Fermi National Accelerator Laboratory

FERMILAB-TM-1854

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

L. Beverly, R. Hance, A. Kristalinski and A. Visser

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

September 1993

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

Disclaimer

TM # 1854
CAT. 6013.000

08/19/93

L. Beverly
R. Hance
A. Kristalinski
A. Visser

Comments about the use of a Zig-Zag transformer to reduce the neutral current created by unbalanced nonlinear loads.

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 transformers[1], delta connected primary windings[2], 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 transformer[5]. L-C filters can create undesirable resonances, which will lead to an increase in harmonic currents.

Another solution[6] 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^{o} to 220^{o}. 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^{o} 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.

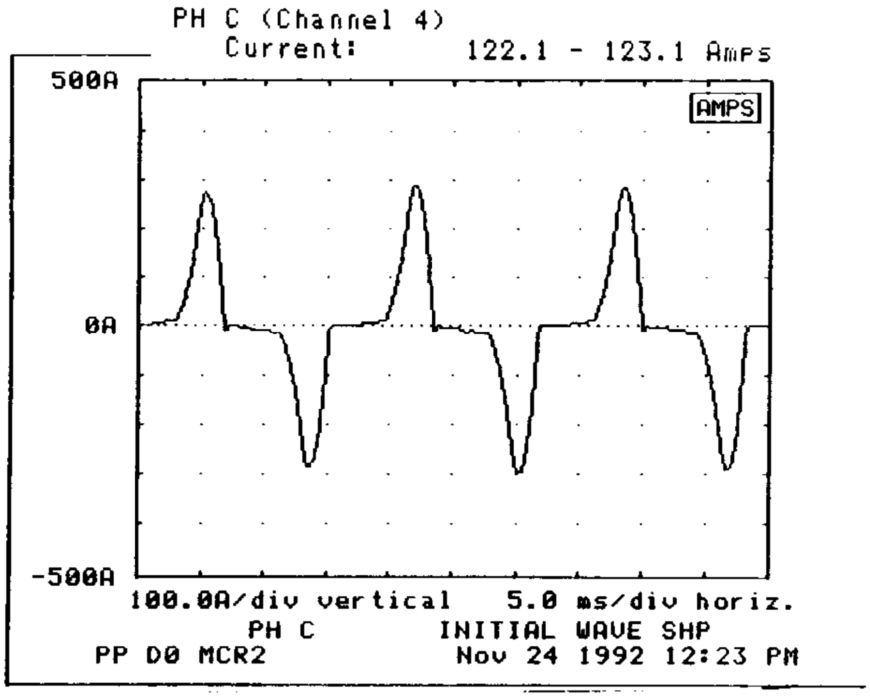
ACKNOWLEDGMENTS

We would like to thank Tim Martin, Julius Lentz, Walt Jaskierny, Steve Morrison, Rick Moore and Demetrius Zafiropolus, 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.

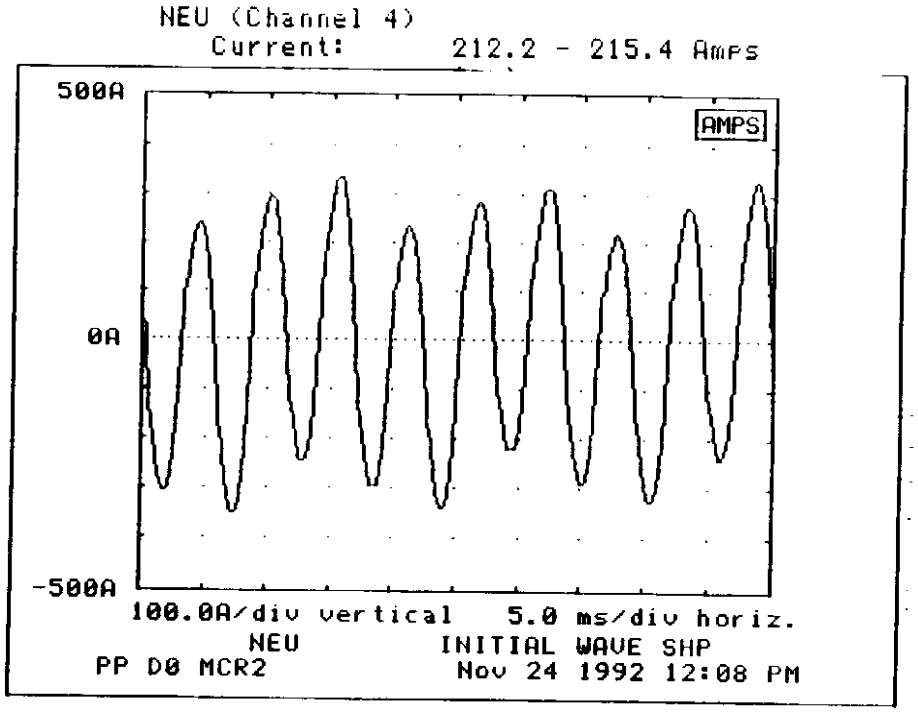
3. Peter Gross, Design and Performance of Harmonic Filters, Power Quality, Premier VI, 1990.
4. Michael Z. Lowenstein, Improving Power Factor in the Presence of Harmonics Using Low-Voltage Tuned Filters, IEEE Transactions on Industry Applications, Vol. 29, No. 3, May/June 1993.
5. Robert H. Lee, Line current harmonics effects on transformers, Teledyne Crittenden, July 1991.
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°	2nd		
3rd	65.5%	167°	4th	0.3%	15°
5th	30.6%	327°	6th		
7th	10.6%	97°	8th		
9th	4.4%	207°	10th		
11th	2.6%	267°	12th		
13th	3.5%	30°	14th		
15th	1.7%	156°	16th		
17th	1.1%	245°	18th		
19th	0.9%	325°	20th		
21st	1.0%	77°	22nd		
23rd	0.6%	178°	24th		
25th	0.8%	266°	26th	0.3%	241°
27th	0.5%	35°	28th	0.3%	13°
29th	0.4%	119°	30th	0.4%	106°
31st	0.4%	215°	32nd	0.4%	209°
33rd	0.5%	318°			
ODD	73.3%		EVEN	0.8%	

