Harmonics in Low Voltage Three-Phase Four-Wire Electric Distribution Systems and Filtering Solutions

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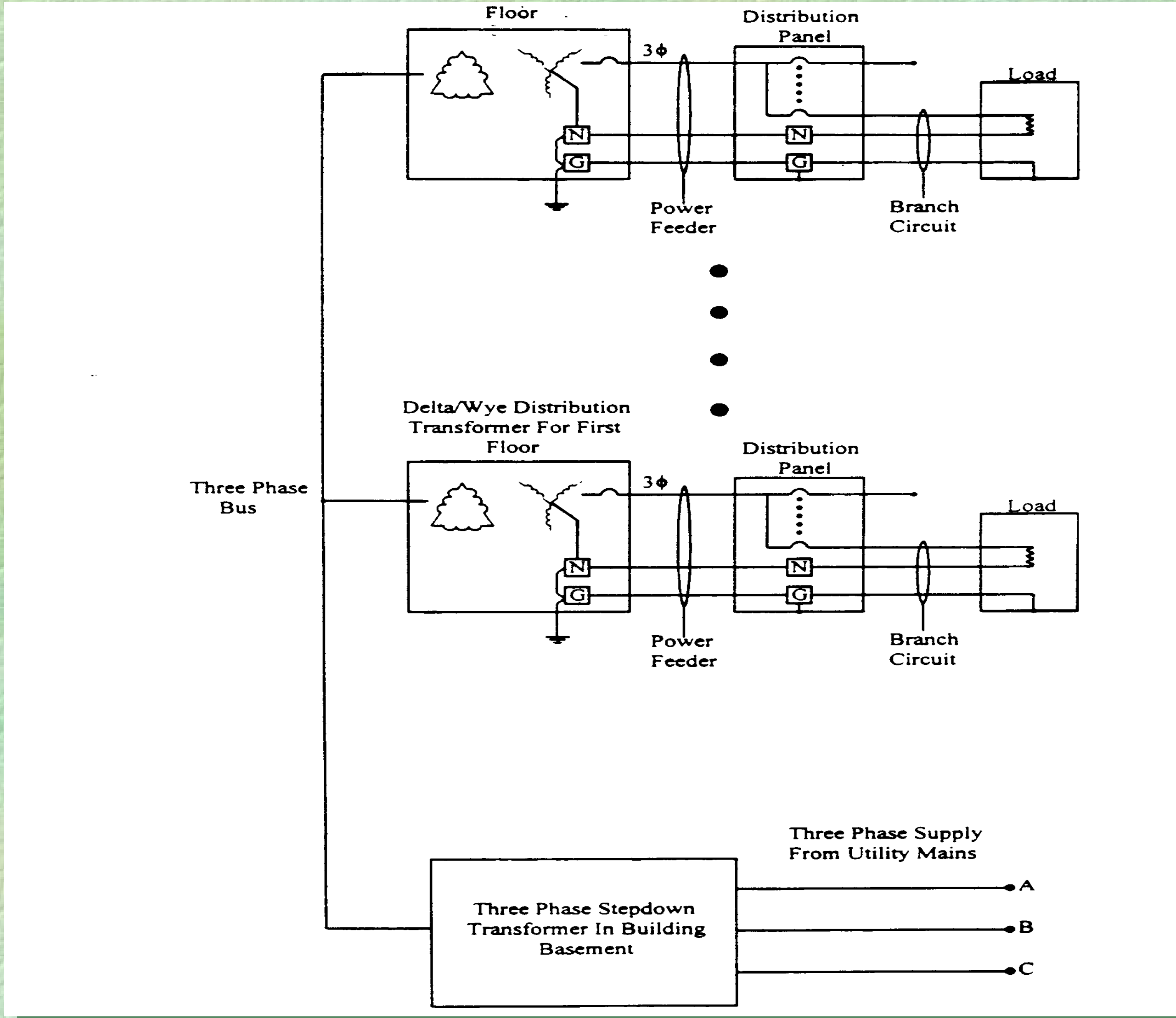
Outline

1. Introduction
2. Harmonic Current Sources
3. Case Studies
4. Solutions:
   - Derating
   - Passive Approach
   - Active Approach
5. Conclusions

Introduction

Typical Building Power Distribution Scheme



Harmonic Current Sources

Harmonic Producing Equipment in Office Buildings

Copy machines	**Recorders**
Electric typewriters	**Televisions**
Light fixture ballasts	**Video tape players**
Personal computers	**SCR drives for motors**
Computer systems	**SCR drives for elevators**
Computer terminals	**UPS systems**
Audio visual equipment	Laboratory testing equipment

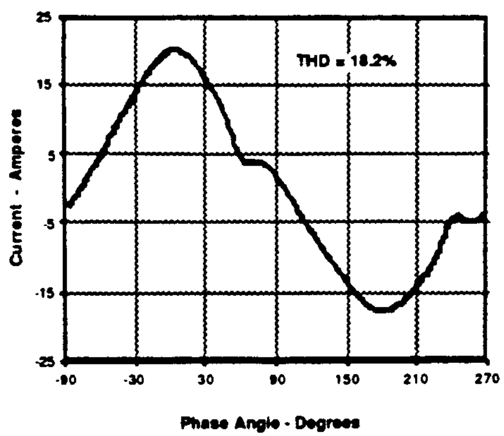
Harmonic Related Problems in Buildings

- Overheating and damage to neutral conductors
- Overheating and damage to panel board feeders
- Line voltage distortion
- Higher Common mode voltage
- Nuisance tripping of circuit breakers
- Overheating and premature failure of distribution transformers

