rd	0.5%	44
4th	0.5%	44	4th	0.3%	181
5th	0.3%	181	5th	0.2%	233
6th	0.2%	233	6th	0.3%	30
7th	0.2%	30	7th	0.4%	56
8th	0.4%	56	8th	0.4%	190
9th	0.4%	190	9th		
10th			10th		
11th			11th		
12th			12th		
13th			13th		
14th			14th		
15th			15th		
16th			16th		
17th			17th		
18th			18th		
19th			19th		
20th			20th		
21st			21st		
ODD	35.4%		EVEN	2.2%	
THD:	35.5%				

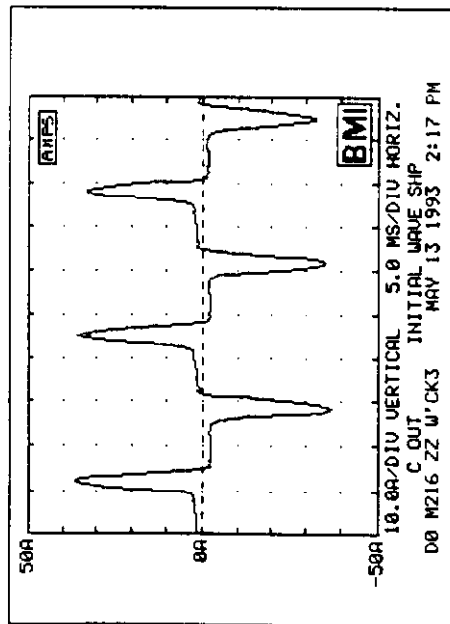
Fig. 16. Rack # M216, phase A current in the load (left) and in the line (right) with Zig-Zag transformer connected in the parallel to the load, choke in the neutral.

B OUT (Channel 2) 7.8 - 7.9 Amps
 Current:
 D0 M216 Z2 W'CK3 May 13 1993
 B OUT INITIAL WAVE SHP 2:15:49 PM