THD: 73.4%

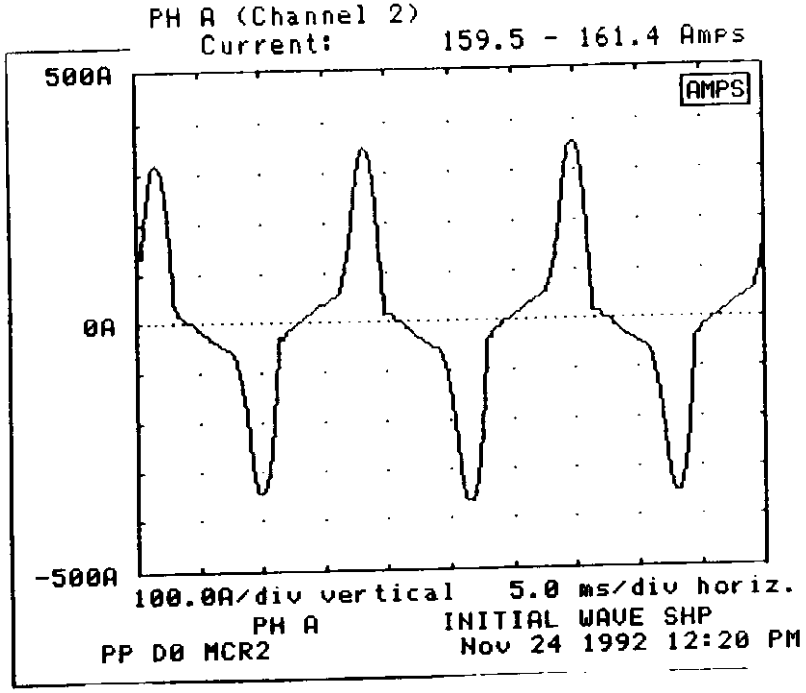


Fundamental frequency: 60.0 Hz

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

THD: 554.3%

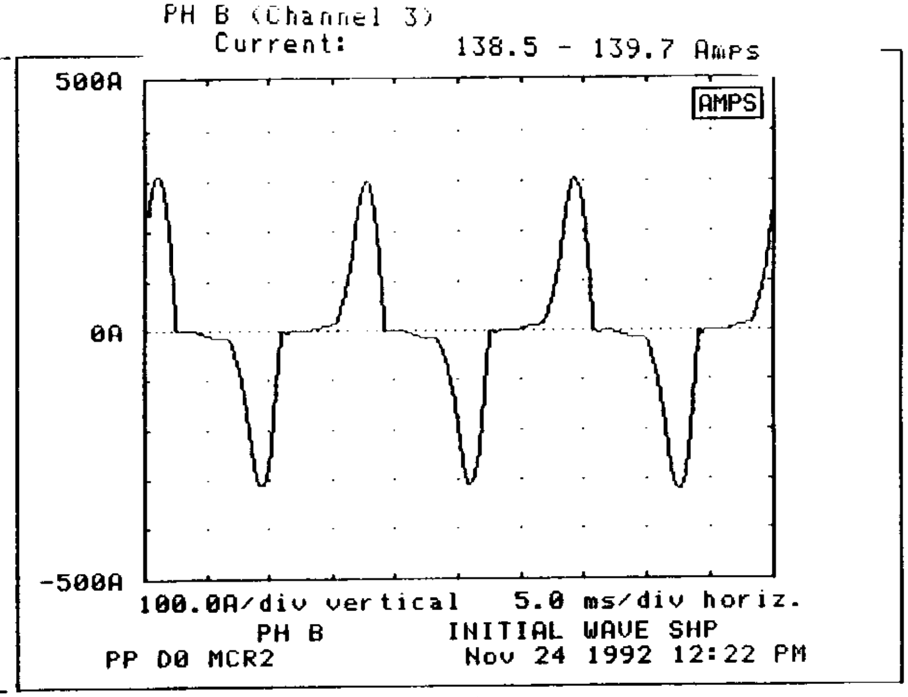
Fig. 1. Panel #1, phase C and neutral currents.



Fundamental frequency: 60.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0°	2nd	0.5%	40°
3rd	51.8%	156°	4th		
5th	25.1%	313°	6th		
7th	7.2%	81°	8th		
9th	4.0%	151°	10th		
11th	3.5%	253°	12th		
13th	2.9%	9°	14th		
15th	1.4%	125°	16th		
17th	1.0%	189°	18th		
19th	1.0%	298°	20th		
21st	0.8%	42°	22nd		
23rd	0.6%	141°	24th		
25th	0.4%	227°	26th		
27th	0.5%	329°	28th	0.3%	131°
29th	0.3%	62°	30th	0.2%	207°
31st	0.4%	150°	32nd	0.3%	296°
33rd	0.3%	246°			
ODD	58.4%		EVEN	0.7%	

THD: 58.4%



Fundamental frequency: 60.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0°	2nd		
3rd	61.5%	168°	4th		
5th	26.5%	325°	6th		
7th	8.3%	85°	8th		
9th	3.4%	176°	10th		
11th	3.6%	254°	12th		
13th	2.9%	31°	14th		
15th	1.3%	111°	16th		
17th	1.5%	218°	18th		
19th	0.9%	321°	20th		
21st	0.7%	46°	22nd		
23rd	0.7%	115°	24th		
25th	0.6%	249°	26th	0.3%	252°
27th	0.5%	326°	28th	0.2%	69°
29th	0.6%	76°	30th	0.3%	69°
31st	0.5%	162°	32nd	0.4%	186°
33rd	0.4%	277°			
ODD	67.8%		EVEN	0.6%	

THD: 67.8%

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

January 5, 1993
Revised: March 8, 1993

Fermilab

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. 3. Zig-Zag transformer specification.

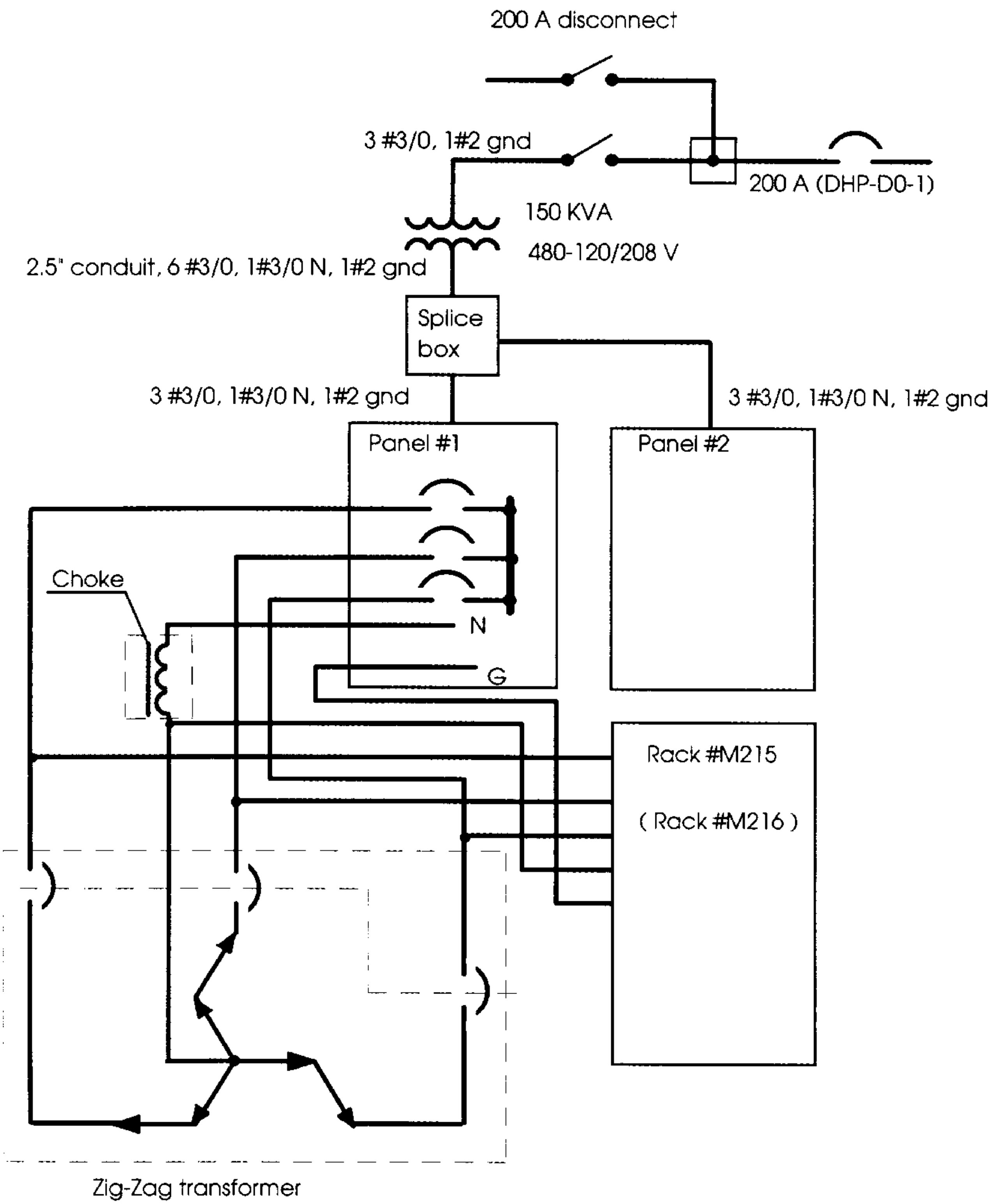
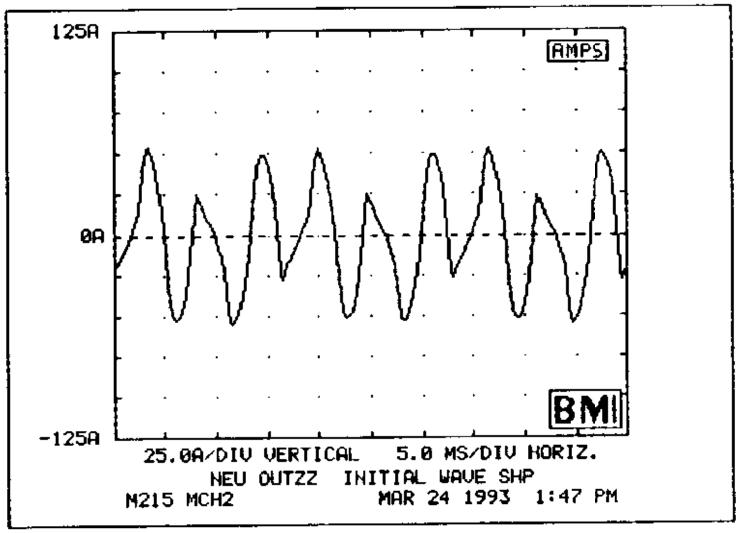


Fig. 4. Single line Distribution Diagram.