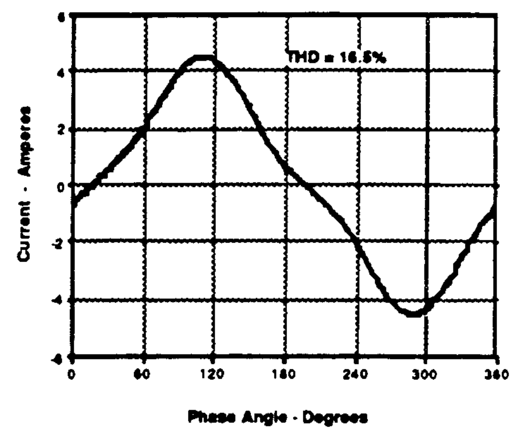
Case Studies

Typical Current Waveforms of Appliances

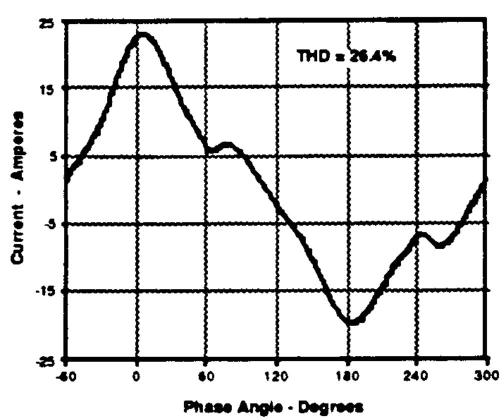
Microwave Oven Current Waveform #1



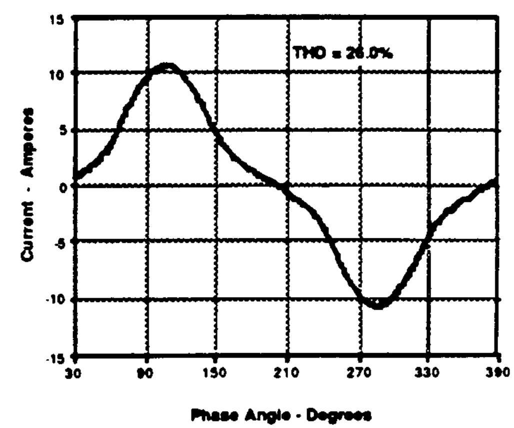
Weed Eater Current Waveform



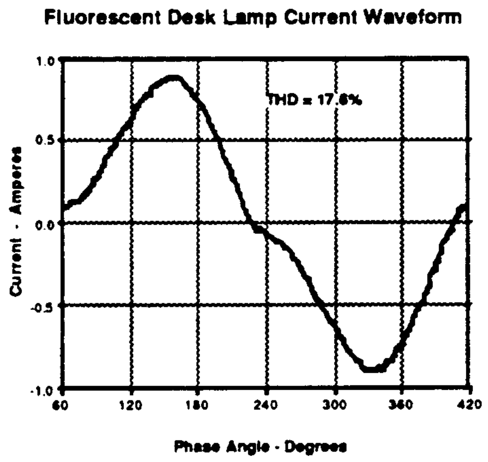
Microwave Oven Current Waveform #2

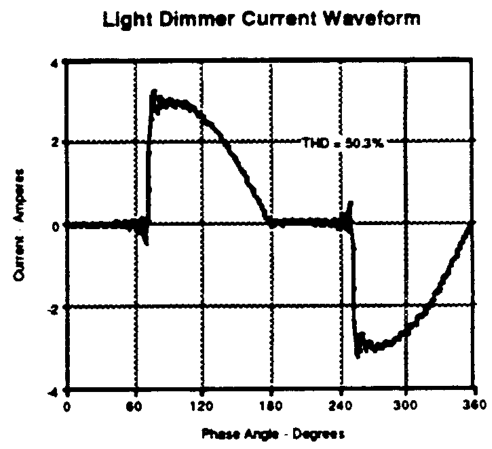


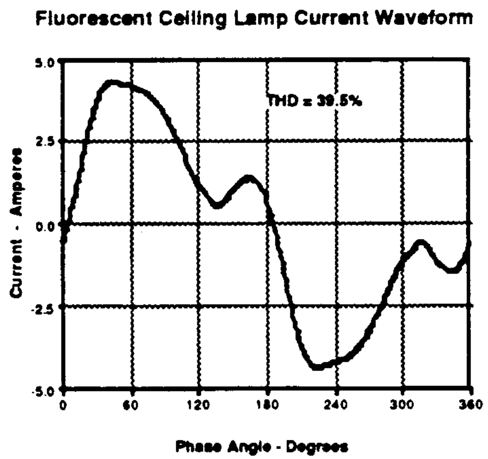
Vacuum Cleaner Current Waveform

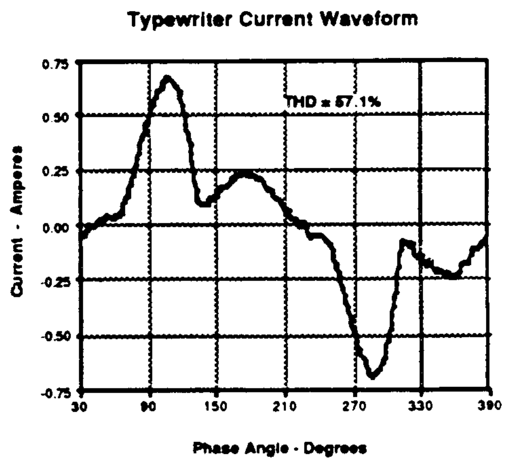


Typical Current Waveforms of Appliances. Contd.