Fundamental frequency: 60.0 Hz					
HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0	2nd	4.9%	191
3rd	1.6%	152	4th	1.6%	152
5th	1.0%	81	6th	1.0%	81
7th	0.8%	69	8th	0.4%	69
9th	0.8%	21	10th	0.8%	21
11th	1.1%	174	12th	1.5%	174
13th	1.7%	36	14th	1.7%	36
15th	1.7%	36	16th	1.7%	36
17th	1.7%	36	18th	1.7%	36
19th	1.7%	36	20th	1.7%	36
21st	1.7%	36	22nd	1.7%	36
23rd	1.7%	36	24th	1.7%	36
25th	1.7%	36	26th	1.7%	36
27th	1.7%	36	28th	1.7%	36
29th	1.7%	36	30th	1.7%	36
31st	1.7%	36	32nd	1.7%	36
33rd	1.7%	36	34th	1.7%	36
35th	1.7%	36	36th	1.7%	36
37th	1.7%	36	38th	1.7%	36
39th	1.7%	36	40th	1.7%	36
41st	1.7%	36	42nd	1.7%	36
43rd	1.7%	36	44th	1.7%	36
45th	1.7%	36	46th	1.7%	36
47th	1.7%	36	48th	1.7%	36
49th	1.7%	36	50th	1.7%	36
51st	1.7%	36	52nd	1.7%	36
53rd	1.7%	36	54th	1.7%	36
55th	1.7%	36	56th	1.7%	36
57th	1.7%	36	58th	1.7%	36
59th	1.7%	36	60th	1.7%	36
61st	1.7%	36	62nd	1.7%	36
63rd	1.7%	36	64th	1.7%	36
65th	1.7%	36	66th	1.7%	36
67th	1.7%	36	68th	1.7%	36
69th	1.7%	36	70th	1.7%	36
71st	1.7%	36	72nd	1.7%	36
73rd	1.7%	36	74th	1.7%	36
75th	1.7%	36	76th	1.7%	36
77th	1.7%	36	78th	1.7%	36
79th	1.7%	36	80th	1.7%	36
81st	1.7%	36	82nd	1.7%	36
83rd	1.7%	36	84th	1.7%	36
85th	1.7%	36	86th	1.7%	36
87th	1.7%	36	88th	1.7%	36
89th	1.7%	36	90th	1.7%	36
91st	1.7%	36	92nd	1.7%	36
93rd	1.7%	36	94th	1.7%	36
95th	1.7%	36	96th	1.7%	36
97th	1.7%	36	98th	1.7%	36
99th	1.7%	36	100th	1.7%	36
101st	1.7%	36	102nd	1.7%	36
103rd	1.7%	36	104th	1.7%	36
105th	1.7%	36	106th	1.7%	36
107th	1.7%	36	108th	1.7%	36
109th	1.7%	36	110th	1.7%	36
111st	1.7%	36	112nd	1.7%	36
113rd	1.7%	36	114th	1.7%	36
115th	1.7%	36	116th	1.7%	36
117th	1.7%	36	118th	1.7%	36
119th	1.7%	36	120th	1.7%	36
121st	1.7%	36	122nd	1.7%	36
123rd	1.7%	36	124th	1.7%	36
125th	1.7%	36	126th	1.7%	36
127th	1.7%	36	128th	1.7%	36
129th	1.7%	36	130th	1.7%	36
131st	1.7%	36	132nd	1.7%	36
133rd	1.7%	36	134th	1.7%	36
135th	1.7%	36	136th	1.7%	36
137th	1.7%	36	138th	1.7%	36
139th	1.7%	36	140th	1.7%	36
141st	1.7%	36	142nd	1.7%	36
143rd	1.7%	36	144th	1.7%	36
145th	1.7%	36	146th	1.7%	36
147th	1.7%	36	148th	1.7%	36
149th	1.7%	36	150th	1.7%	36
151st	1.7%	36	152nd	1.7%	36
153rd	1.7%	36	154th	1.7%	36
155th	1.7%	36	156th	1.7%	36
157th	1.7%	36	158th	1.7%	36
159th	1.7%	36	160th	1.7%	36