NEU_OUTZZ (Channel 3)
Current: 32.4 - 32.7 Amps

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

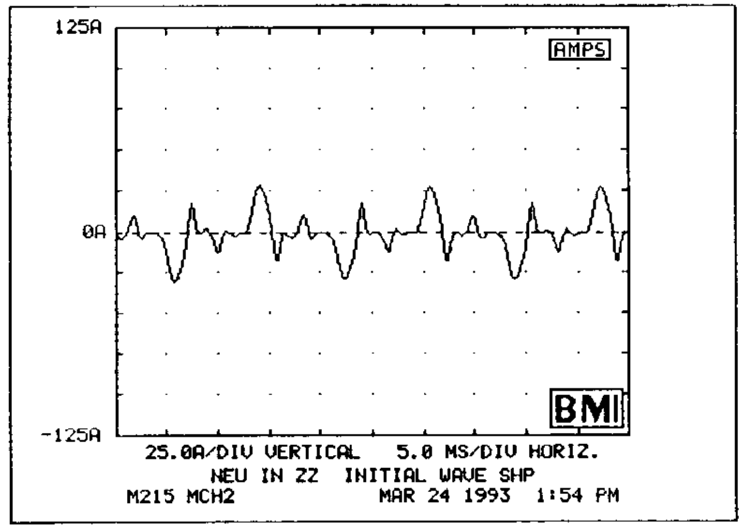


HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0	2nd	1.9%	280
3rd	252.6%	35	4th	1.4%	272
5th	56.2%	17	6th	0.8%	285
7th	23.7%	225	8th		
9th	18.2%	50	10th		
11th	18.3%	26	12th		
13th	6.8%	213	14th		
15th	1.8%	14	16th		
17th	4.6%	42	18th		
19th	3.1%	209	20th		
21st	2.2%	81	22nd		
23rd	0.7%	355	24th		
25th	1.7%	240	26th		
27th	2.0%	157	28th	0.6%	199
29th			30th	0.8%	139
31st			32nd		
33rd	0.7%	177			
ODD	261.3%		EVEN	2.7%	

THD: 261.3%

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



Fundamental frequency: 60.0 Hz

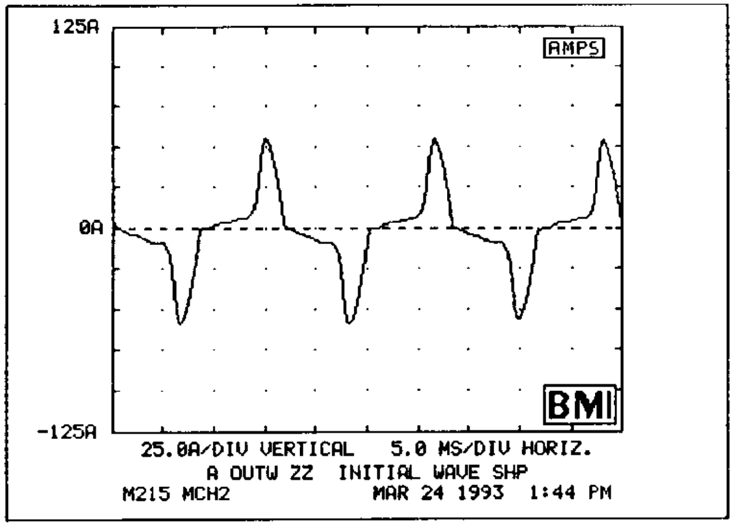
HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0	2nd	3.6%	218
3rd	128.0%	199	4th	2.1%	111
5th	98.8%	344	6th	1.7%	351
7th	39.2%	172	8th		
9th	40.6%	257	10th	1.0%	5
11th	32.8%	293	12th	1.1%	316
13th	11.5%	97	14th		
15th	17.0%	196	16th		
17th	8.4%	268	18th	0.5%	198
19th	4.6%	45	20th		
21st	4.9%	149	22nd		
23rd	2.9%	221	24th	0.8%	329
25th	2.2%	33	26th	0.8%	126
27th	1.5%	69	28th		
29th	1.5%	206	30th	0.7%	321
31st	0.4%	145	32nd	0.6%	172
33rd	1.8%	352			
ODD	176.0%		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 1:44 PM
A OUTW ZZ (Channel 1)
Current: 24.2 - 24.4 Amps

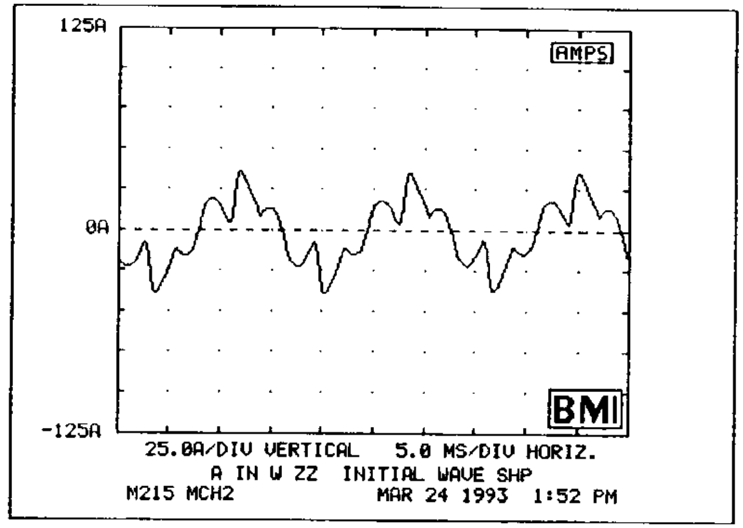
M215 MCH2 Mar 24 1993
A OUTW ZZ INITIAL WAVE SHP 1:44:54 PM



HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0	2nd	0.9%	86
3rd	60.0%	146	4th		
5th	32.4%	302	6th	0.3%	63
7th	10.2%	114	8th		
9th	5.3%	1	10th		
11th	6.3%	172	12th		
13th	3.2%	325	14th		
15th	0.4%	214	16th		
17th	1.9%	55	18th		
19th	1.4%	192	20th		
21st	0.4%	271	22nd		
23rd	0.8%	322	24th		
25th	0.8%	86	26th	0.2%	34
27th	0.4%	96	28th	0.2%	180
29th	0.3%	226	30th	0.3%	190
31st	0.4%	330	32nd	0.3%	291
33rd	0.3%	59			
ODD	69.6%		EVEN	1.1%	
THD:	69.6%				

M215 MCH2 Mar 24 1993
HARMONIC REPORT 1:51 PM
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

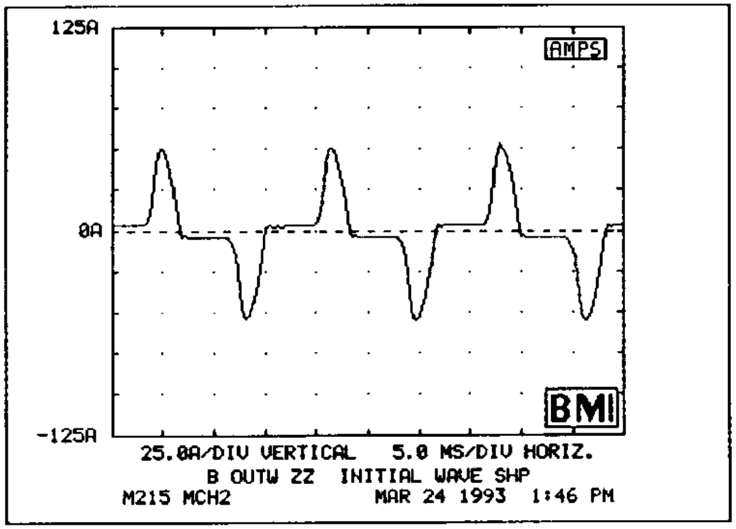


HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0	2nd	1.4%	176
3rd	13.5%	62	4th	0.3%	210
5th	37.5%	321	6th	0.2%	162
7th	9.8%	137	8th	0.2%	97
9th	8.4%	1	10th		
11th	7.2%	217	12th		
13th	3.6%	12	14th		
15th	2.0%	256	16th		
17th	2.0%	124	18th		
19th	1.2%	263	20th		
21st	0.4%	106	22nd		
23rd	0.9%	55	24th		
25th	0.7%	166	26th	0.2%	295
27th	0.3%	297	28th		
29th	0.4%	335	30th	0.2%	144
31st	0.3%	82	32nd	0.3%	273
33rd	0.3%	255			
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.