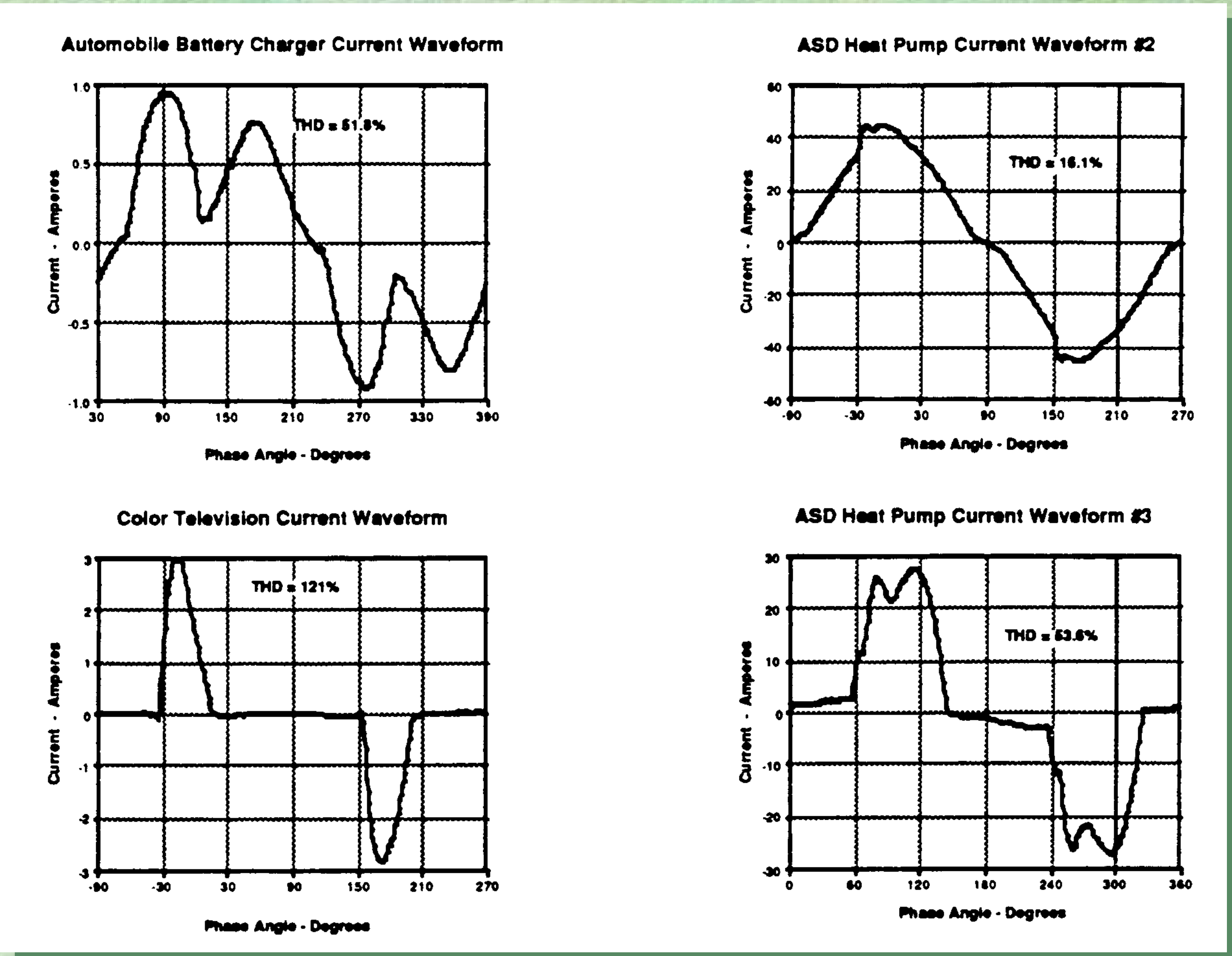




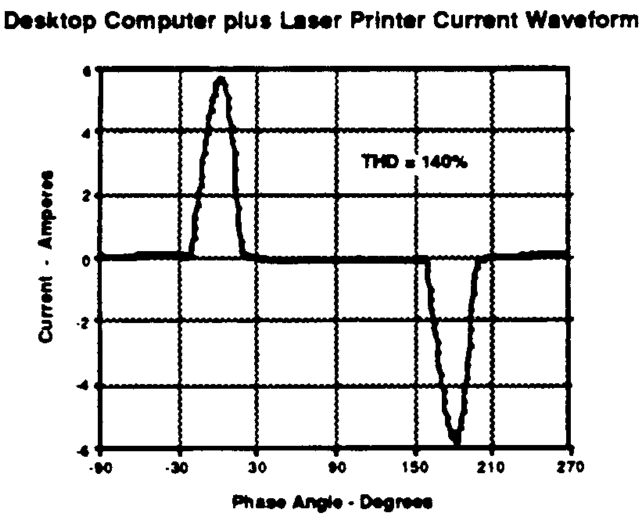


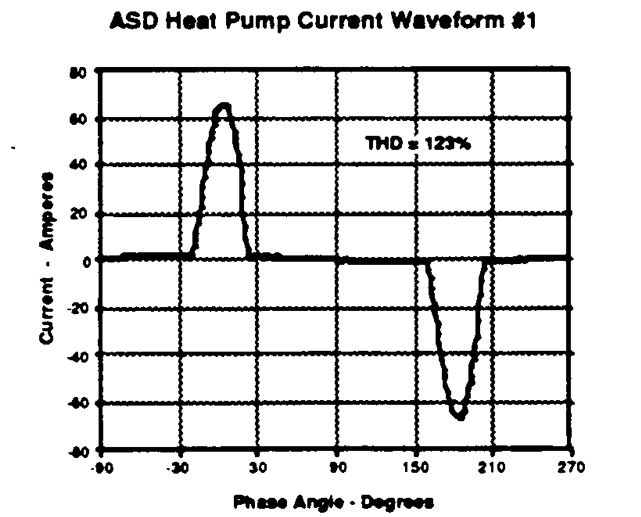


Typical Current Waveforms of Appliances. Contd.

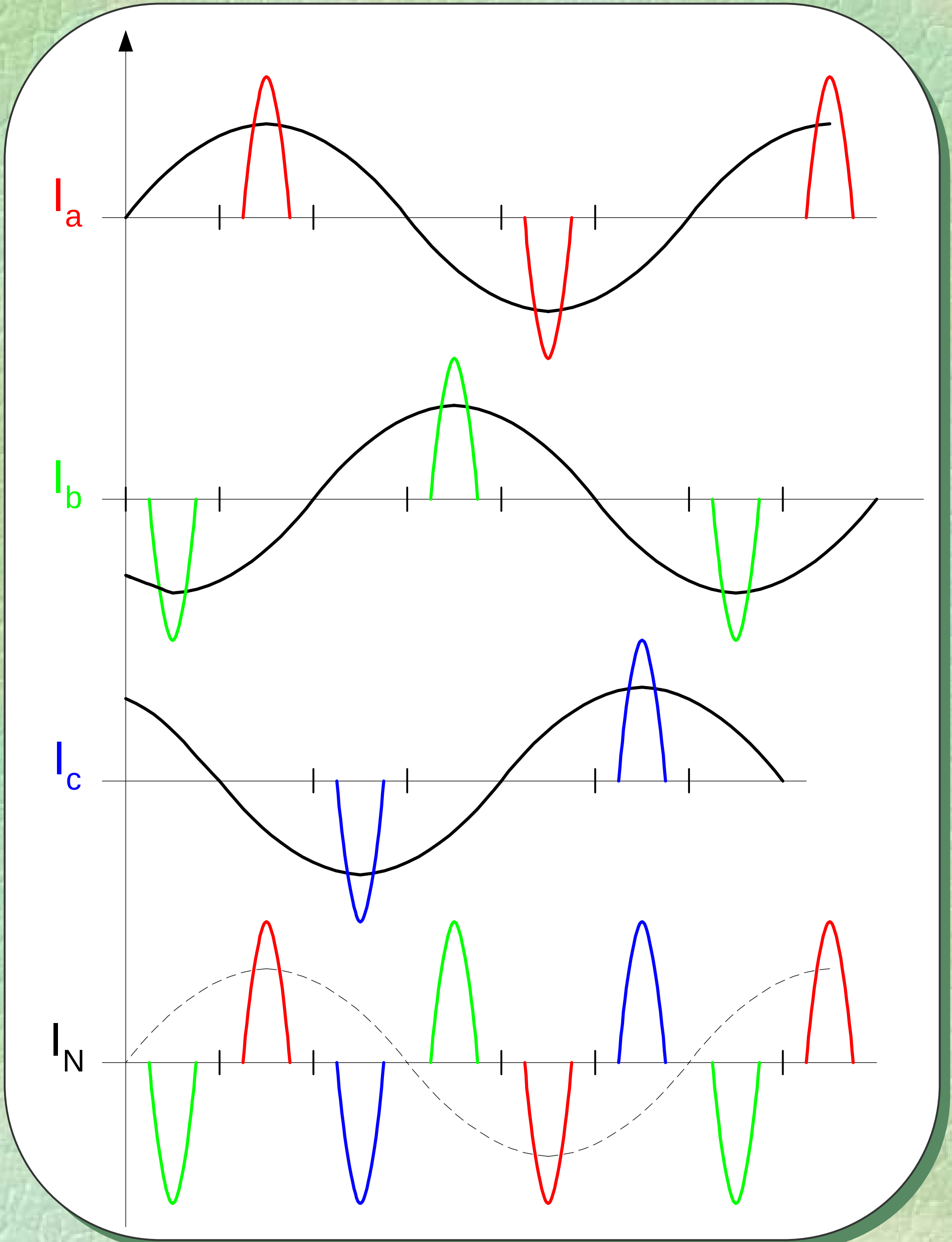


Typical Current Waveforms of Appliances. Contd.