161st	1.7%	36	162nd	1.7%	36
163rd	1.7%	36	164th	1.7%	36
165th	1.7%	36	166th	1.7%	36
167th	1.7%	36	168th	1.7%	36
169th	1.7%	36	170th	1.7%	36
171st	1.7%	36	172nd	1.7%	36
173rd	1.7%	36	174th	1.7%	36
175th	1.7%	36	176th	1.7%	36
177th	1.7%	36	178th	1.7%	36
179th	1.7%	36	180th	1.7%	36
181st	1.7%	36	182nd	1.7%	36
183rd	1.7%	36	184th	1.7%	36
185th	1.7%	36	186th	1.7%	36
187th	1.7%	36	188th	1.7%	36
189th	1.7%	36	190th	1.7%	36
191st	1.7%	36	192nd	1.7%	36
193rd	1.7%	36	194th	1.7%	36
195th	1.7%	36	196th	1.7%	36
197th	1.7%	36	198th	1.7%	36
199th	1.7%	36	200th	1.7%	36
201st	1.7%	36	202nd	1.7%	36
203rd	1.7%	36	204th	1.7%	36
205th	1.7%	36	206th	1.7%	36
207th	1.7%	36	208th	1.7%	36
209th	1.7%	36	210th	1.7%	36
211st	1.7%	36	212nd	1.7%	36
213rd	1.7%	36	214th	1.7%	36
215th	1.7%	36	216th	1.7%	36
217th	1.7%	36	218th	1.7%	36
219th	1.7%	36	220th	1.7%	36
221st	1.7%	36	222nd	1.7%	36
223rd	1.7%	36	224th	1.7%	36
225th	1.7%	36	226th	1.7%	36
227th	1.7%	36	228th	1.7%	36
229th	1.7%	36	230th	1.7%	36
231st	1.7%	36	232nd	1.7%	36
233rd	1.7%	36	234th	1.7%	36
235th	1.7%	36	236th	1.7%	36
237th	1.7%	36	238th	1.7%	36
239th	1.7%	36	240th	1.7%	36
241st	1.7%	36	242nd	1.7%	36
243rd	1.7%	36	244th	1.7%	36
245th	1.7%	36	246th	1.7%	36
247th	1.7%	36	248th	1.7%	36
249th	1.7%	36	250th	1.7%	36
251st	1.7%	36	252nd	1.7%	36
253rd	1.7%	36	254th	1.7%	36
255th	1.7%	36	256th	1.7%	36
257th	1.7%	36	258th	1.7%	36
259th	1.7%	36	260th	1.7%	36
261st	1.7%	36	262nd	1.7%	36
263rd	1.7%	36	264th	1.7%	36
265th	1.7%	36	266th	1.7%	36
267th	1.7%	36	268th	1.7%	36
269th	1.7%	36	270th	1.7%	36
271st	1.7%	36	272nd	1.7%	36
273rd	1.7%	36	274th	1.7%	36
275th	1.7%	36	276th	1.7%	36
277th	1.7%	36	278th	1.7%	36
279th	1.7%	36	280th	1.7%	36
281st	1.7%	36	282nd	1.7%	36
283rd	1.7%	36	284th	1.7%	36
285th	1.7%	36	286th	1.7%	36
287th	1.7%	36	288th	1.7%	36
289th	1.7%	36	290th	1.7%	36
291st	1.7%	36	292nd	1.7%	36
293rd	1.7%	36	294th	1.7%	36
295th	1.7%	36	296th	1.7%	36
297th	1.7%	36	298th	1.7%	36
299th	1.7%	36	300th	1.7%	36
301st	1.7%	36	302nd	1.7%	36
303rd	1.7%	36	304th	1.7%	36
305th	1.7%	36	306th	1.7%	36
307th	1.7%	36	308th	1.7%	36
309th	1.7%	36	310th	1.7%	36
311st	1.7%	36	312nd	1.7%	36
313rd	1.7%	36	314th	1.7%	36
315th	1.7%	36	316th	1.7%	36
317th	1.7%	36	318th	1.7%	36
319th	1.7%	36	320th	1.7%	36