B OUTW ZZ (Channel 2)
Current: 22.8 - 22.9 Amps

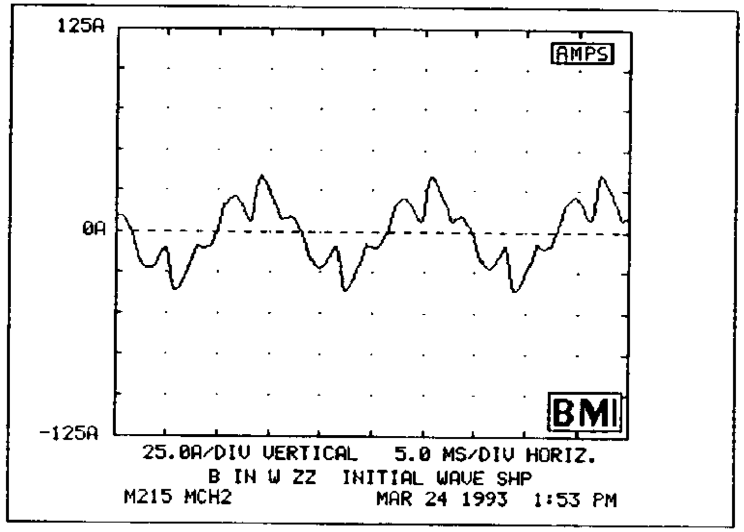
M215 MCH2 Mar 24 1993
B OUTW ZZ INITIAL WAVE SHP 1:46:10 PM



HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0	2nd	1.2%	70
3rd	69.8%	150	4th	0.7%	158
5th	35.1%	309	6th	0.6%	302
7th	7.7%	125	8th		
9th	6.9%	37	10th	0.4%	19
11th	7.0%	197	12th	0.3%	208
13th	2.7%	339	14th		
15th	1.2%	315	16th		
17th	2.4%	95	18th		
19th	1.2%	224	20th		
21st	0.4%	243	22nd		
23rd	0.9%	352	24th		
25th	0.6%	109	26th		
27th	0.4%	187	28th		
29th	0.5%	248	30th	0.2%	153
31st	0.3%	348	32nd	0.3%	242
33rd	0.2%	32			
ODD	79.2%		EVEN	1.7%	
THD:	79.2%				

B IN W ZZ (Channel 2)
Current: 19.0 - 19.2 Amps

M215 MCH2 Mar 24 1993
B IN W ZZ INITIAL WAVE SHP 1:53:22 PM

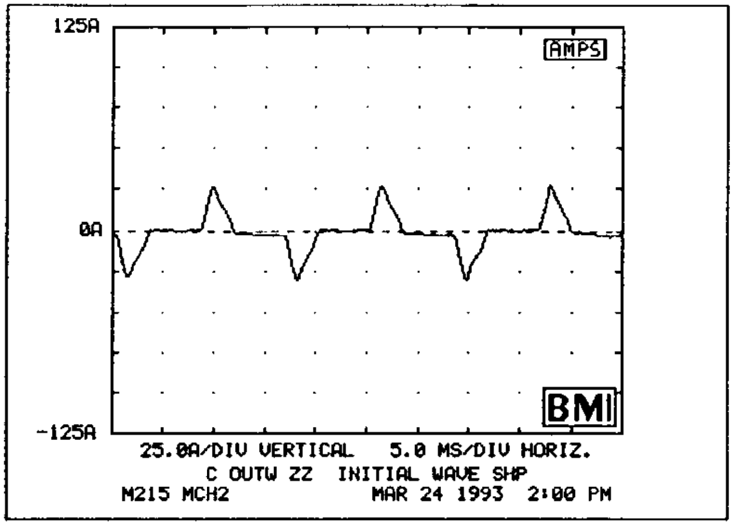


HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0	2nd	1.8%	108
3rd	12.7%	56	4th	0.8%	312
5th	33.2%	281	6th	0.7%	145
7th	8.8%	89	8th	0.4%	325
9th	8.0%	305	10th		
11th	6.7%	132	12th	0.3%	319
13th	2.7%	266	14th		
15th	2.1%	164	16th		
17th	2.2%	354	18th		
19th	1.4%	123	20th		
21st	0.5%	349	22nd		
23rd	0.9%	225	24th		
25th	0.6%	333	26th	0.2%	78
27th	0.2%	137	28th		
29th	0.5%	97	30th	0.2%	229
31st	0.4%	167	32nd	0.4%	300
ODD	38.4%		EVEN	2.2%	
THD:	38.4%				

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.

C OUTW ZZ (Channel 2)
Current: 10.9 - 10.9 Amps

M215 MCH2 Mar 24 1993
C OUTW ZZ INITIAL WAVE SHP 2:00:16 PM



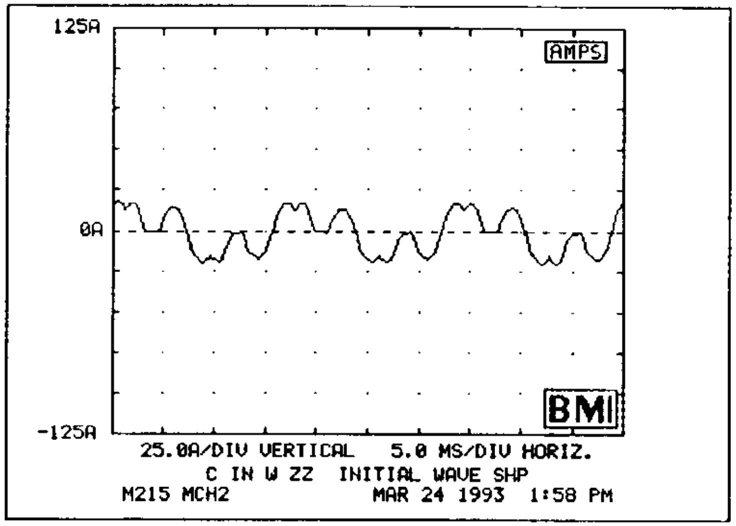
Fundamental frequency: 60.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0	2nd	2.8%	186
3rd	70.3%	151	4th	0.3%	24
5th	36.1%	315	6th	1.0%	153
7th	13.9%	157	8th	0.4%	357
9th	13.7%	8	10th		
11th	9.6%	173	12th		
13th	2.4%	322	14th		
15th	1.1%	316	16th		
17th	0.7%	35	18th		
19th	2.0%	95	20th		
21st	2.1%	253	22nd		
23rd			24th		
25th	1.2%	12	26th		
27th	1.3%	151	28th		
29th	0.3%	232	30th	0.5%	212
31st	0.5%	219	32nd	0.6%	55
ODD	82.1%		EVEN	3.1%	

THD: 82.1%

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

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



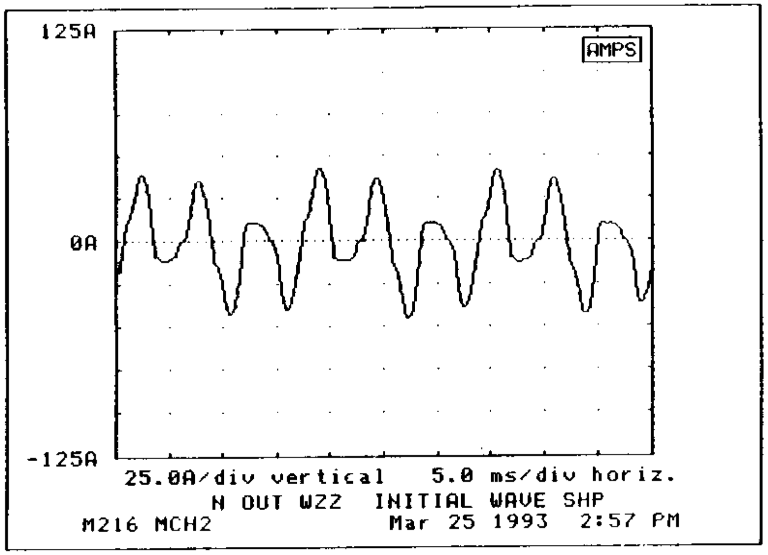
Fundamental frequency: 60.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0	2nd	2.3%	28
3rd	78.5%	296	4th	0.5%	263
5th	26.6%	350	6th	0.6%	288
7th	10.5%	216	8th	0.3%	209
9th	4.2%	110	10th	0.4%	51
11th	7.8%	258	12th		
13th	1.9%	60	14th		
15th	3.8%	102	16th		
17th	0.9%	207	18th		
19th	1.4%	252	20th		
21st	2.1%	3	22nd		
23rd			24th		
25th	1.0%	198	26th	0.3%	38
27th			28th	0.5%	167
29th			30th	0.4%	274
31st	0.6%	127	32nd	0.3%	61
33rd	0.6%	353			
ODD	84.1%		EVEN	2.6%	

THD: 84.2%

Fig. 8. Rack # M215, phase C current in the load (left) and in the line (right) with Zig-Zag transformer connected in the parallel to the load.