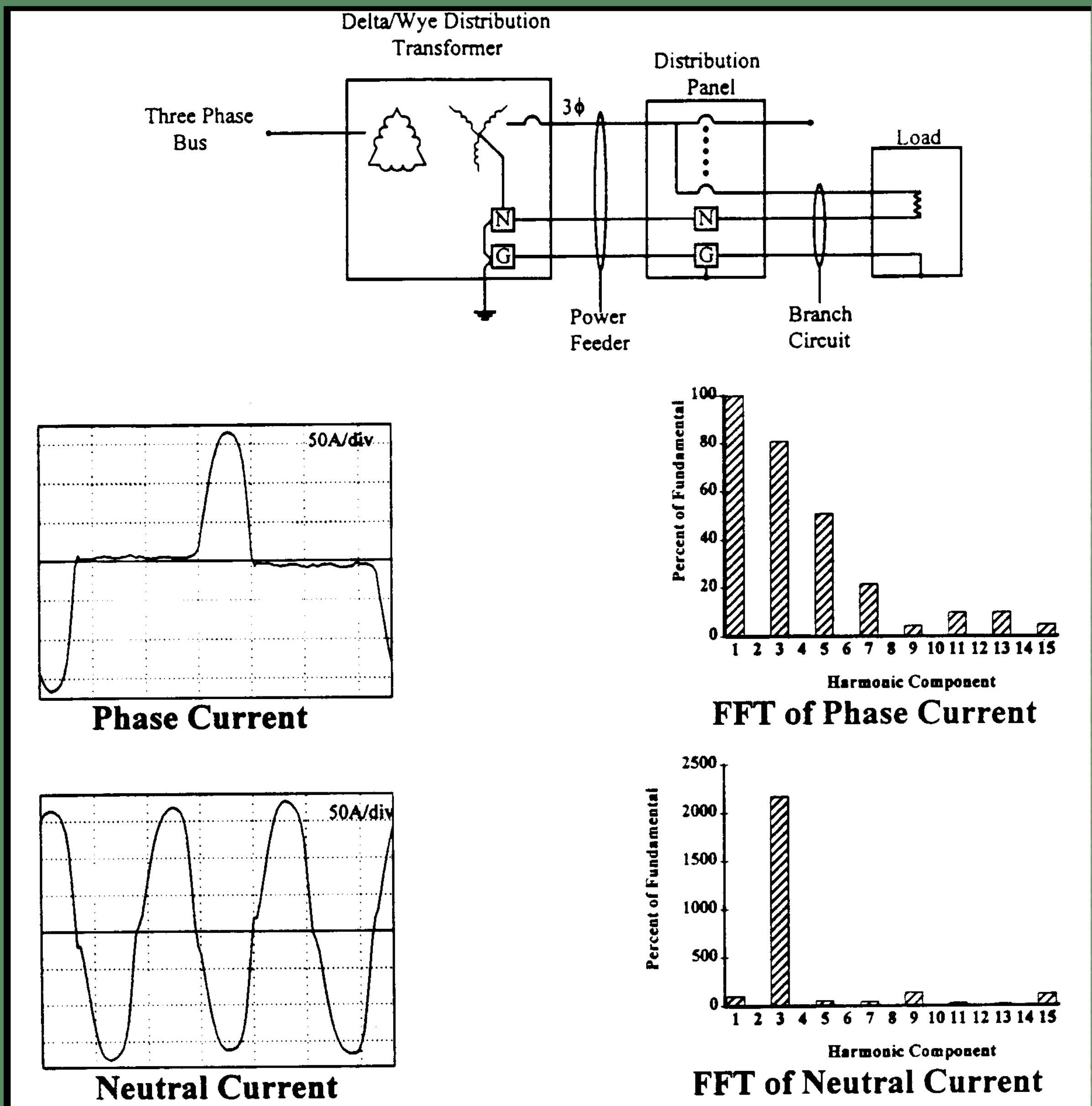
Effect of Triplen Harmonics in Neutral Conductors



$$I_{N,rms} = \sqrt{I_{a,rms}^2 + I_{b,rms}^2 + I_{c,rms}^2}$$

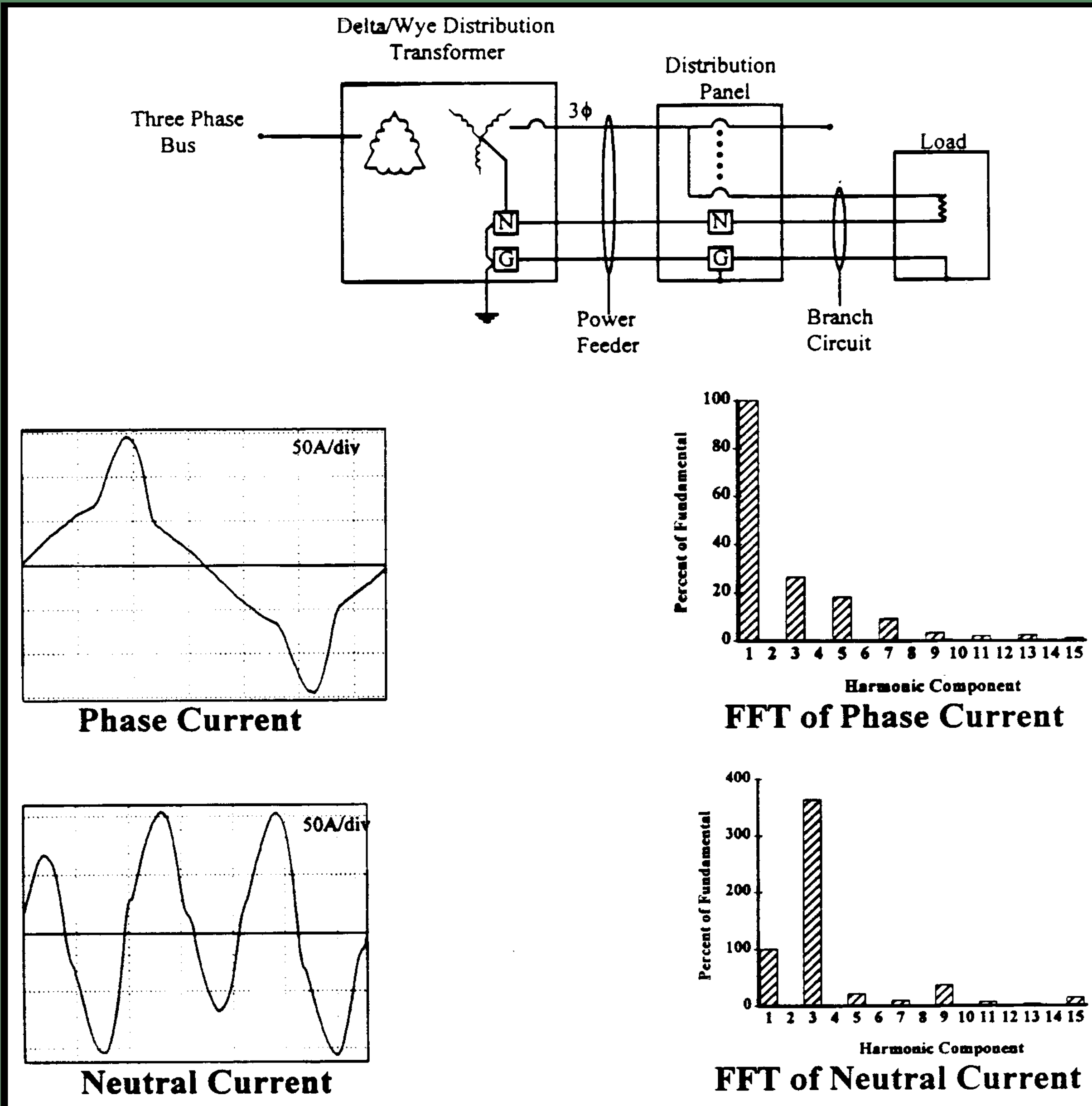
$$I_{N,rms} = \sqrt{3} * I_{phase,rms}$$

Survey results, Building I



	WITH THIRD HARMONIC	WITHOUT THIRD HARMONIC
APPARENT POWER	≅ 48kVA	≅ 40kVA
POWER FACTOR	≅ .73	≅ .89
CREST FACTOR	≅ 2.36	
K RATING	≅ 5.8	≅ 5.34

Survey results, Building II



	WITH THIRD HARMONIC	WITHOUT THIRD HARMONIC
APPARENT POWER	≅ 47.7kVA	≅ 46.4kVA
POWER FACTOR	≅ .93	≅ .97
CREST FACTOR	≅ 1.76	
K RATING	≅ 2.19	≅ 2.09

Summary of Building Measurement

Phase / Building	A	B	C	N	Neutral to Phase, %
Building I	66.8A	77.3A	72.5A	120.0A	170%
Building II	50.0A	65.6A	41.1A	53.7A	103%
Building III	12.8A	36.1A	24.5A	27.5A	80.9%
Building IV	80.6A	77.2A	90.0A	142.0A	171.3%
Building V	23.0A	17.4A	26.0A	12.7A	57.4%
Building VI	44.6A	41.2A	41.9A	60.7A	143%

Harmonic Profiles for Typical Buildings

OFFICE BUILDINGS

- 9 Buildings surveyed.
- Typical loads include computers and office equipment.
- Average neutral to phase ratio of 1.13
- Average crest factor of 2.12

MEDICAL FACILITIES

- 22 facilities surveyed.
- Typical loads include computers, office equipment, diagnostic and patient care equipment.
- Average crest factor of 2.02

INDUSTRIAL FACILITIES

- 14 sites surveyed.
- Typical loads include computers, laboratory equipment, telecommunication equipment.
- Average neutral to phase of 1.04
- Average crest factor of 2.12

Harmonic Profiles for Typical Buildings. Contd.