321st	1.7%	36	322nd	1.7%	36
323rd	1.7%	36	324th	1.7%	36
325th	1.7%	36	326th	1.7%	36
327th	1.7%	36	328th	1.7%	36
329th	1.7%	36	330th	1.7%	36
331st	1.7%	36	332nd	1.7%	36
333rd	1.7%	36	334th	1.7%	36
335th	1.7%	36	336th	1.7%	36
337th	1.7%	36	338th	1.7%	36
339th	1.7%	36	340th	1.7%	36
341st	1.7%	36	342nd	1.7%	36
343rd	1.7%	36	344th	1.7%	36
345th	1.7%	36	346th	1.7%	36
347th	1.7%	36	348th	1.7%	36
349th	1.7%	36	350th	1.7%	36
351st	1.7%	36	352nd	1.7%	36
353rd	1.7%	36	354th	1.7%	36
355th	1.7%	36	356th	1.7%	36
357th	1.7%	36	358th	1.7%	36
359th	1.7%	36	360th	1.7%	36
361st	1.7%	36	362nd	1.7%	36
363rd	1.7%	36	364th	1.7%	36
365th	1.7%	36	366th	1.7%	36
367th	1.7%	36	368th	1.7%	36
369th	1.7%	36	370th	1.7%	36
371st	1.7%	36	372nd	1.7%	36
373rd	1.7%	36	374th	1.7%	36
375th	1.7%	36	376th	1.7%	36
377th	1.7%	36	378th	1.7%	36
379th	1.7%	36	380th	1.7%	36
381st	1.7%	36	382nd	1.7%	36
383rd	1.7%	36	384th	1.7%	36
385th	1.7%	36	386th	1.7%	36
387th	1.7%	36	388th	1.7%	36
389th	1.7%	36	390th	1.7%	36
391st	1.7%	36	392nd	1.7%	36
393rd	1.7%	36	394th	1.7%	36
395th	1.7%	36	396th	1.7%	36
397th	1.7%	36	398th	1.7%	36
399th	1.7%	36	400th	1.7%	36
401st	1.7%	36	402nd	1.7%	36
403rd	1.7%	36	404th	1.7%	36
405th	1.7%	36	406th	1.7%	36
407th	1.7%	36	408th	1.7%	36
409th	1.7%	36	410th	1.7%	36
411st	1.7%	36	412nd	1.7%	36
413rd	1.7%	36	414th	1.7%	36
415th	1.7%	36	416th	1.7%	36
417th	1.7%	36	418th	1.7%	36
419th	1.7%	36	420th	1.7%	36
421st	1.7%	36	422nd	1.7%	36
423rd	1.7%	36	424th	1.7%	36
425th	1.7%	36	426th	1.7%	36
427th	1.7%	36	428th	1.7%	36
429th	1.7%	36	430th	1.7%	36
431st	1.7%	36	432nd	1.7%	36
433rd	1.7%	36	434th	1.7%	36
435th	1.7%	36	436th	1.7%	36
437th	1.7%	36	438th	1.7%	36
439th	1.7%	36	440th	1.7%	36
441st	1.7%	36	442nd	1.7%	36
443rd	1.7%	36	444th	1.7%	36
445th	1.7%	36	446th	1.7%	36
447th	1.7%	36	448th	1.7%	36
449th	1.7%	36	450th	1.7%	36
451st	1.7%	36	452nd	1.7%	36
453rd	1.7%	36	454th	1.7%	36
455th	1.7%	36	456th	1.7%	36
457th	1.7%	36	458th	1.7%	36
459th	1.7%	36	460th	1.7%	36
461st	1.7%	36	462nd	1.7%	36
463rd	1.7%	36	464th	1.7%	36
465th	1.7%	36	466th	1.7%	36
467th	1.7%	36	468th	1.7%	36
469th	1.7%	36	470th	1.7%	36
471st	1.7%	36	472nd	1.7%	36
473rd	1.7%	36	474th	1.7%	36
475th	1.7%	36	476th	1.7%	36
477th	1.7%	36	478th	1.7%	