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

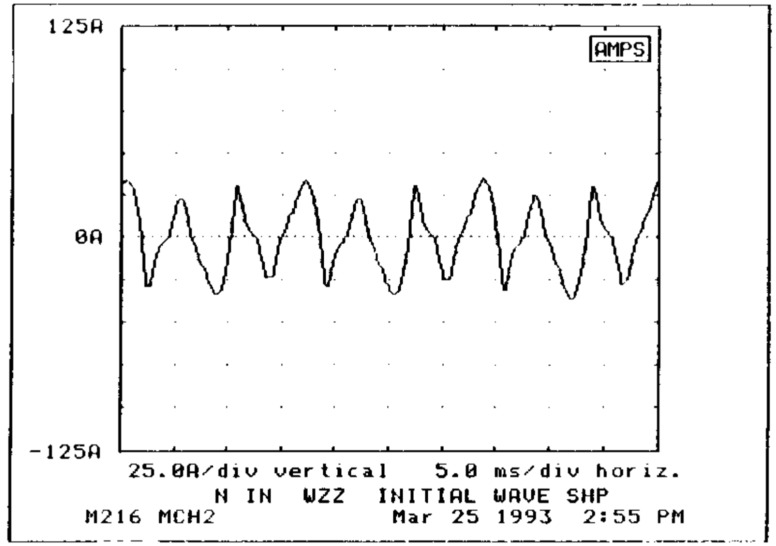


Fundamental frequency: 60.0 Hz

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

THD: 280.9%

N IN WZZ (Channel 2)
Current: 19.7 - 19.9 Amps



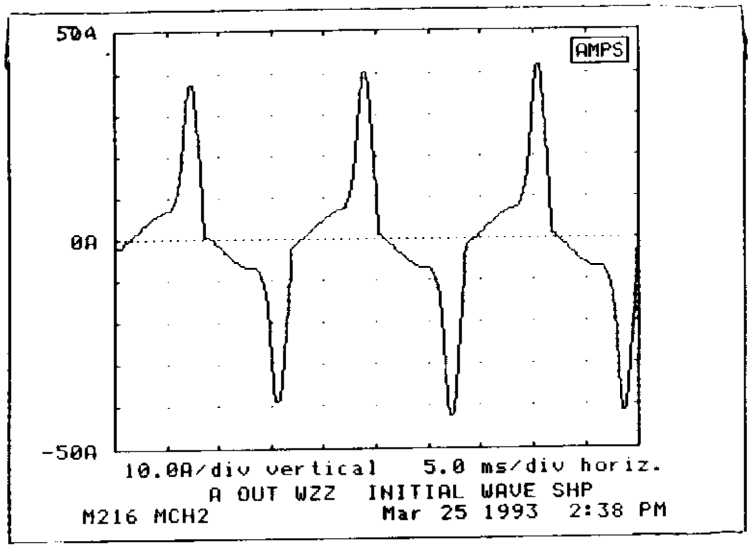
Fundamental frequency: 60.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0°	2nd	4.4%	238°
3rd	252.7%	220°	4th	1.9%	24°
5th	51.5%	325°	6th	2.7%	307°
7th	53.0%	138°	8th		
9th	33.6%	188°	10th		
11th	14.3%	302°	12th	0.5%	266°
13th	11.5%	57°	14th		
15th	5.2%	145°	16th		
17th	5.8%	275°	18th		
19th	0.9%	42°	20th		
21st	4.6%	105°	22nd		
23rd	0.8%	52°	24th		
25th	0.7%	40°	26th	0.5%	82°
27th	2.6%	73°	28th	1.8%	146°
29th	0.5%	53°	30th		
31st			32nd	0.7%	64°
33rd	2.1%	16°			
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 WZZ (Channel 4)
Current: 16.2 - 16.4 Amps

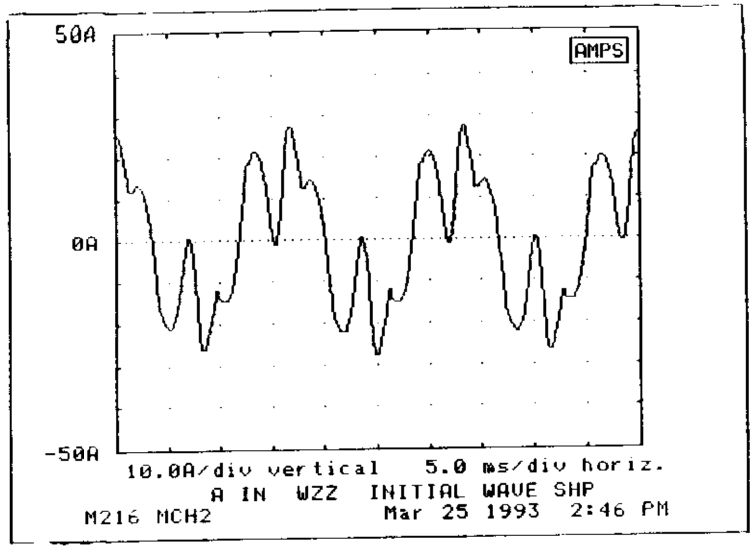


Fundamental frequency: 60.0 Hz

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°			
ODD	69.2%		EVEN	2.1%	

THD: 69.2%

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



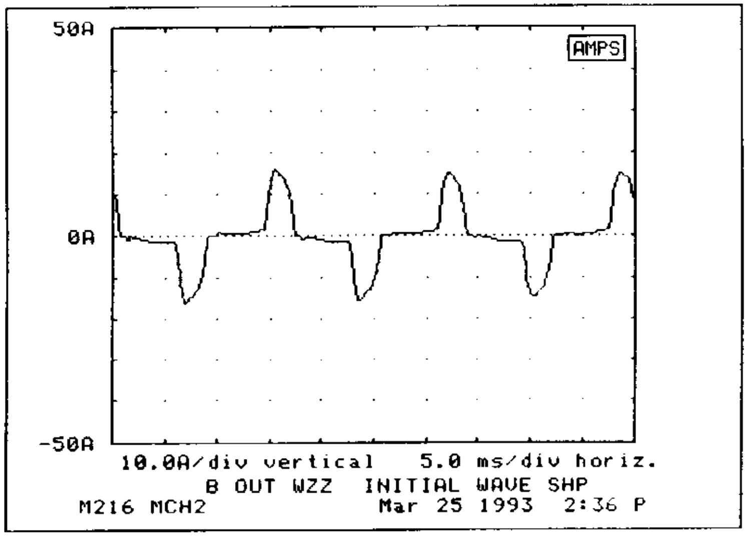
Fundamental frequency: 60.0 Hz

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°			
ODD	66.5%		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 OUT WZZ (Channel 2)
Current: 6.7 - 6.9 Amps

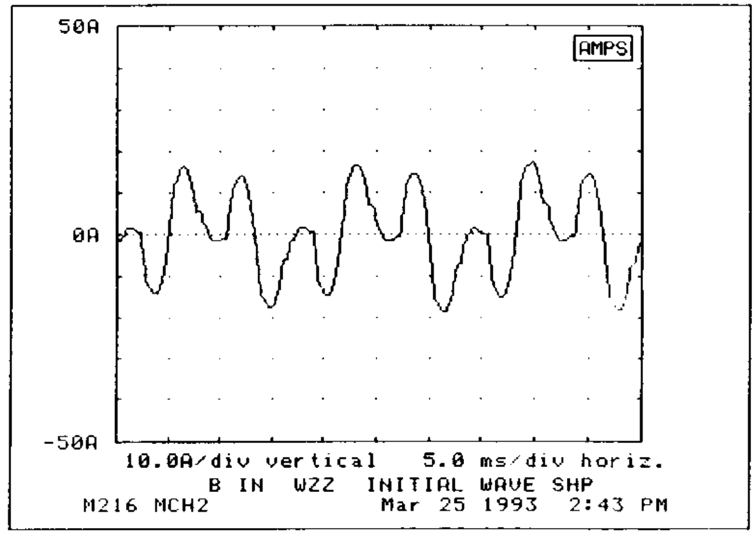


Fundamental frequency: 60.0 Hz

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%	94°	16th		
17th	3.8%	180°	18th		
19th	1.7%	339°	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%