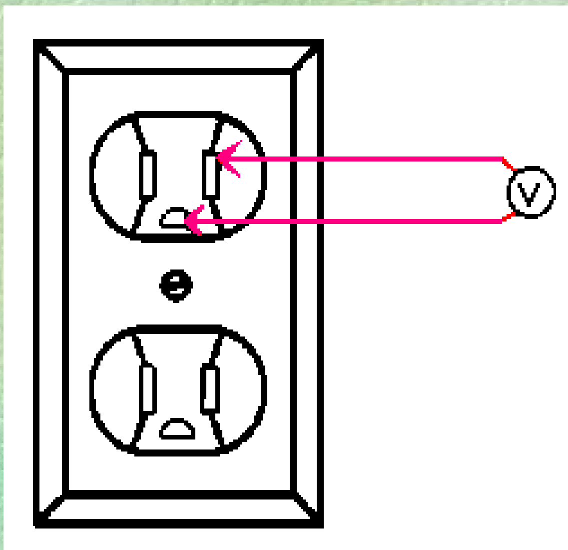
GOVERNMENT BUILDINGS

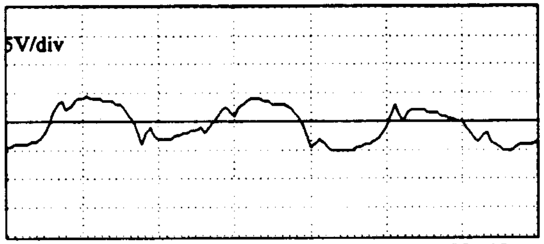
- 6 sites surveyed.
- Typical loads include computers, data processing equipment, office equipment.
- Average neutral to phase of 0.77
- Average crest of 1.78

AUDIO VISUAL STUDIOS

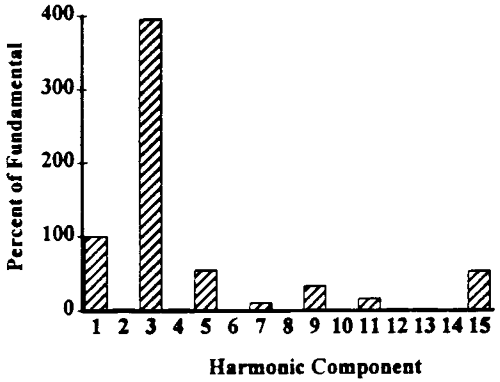
- 8 studios surveyed.
- Average neutral to phase of 0.65
- Average crest of 1.74