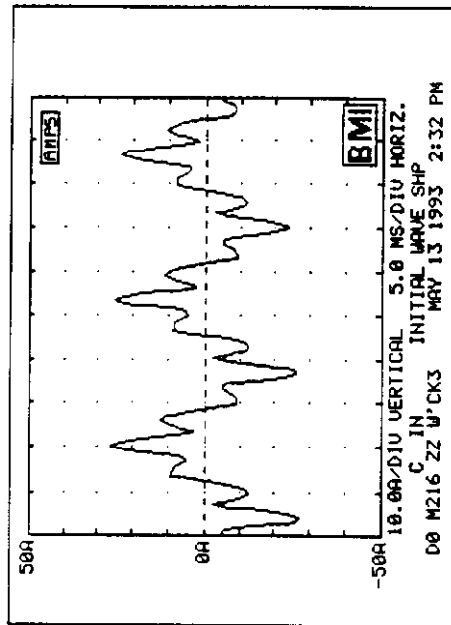
C OUT (Channel 3) 13.9 - 14.4 Amps
Current:
D0 M216 ZZ W'CK3 May 13 1993
C OUT INITIAL WAVE SHP 2:17:08 PM



Fundamental frequency: 60.0 Hz

Harm	PCT	Phase	Harm	PCT	Phase
FUND	100%	0	2nd	1.7%	339°
3rd	75.8%	152°	4th		
5th	45.3%	310°	6th	0.6%	222°
7th	17.5%	105°	8th		
9th	0.8%	327°	10th		
11th	5.0%	233°	12th		
13th	3.2%	26°	14th		
15th			16th		
17th	1.8%	150°	18th		
19th	1.6%	310°	20th		
21st	0.6%	140°	22nd		
23rd	0.8%	14°	24th		
25th	0.9%	200°	26th		
27th	0.4%	16°	28th	0.5%	57°
29th	0.5%	260°	30th	0.4%	218°
31st	0.8%	93°	32nd		
33rd	0.7%	255°			
QDD	90.3%		EVEN	2.0%	
THD:	90.3%				

C IN (Channel 3) 12.1 - 12.3 Amps
Current:
D0 M216 ZZ W'CK3 May 13 1993
C IN INITIAL WAVE SHP 2:32:09 PM



Fundamental frequency: 60.0 Hz

Harm	PCT	Phase	Harm	PCT	Phase
FUND	100.0%	0	2nd	1.8%	2
3rd	47.4%	190	4th	0.5%	324
5th	9.6%	175	6th	0.3%	55
7th	3.1%	155	8th		
9th	2.2%	140	10th		
11th	1.7%	130	12th		
13th	1.8%	110	14th		
15th	0.8%	90	16th		
17th	0.8%	70	18th		
19th	0.8%	50	20th		
21st	0.8%	30	22nd		
23rd	0.8%	10	24th		
25th	0.8%	0	26th		
27th	0.8%	330	28th		
29th	0.8%	310	30th		
31st	0.8%	290	32nd		
33rd	0.8%	270			
QDD	49.5%		EVEN	2.0%	
THD:	49.5%				

Fig. 18. Rack # M216, phase C current in the load (left) and in the line (right) with Zig-Zag transformer connected in the parallel to the load, choke in the neutral.

APPENDIX # 1.Calculation of choke parameters.**Design goal parameters.**

Inductance - 1 mH
 Maximum working RMS current - 7 A
 Winding rating - 46 A RMS
 Prevailing frequency - 180 Hz

The choke core has to be unsaturated during normal operation mode, but is allowed to saturate under the worst case conditions. The worst case conditions occur when the circuit breaker protecting the Zig-Zag transformer trips off.

Core selection.

To select a core we can start with calculating the inductance for a core with a cross section area of 1 in². From an Arnold Engineering catalog we can choose two tape wound cut cores: AH-21 made out of 4 mill Silectron and AA-36 made out of 12 mill Silectron.

Core parameters

Core type	AH-21	AA-36
Area cross section, in ² (cm ²)	1.031 (6.65)	1.13 (7.29)
Tape thickness, mill	4	12
Stack factor	0.9	0.95
Window width F, in (cm)	0.75 (1.9)	0.75 (1.9)
Window length G, in (cm)	2.312 (5.873)	2.312 (5.873)
Build up E, in (cm)	0.75 (1.9)	0.75 (1.9)
Weight, lb.	2.13	2.45
Strip width D, in (cm)	1.375 (3.49)	1.5 (3.81)

1. AH-21 CORE**Choke calculations.**

The B-H curve for a 4 mill Silectron tape wound core shows a maximum induction of 16 kGauss to 18 kGauss for uncut cores. 12 kGauss is a safe choice for the working magnetic field induction value. As one can see from Arnold data 12 kGauss induction requires a magnetizing force H of approximately 1 Oersted

or 80 A·turn/m. The mean magnetic path length $\mathcal{L}$ can be calculated as:

$$\mathcal{L} = 2 \cdot F + 2 \cdot G + 2.9 \cdot E = 21.1 \text{ [cm]} = 0.211 \text{ [m]}$$