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



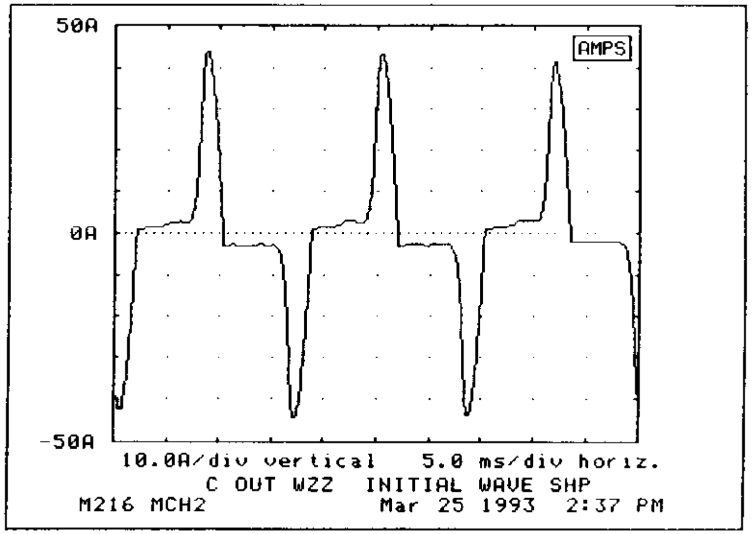
Fundamental frequency: 60.0 Hz

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

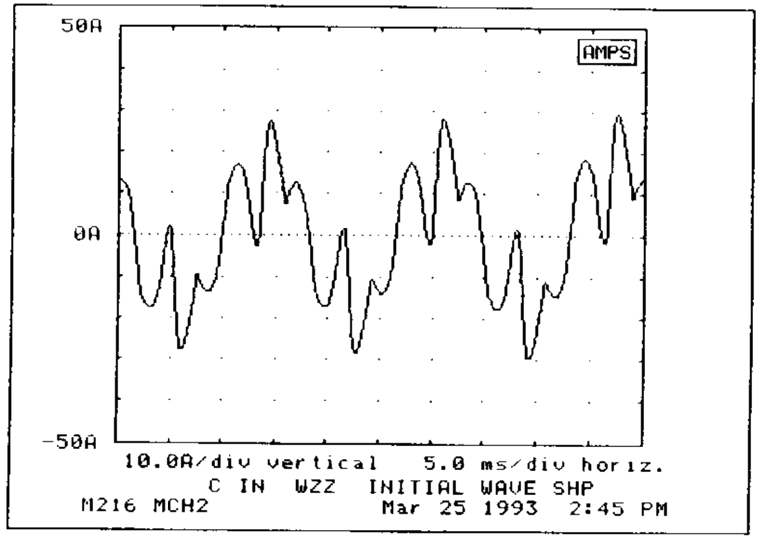


Fundamental frequency: 60.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0°	2nd	1.8%	353°
3rd	76.7%	153°	4th		
5th	48.1%	311°	6th	0.7%	274°
7th	21.0%	110°	8th		
9th	3.7%	286°	10th	0.3%	261°
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		
25th	0.6%	227°	26th	0.2%	184°
27th	0.7%	336°	28th	0.2%	8°
29th	0.7%	66°	30th	0.3%	45°
31st	0.4%	178°	32nd	0.3%	158°
33rd	0.3%	237°			
ODD	93.3%		EVEN	2.0%	

THD: 93.3%

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



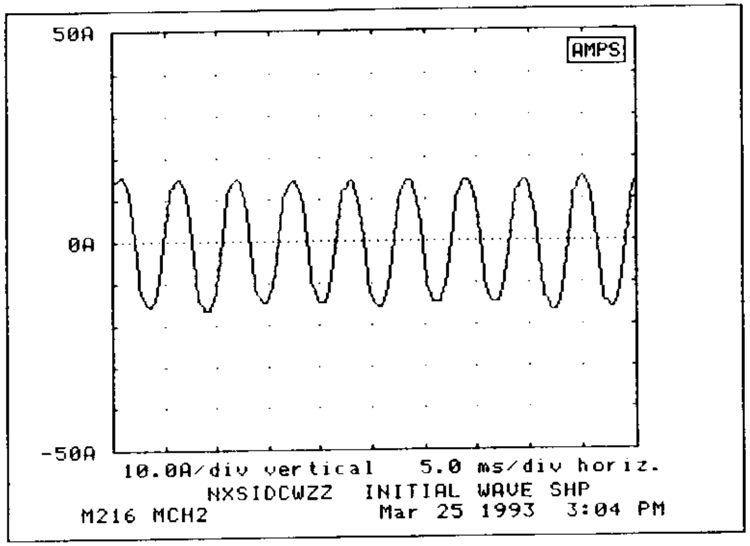
Fundamental frequency: 60.0 Hz

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.

NXSIDCWZZ (Channel 3)
Current: 11.8 - 11.8 Amps

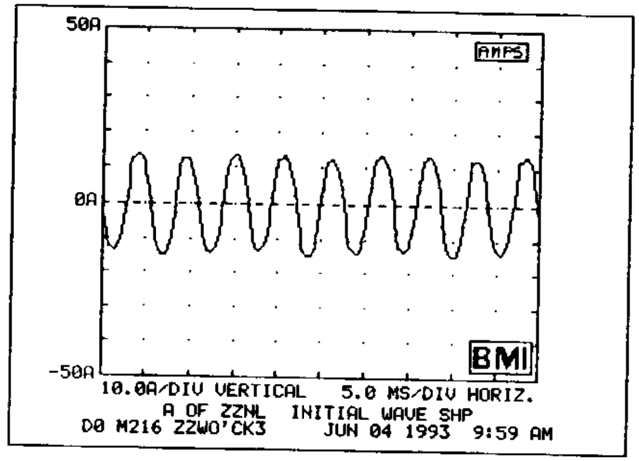


Fundamental frequency: 180.0 Hz

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 ZZWO'CK3 Jun 04 1993
HARMONIC REPORT 9:59 AM
A OF ZZNL (Channel 1)
Current: 10.8 - 10.8 Amps

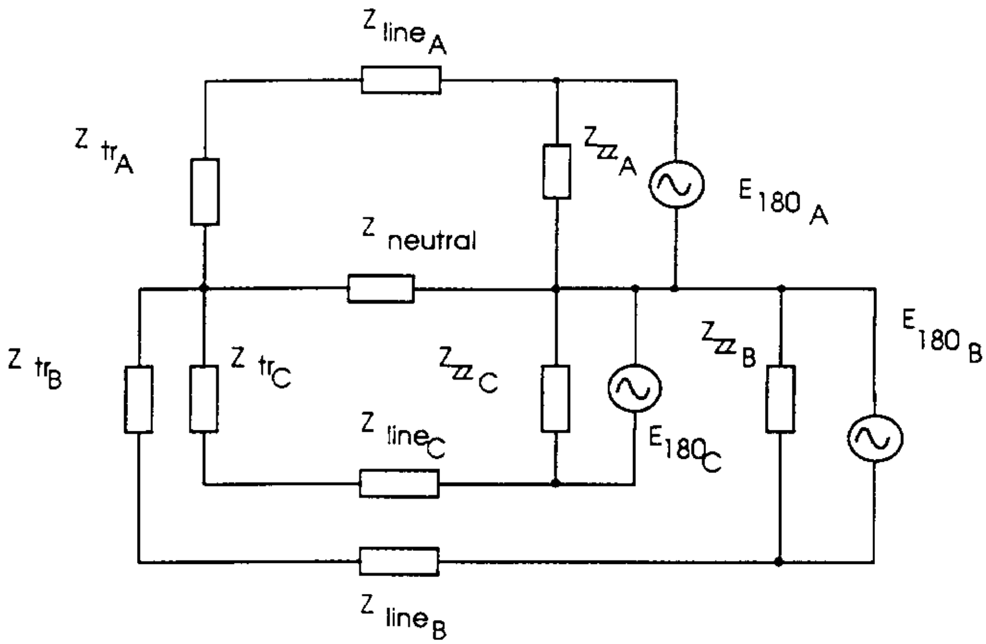
D0 M216 ZZWO'CK3 Jun 04 1993
A OF ZZNL INITIAL WAVE SHP 9:59:22 AM