Common Mode Noise, Building I

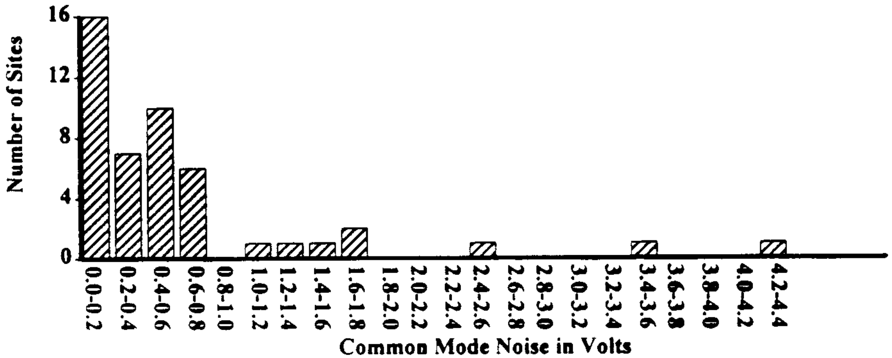




Common Mode Noise at Wall Receptacle In Building I

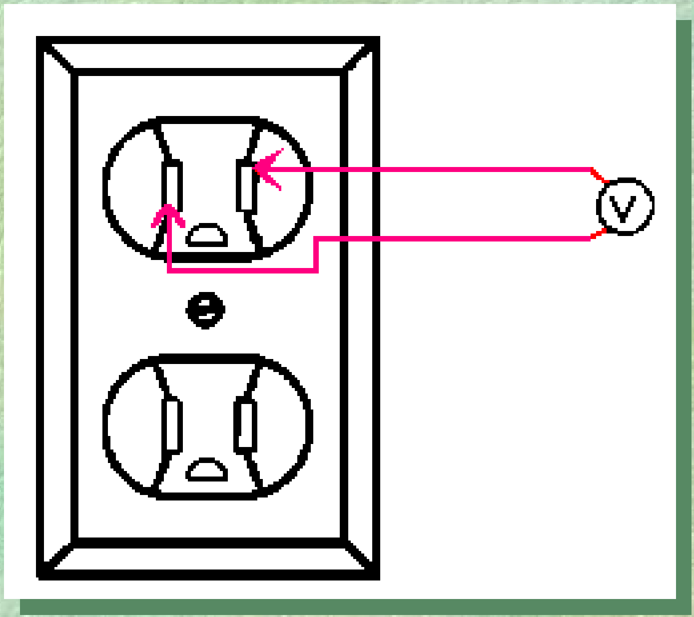


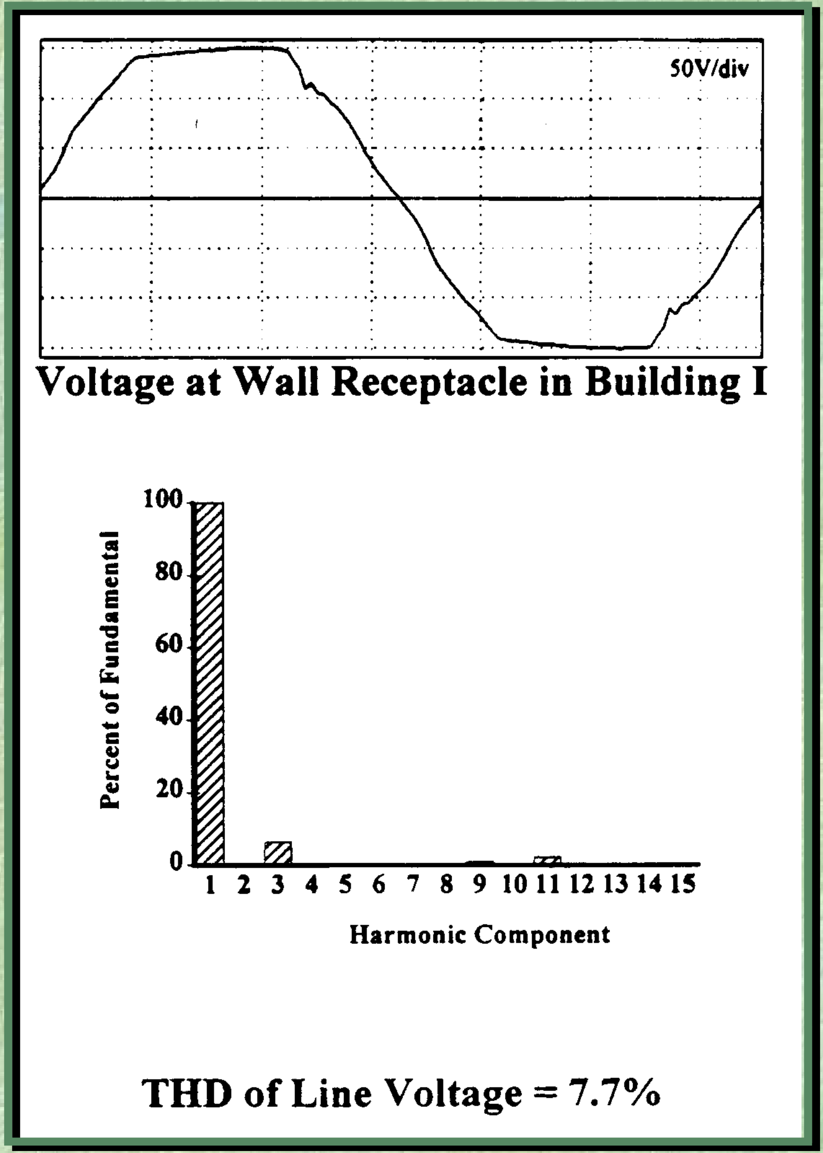
Frequency Spectrum of Common Mode Noise



Breakdown of Common Mode Noise Results

Line Voltage Distortion, Building I





Harmonic Effects on Transformers

TRANSFORMER LOSSES DUE TO TRIPLEN HARMONICS

- Losses in transformers are subdivided into core and winding losses.
- Core loss is of minor concern since it is due to flux generated in the core by the bus voltage.
- Winding losses are increased due to I^2R and stray losses.

EFFECTS OF TRIPLEN HARMONICS

- Excessive stress due to heating
- Insulation breakdown
- Lower operating efficiency
- Short life span
- Acoustic noise

Solutions:

-Derating

-Passive Approach

-Active Approach

Recommendations by CBEMA

1. Derate transformers or use K-Factor Transformers.

2. Oversize all neutral components for 1.73 times rated full load amps.

3. Use separate neutral conductors for nonlinear loads and avoid shared neutral conductors where practical.

4. Use neutral over current sensors to trip phase conductors.

5. Use true rms. ammeters and instruments with sufficient bandwidth for measurement.

Transformer Derating Schemes

Derating is a means of determining the maximum load that may be safely placed on a transformer that supplies harmonic loads.

The most common derating method is the CBEMA approved "crest factor" method which provides a transformer harmonic derating factor, THDF.

$$\mathrm{THDF} = \frac{1.414(\text{True rms of the phase current})}{\text{peak of the phase current}}$$

Example of Transformer Derating. Building I

Phase	True RMS Phase Current	Peak Value of Phase Current
A	70A	178A
B	76A	181A
C	73A	180A

$$\text{AVG RMS} = \frac{(70+76+73)}{3} = 73\text{A}$$

$$\text{AVG PEAK} = \frac{(178+181+180)}{3} = 180\text{A}$$

$$\text{THDF} = \frac{1.414(73)}{180} = .57$$

HENCE, THE TRANSFORMER SHOULD BE DERATED TO 57% OF ITS NAME PLATE RATING!!!

K Factor Rated Transformers

- K factor was developed by Underwriters Laboratory in UL 1561.
- K factor transformers are designed to supply nonsinusoial loads.
- They contain enlarged primary windings to carry circulating triplen harmonic currents.
- The magnetic core has a lower flux density as it is designed with higher grades of iron.
- K factor transformers use smaller, insulated, secondary conductors in parallel to reduce skin effect.
- K factor transformers are more expensive than conventional transformers.

K Factor Rated Transformers. Contd.

K factor is a means of rating a transformer with respect to the harmonic magnitude and frequency of the load.

$$K = \sum_{h=1}^{\infty} \left(I_{h\,pu}\right)^2 h^2$$

The K factor numbers do not linearly indicate transformer harmonic tolerance. For example, a K4 rated transformer has four times the eddy current tolerance as a K1 transformer. A K13 rated transformer has approximately twice the tolerance of a K4 and K30 has twice of a K13.

Example K Factor Calculation. Building I

TRUE RMS = 73.3A = 1 pu

h	I_{RMS}	$I_{P.U.}$	$I^2_{P.U.}$	h^2	$I^2_{P.U.}\ h^2$
1	52.45A	.715	.511	1	0.511
3	42.27A	.577	.333	9	3.000
5	24.97A	.341	.116	25	2.900
7	9.44A	.129	.016	49	0.784
9	3.72A	.051	.003	81	0.243
11	5.51A	.075	.006	121	0.726
13	4.77A	.065	.004	169	0.676
			$\Sigma = 1$		k = 8.84

K Factor = 8.84

Solutions. Neutral Cable

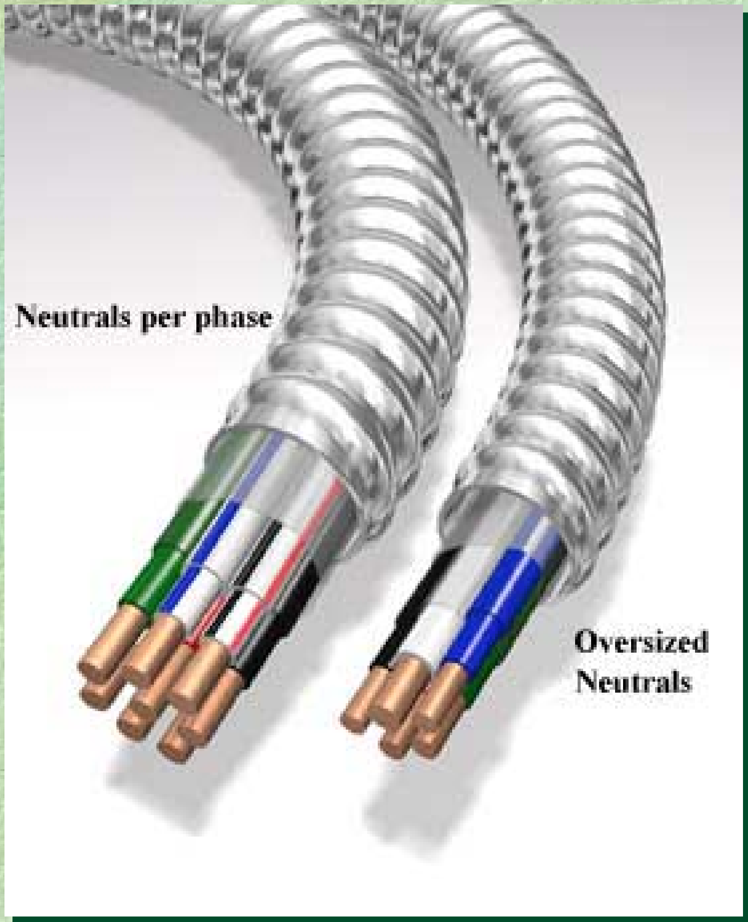
Super Neutral Cable®

Super Neutral Cable is a metal-clad, Type MC Cable, manufactured with an oversized neutral conductor or one neutral per phase for three-phase/four-wire power supply systems to computers (with dc drive fan motors, tape and disk drives) office machines, programmable controllers, and similar electronic equipment where non-linear switching loads produce additive, odd order harmonic currents which may create overloaded neutral conductors.

The oversized neutral conductor(s) are sized 150% to 200% of the phase conductor ampacity to minimize the effects of harmonics generated by the non-linear loads. The neutral per phase (striped with color to match the phase conductor) accomplishes the same objective.