We now can calculate the maximum permissible amount of A·turns $H_{\max}^*$ for this core:

$$H_{\max}^* = H \cdot \mathcal{L} = 80 \cdot 0.211 = 16.88 \text{ [A·turns]}$$

Next we will calculate the required amount of turns N necessary to yield an inductance value L of 1 mH at 12 kGauss:

$$N = \frac{L \cdot I}{\Phi} = \frac{L \cdot I}{B \cdot S_{\text{eff}}} = \frac{L \cdot I}{B \cdot S \cdot k_{St}} = \frac{9.87 \cdot 10^{-3}}{1.2 \cdot 0.9 \cdot 6.65 \cdot 10^{-4}} = 13.74,$$

where $S_{\text{eff}} = k_{St} \cdot S$ is an effective area cross section,
 k_{St} is a stack factor and

$I = I_{\text{RMS}} \cdot \sqrt{2}$ is the peak value of the working current.

Because the number of turns has to be integer we choose $N = 14$. This gives us the amount of A·turns H^* equal to:

$$H^* = I \cdot N = 9.87 \cdot 14 = 138.18 \text{ [A·turns]}$$

It is obvious that without an air gap the core will be in deep saturation because H^* is much greater than maximum permissible $H_{\max}^*$. The required air gap can be calculated from the assumption that all the difference between H^* and $H_{\max}^*$ is applied to the air gap.

$$H_{\text{air}}^* = H^* - H_{\max}^* = 121.3 \text{ [A·turns]}$$

Magnetic field induction in the air B_{air} is equal to the induction in the core:

$$B_{\text{air}} = \mu_0 \cdot H_{\text{air}} = \frac{\mu_0 \cdot H_{\text{air}}^*}{\Delta} = 1.2 \text{ [Tesla]},$$

where Δ is the air gap length. From this we can calculate Δ :

$$\Delta = \frac{\mu_0 \cdot H_{\text{air}}^*}{B_{\text{air}}} = \frac{4 \cdot \pi \cdot 121.3 \cdot 10^{-7}}{1.2} = 1.3 \cdot 10^{-4} \text{ [m]} = 0.13 \text{ [mm]}.$$

That means we have to put one 0.065 mm shim at each core cut.

Core losses.

The biggest core losses occur during the worst case scenario at the maximum choke current of 46 A_{RMS}. The instantaneous current I is equal to:

$$I = I_{RMS} \cdot \sqrt{2} = 65 \text{ [A].}$$

The A·turns H^* , produced by this current are equal to:

$$H^* = I \cdot N = 65 \cdot 14 = 910 \text{ [A·turns]}$$

and they will be distributed between core material and air gap according to the ratio M between calculated above H^*_{max} and H^*_{air} :

$$M = \frac{H^*_{AIR}}{H^*_{MAX}} = \frac{121.3}{16.88} = 7.2, \text{ from which}$$

$$H^*_{max} = H^* / (M + 1) = H^* / 8.2 = 910 / 8.2 = 110 \text{ [A·turns]}$$

Now we can calculate the magnetizing force H caused by the worst case current in the core material:

$$H = H^*_{max} / \mathcal{L} = 110 / 0.211 = 521 \text{ [A·turn/m]} = 6.5 \text{ [Oersted].}$$

From B-H curve we can find the magnetic field inductance value $B_m = 16$ Tesla at 6.5 Oersted. This magnetic field will create 3.5 W of losses per pound of the core material at 180 Hz. The total losses in the core are equal to 7.5 W or 0.5 W per in². The estimated core temperature rise is about 50°C.

2. AA-36 CORE

The same calculations made for AA-36 core released following results:

$$N = 12$$

$$\Delta = 0.114 \text{ mm}$$

$$W = 14.21 \text{ W}$$

AA-36 core causes about 15 W worst case losses, which is about 0.9 W per in² and corresponding core temperature rise is about 90°C, compared to 50°C for core AH-21, which is not acceptable. AH-21 is the only choice.

Winding choice.

The coil winding which has to be rated for 46 A_{RMS} and can be made from AWG # 8 building wire, 600 V, 90°C.