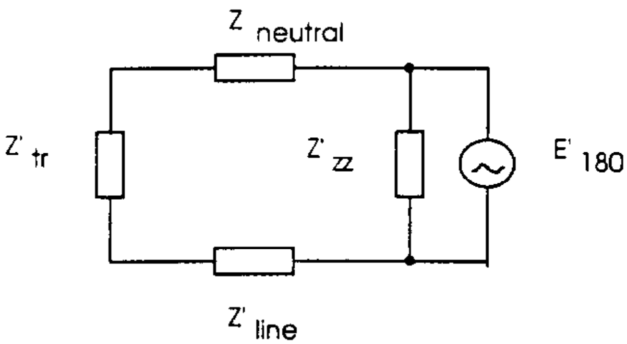
Fundamental frequency: 180.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0	2nd	0.4%	72
3rd	8.9%	340	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, rack disconnected, 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:



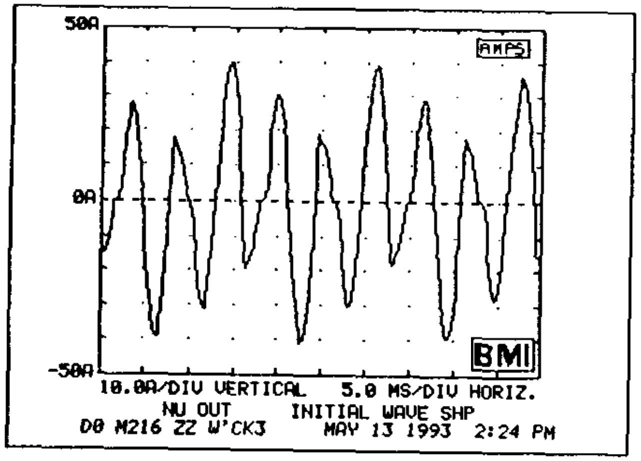
Because all three phases are symmetrical: $Z'_{tr} = Z_{tr} / 3$; $Z'_{ZZ} = Z_{ZZ} / 3$; $Z'_{line} = Z_{line} / 3$; $E'_{180} = E_{180} / 3$.

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 ZZ W'CK3 May 13 1993

NU OUT INITIAL WAVE SHP 2:24:22 PM



Fundamental frequency: 60.0 Hz

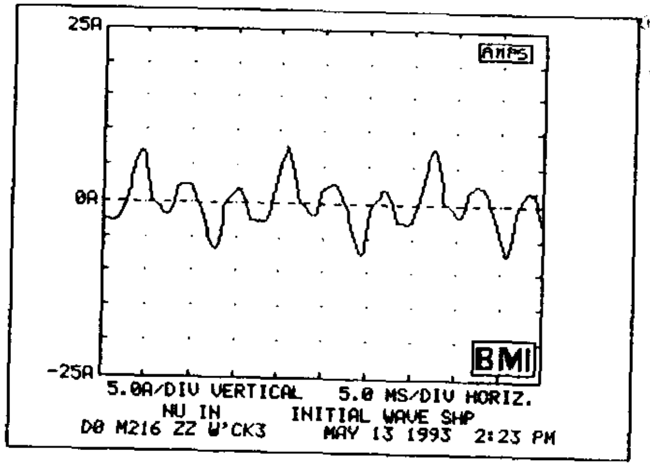
HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0	2nd	1.8%	117
3rd	262.1%	283	4th	1.6%	112
5th	42.8%	171	6th		
7th	39.5%	301	8th		
9th	8.8%	68	10th		
11th	5.1%	349	12th		
13th	11.4%	108	14th		
15th	6.3%	247	16th		
17th	1.5%	29	18th		
19th	4.5%	275	20th		
21st	3.4%	28	22nd		
23rd	2.6%	258	24th		
25th	2.0%	48	26th		
27th	1.0%	25	28th	0.9%	207
29th	0.8%	110	30th		
31st	1.4%	200	32nd	0.6%	112
33rd	1.9%	254			
ODD	269.1%		EVEN	2.6%	

THD: 269.1%

NU IN (Channel 2)
Current: 3.4 - 3.4 Amps

D0 M216 ZZ W'CK3 May 13 1993

NU IN INITIAL WAVE SHP 2:23:05 PM



Fundamental frequency: 60.0 Hz

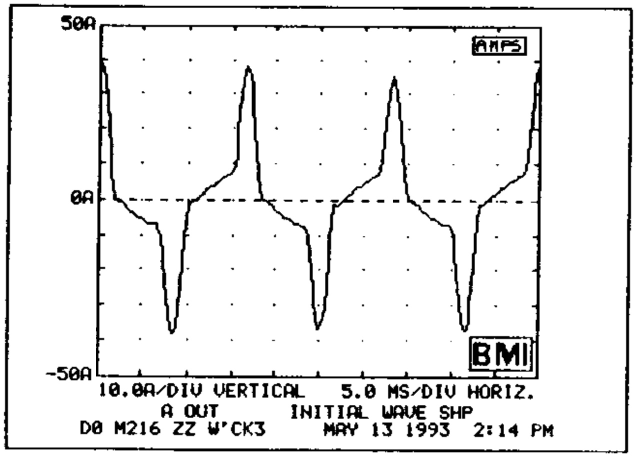
HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0	2nd	13.3%	287
3rd	162.8%	245	4th	1.8%	243
5th	28.5%	78	6th	3.4%	107
7th	21.1%	325	8th	0.9%	72
9th	17.7%	85	10th	1.2%	278
11th	3.2%	216	12th	0.7%	287
13th	5.6%	120	14th	1.0%	69
15th	3.0%	211	16th		
17th	2.0%	279	18th		
19th	0.9%	279	20th		
21st	2.6%	298	22nd		
23rd	1.0%	349	24th		
25th	0.9%	30	26th		
27th	1.4%	86	28th		
29th			30th		
31st	0.6%	137	32nd	0.5%	300
33rd	0.5%	203			
ODD	167.7%		EVEN	14.0%	

THD: 168.3%

Fig .15. Rack # M216, neutral 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.

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

D0 M216 ZZ W'CK3 May 13 1993
A OUT INITIAL WAVE SHP 2:14:33 PM



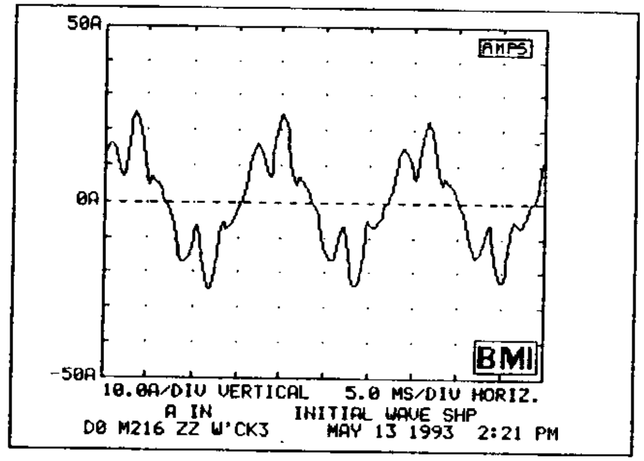
Fundamental frequency: 60.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0	2nd	1.9%	281
3rd	55.0%	141	4th	0.5%	96
5th	32.0%	292	6th		
7th	12.3%	80	8th		
9th	1.0%	165	10th	0.2%	62
11th	3.0%	214	12th		
13th	1.7%	5	14th		
15th	0.3%	312	16th		
17th	0.8%	99	18th		
19th			20th		
21st	0.8%	207	22nd		
23rd	1.0%	354	24th		
25th	0.4%	127	26th	0.2%	275
27th	0.2%	20	28th		
29th	0.6%	244	30th	0.3%	30
31st	0.3%	46	32nd	0.4%	225
ODD	65.0%		EVEN	2.1%	

THD: 65.0%

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

D0 M216 ZZ W'CK3 May 13 1993
A IN INITIAL WAVE SHP 2:21:48 PM



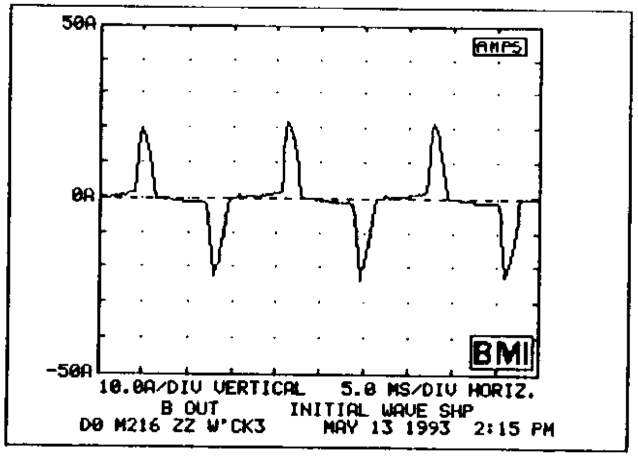
Fundamental frequency: 60.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0	2nd	2.0%	248
3rd	9.4%	65	4th		
5th	30.2%	259	6th	0.5%	44
7th	14.9%	70	8th	0.3%	181
9th	2.9%	155	10th		
11th	2.9%	154	12th		
13th	3.2%	333	14th		
15th	1.0%	52	16th		
17th	1.1%	35	18th		
19th	1.0%	244	20th		
21st	0.2%	94	22nd		
23rd	0.7%	220	24th		
25th	0.7%	24	26th	0.2%	233
27th	0.4%	18	28th	0.3%	30
29th	0.6%	72	30th	0.4%	56
31st	0.5%	188	32nd	0.4%	190
33rd	0.4%	247			
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)
Current: 7.8 - 7.9 Amps
D0 M216 ZZ W'CK3 May 13 1993
B OUT INITIAL WAVE SHP 2:15:49 PM