Super Neutral Cable can be used under computer room floors, raised floors, or overhead in the space above hung ceilings used for environmental air handling. It handles branch and feeder, plus power, lighting, signal, and control circuits in dry locations.

AFC CABLE SYSTEMS



Solutions. Transformers

K-factor transformers:

Sola

Dongan

Disadvantages and Risks

Derating a transformer is a temporary fix and often translates into lower efficiency operation and increased heat for losses.

Derated transformers also run the risk of being perceived to be partially loaded and future load additions are possible.

While derating removes some stresses from the transformer, a typical dry type transformer is not designed to supply harmonic loads. Hence, it may be subject to a shorter life span and lower efficiency.

Oversizing of transformers, or selection of unnecessarily high K factor ratings of transformers, can increase the harmonic currents due to lower impedance.

Separate neutral conductors for computer loads is almost impossible to implement, due to a wide scattering of data processing equipment all over the building.

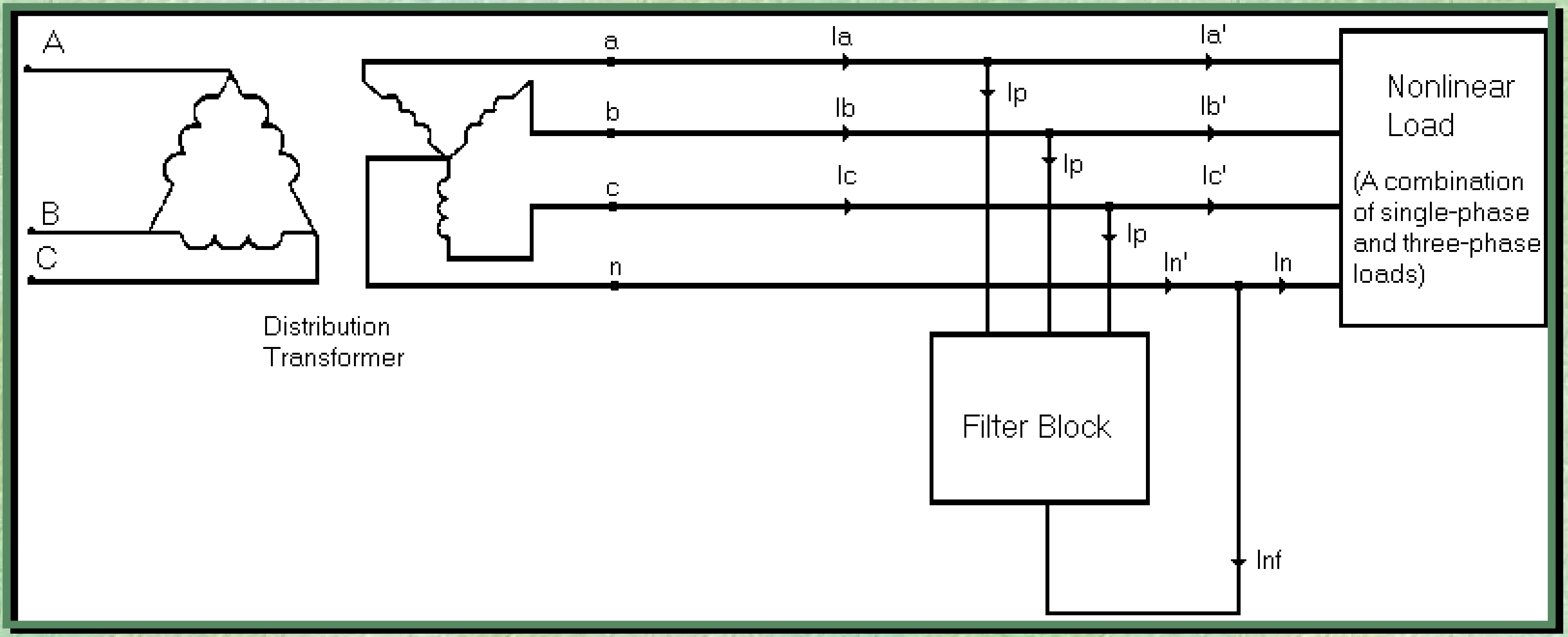
Solutions:

-Derating

-Passive Approach

-Active Approach

Passive Approach for Neutral Current Reduction

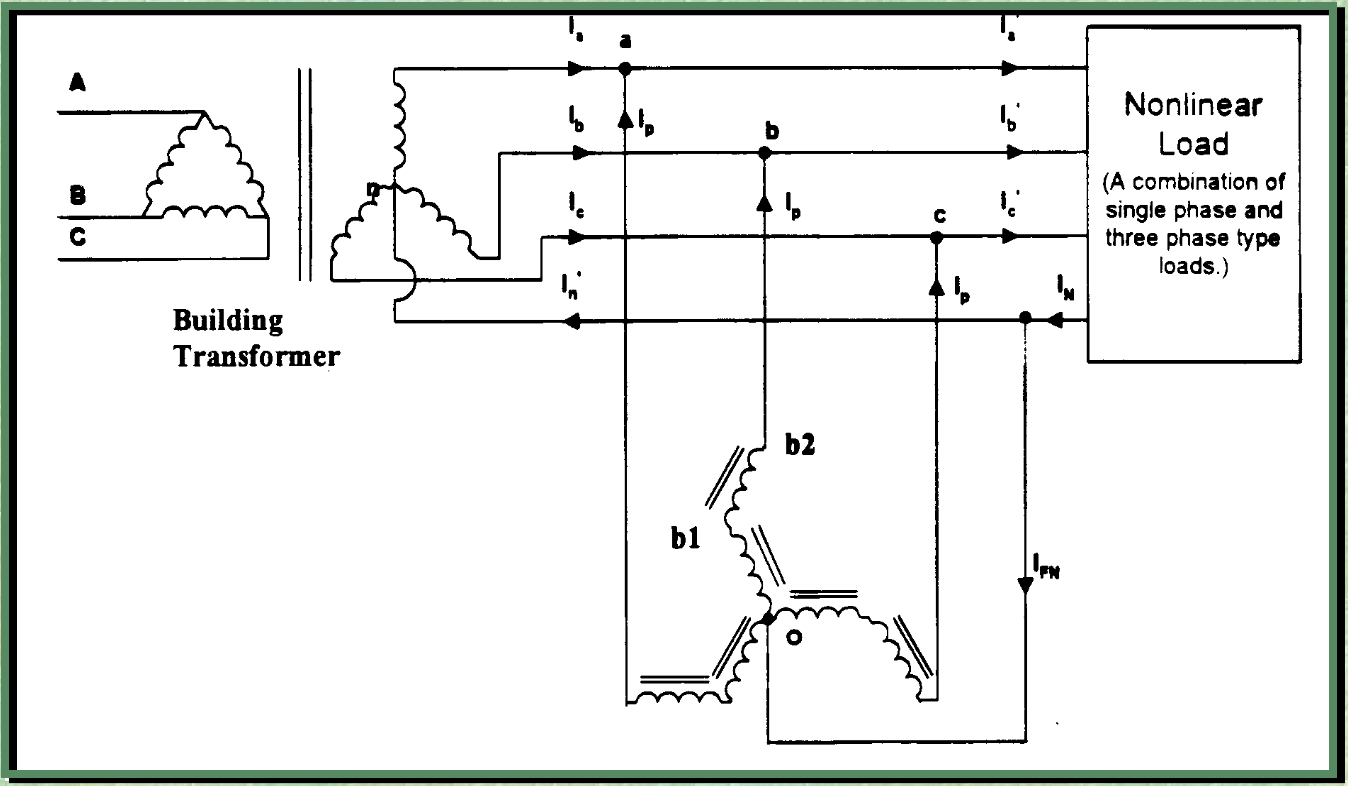


Circulates excessive triplen harmonics through the filter and back to the load.