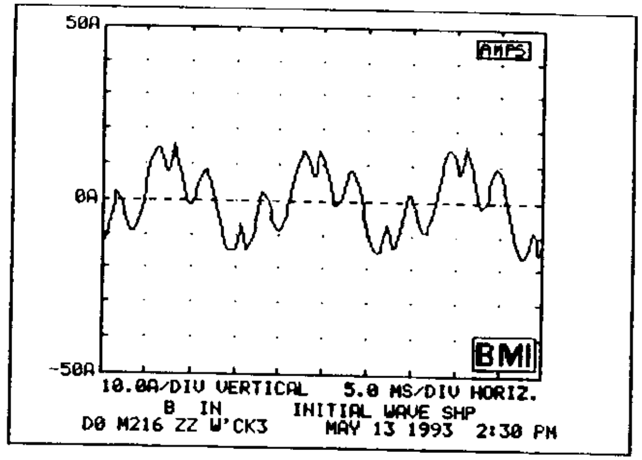


Fundamental frequency: 60.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0	2nd	4.9%	191
3rd	75.0%	158	4th	1.6%	3
5th	53.2%	321	6th	2.3%	152
7th	29.5%	131	8th	1.0%	336
9th	11.7%	316	10th	0.6%	81
11th	7.8%	197	12th		
13th	10.0%	28	14th		
15th	8.0%	199	16th	0.4%	69
17th	3.8%	9	18th		
19th	1.8%	237	20th		
21st	2.3%	83	22nd		
23rd	2.1%	247	24th		
25th	1.8%	27	26th	0.8%	21
27th	1.2%	168	28th		
29th	0.3%	7	30th	1.1%	174
31st	1.2%	249	32nd	1.5%	3
33rd	1.7%	36			
ODD	98.6%		EVEN	6.2%	

THD: 98.8%

B IN (Channel 2)
Current: 9.5 - 9.6 Amps
D0 M216 ZZ W'CK3 May 13 1993
B IN INITIAL WAVE SHP 2:30:52 PM



Fundamental frequency: 60.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0	2nd	2.6%	168
3rd	55.5%	257	4th	0.9%	55
5th	38.0%	271	6th	0.9%	187
7th	17.6%	57	8th	0.7%	48
9th	5.3%	248	10th	0.3%	101
11th	5.6%	108	12th		
13th	4.1%	290	14th		
15th	3.5%	94	16th		
17th	2.5%	267	18th		
19th	0.6%	92	20th		
21st	1.1%	349	22nd		
23rd	1.1%	47	24th		
25th	1.0%	177	26th	0.5%	245
27th	0.4%	316	28th	0.3%	14
29th	0.4%	184	30th	0.7%	250
31st	0.6%	1	32nd	1.0%	84
33rd	0.6%	177			
ODD	70.2%		EVEN	3.3%	

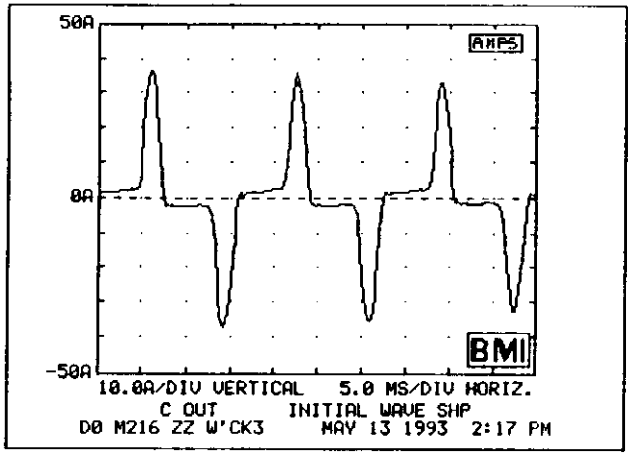
THD: 70.3%

Fig. 17. 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, choke in the neutral.

C OUT (Channel 3)
Current: 13.9 - 14.4 Amps

D0 M216 ZZ W'CK3 May 13 1993

C OUT INITIAL WAVE SHP 2:17:08 PM



Fundamental frequency: 60.0 Hz

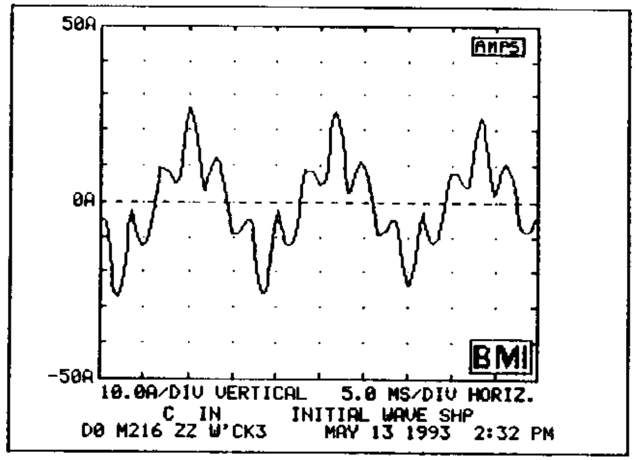
Harm	PCT	Phase	Harm	PCT	Phase
FUND	100%	0	2 nd	1.7%	339°
3 rd	75.8%	152°	4 th		
5 th	45.3%	310°	6 th	0.6%	222°
7 th	17.5%	109°	8 th		
9 th	0.8%	327°	10 th		
11 th	5.0%	233°	12 th		
13 th	3.2%	26°	14 th		
15 th			16 th		
17 th	1.8%	150°	18 th		
19 th	1.6%	310°	20 th		
21 st	0.6%	140°	22nd		
23 rd	0.8%	14°	24 th		
25 th	0.9%	200°	26 th		
27 th	0.4%	16°	28 th	0.5%	57°
29 th	0.5%	280°	30 th	0.4%	218°
31 st	0.8%	93°	32 nd		
33 rd	0.7%	255°			
ODD	90.3%		EVEN	2.0%	

THD: 90.3%

C IN (Channel 3)
Current: 12.1 - 12.3 Amps

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	8.0%	190	4th	0.5%	324
5th	47.4%	17	6th	0.5%	35
7th	9.6%	179	8th		
9th	2.3%	355	10th		
11th	5.3%	8	12th		
13th	1.2%	148	14th		
15th	1.7%	319	16th		
17th	1.8%	336	18th		
19th	1.0%	170	20th		
21st	0.9%	320	22nd		
23rd	1.0%	299	24th		
25th	0.5%	125	26th		
27th	0.3%	269	28th	0.3%	157
29th	0.4%	270	30th	0.3%	279
31st	0.5%	89	32nd	0.2%	266
33rd	0.5%	221			
ODD	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 in^2. 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 $\mathscr{L}$ can be calculated as:

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

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

$H^*_{max} = H \cdot \mathscr{L} = 80 \cdot 0.211 = 16.88$ [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:

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

where $S_{eff} = k_{St} \cdot S$ is an effective area cross section,
k_{St} is a stack factor and
$I = I_{RMS} \cdot \sqrt{2}$ 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:

$H^* = I \cdot N = 9.87 \cdot 14 = 138.18$ [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.

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

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

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

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

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

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:

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

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

$H^* = I \cdot N = 65 \cdot 14 = 910$ [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}:

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

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

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

$H = H^*_{max}/\mathscr{L} = 110/0.211 = 521$ [A·turn/m] = 6.5 [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 in^2. The estimated core temperature rise is about 50^oC.

2. AA-36 CORE

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

$N = 12$

$\Delta = 0.114$ mm

W = 14.21 W

AA-36 core causes about 15 W worst case losses , which is about 0.9 W per in^2 and corresponding core temperature rise is about 90^oC, compared to 50^oC for core AH-21, which is not acceptible. 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^{o}C.