Protects the distribution transformer and neutral conductor from excessive neutral currents.

Improves transformer power factor.

Zig-Zag Transformer for Neutral Current Reduction

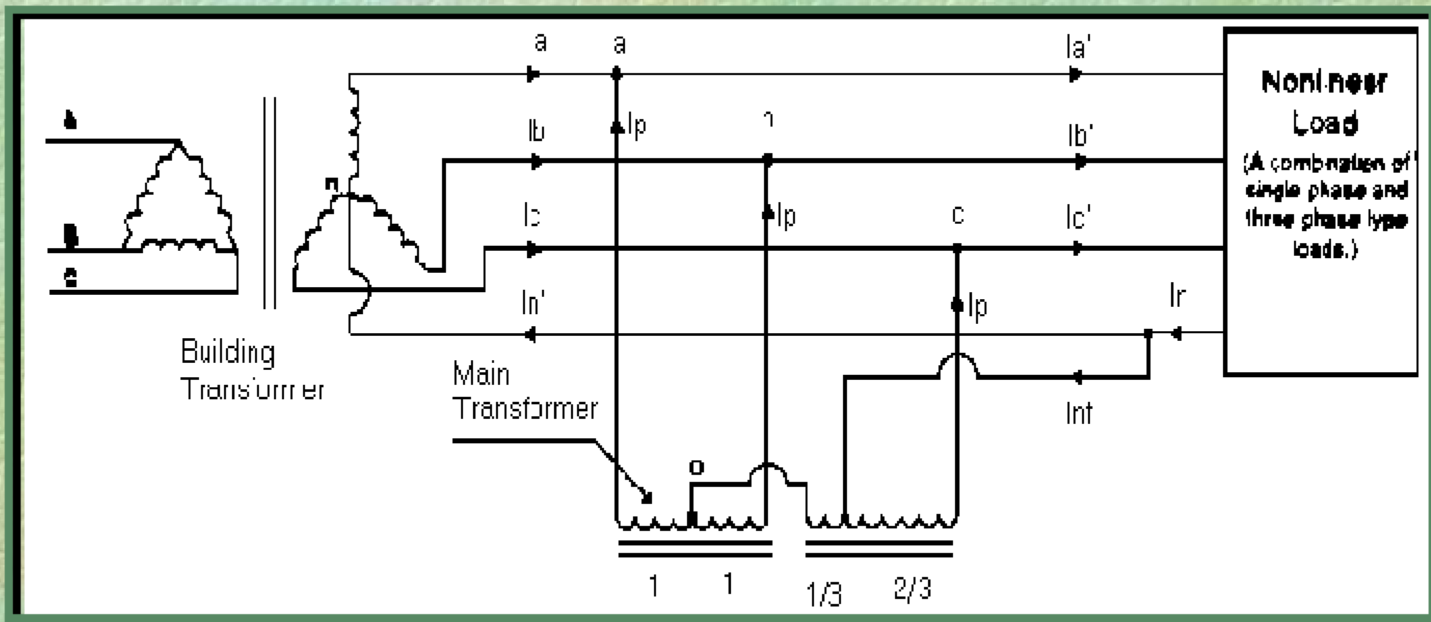


VA Rating Calculation

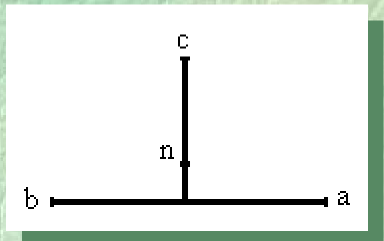
$$\text{VA rating} = \frac{3}{2}\left(\frac{V_{b1,o}}{\sqrt{3}} + \frac{V_{b2,b1}}{\sqrt{3}}\right)\frac{I_{FN}}{3}$$

$$\text{VA rating} = \frac{3}{2}\,\frac{2V_{ab}}{3}\left(\frac{I_{FN}}{3}\right) \qquad = 0.333\ V_{ab}\ I_{FN}$$

T-Connected Transformer for Neutral Current Reduction



VA Rating Calculation



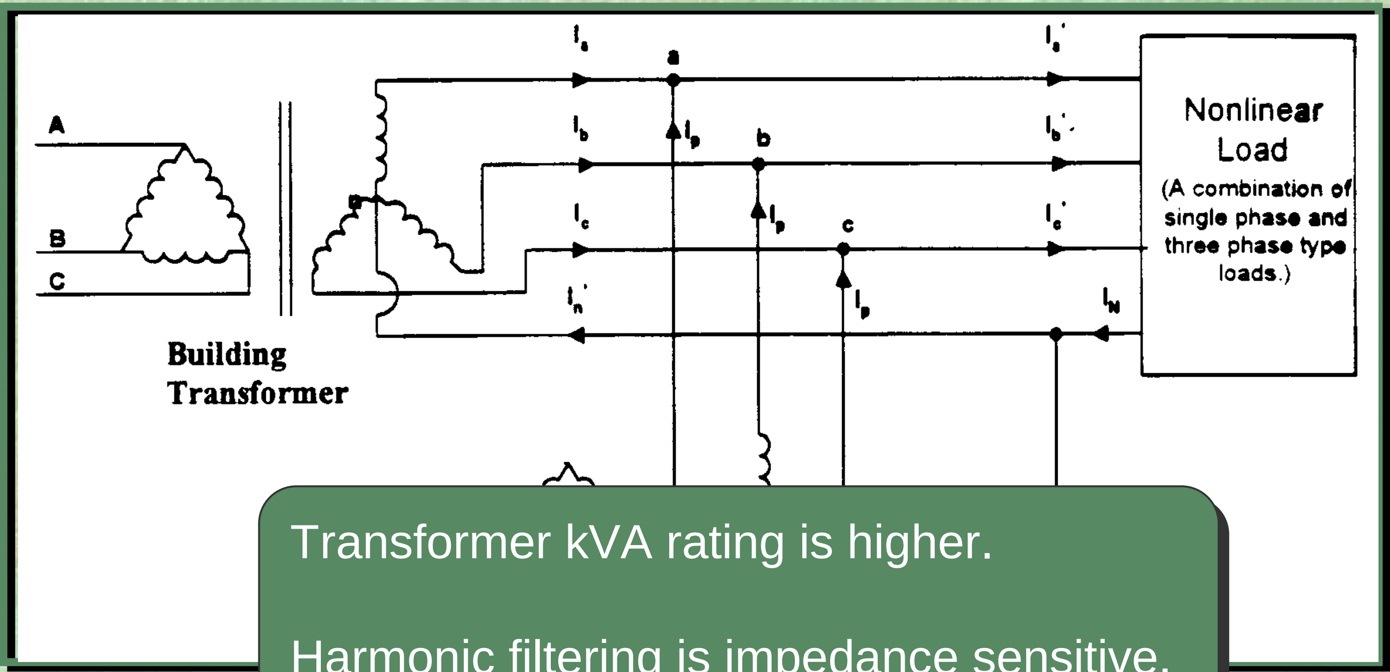
$$V_{an} = V_{bo} = \frac{V_{ab}}{2}, \qquad V_{co} = \frac{\sqrt{3}\, V_{ca}}{2}$$

Transfor

kVA rating is higher

$$= 0.359\, V_{ab}\, I_{FN}$$

Star-Delta Transformer for Neutral Current Reduction



Transformer kVA rating is higher.

Harmonic filtering is impedance sensitive.

VA Rating Calculation

$$\text{Transformer VA rating} = 3\frac{V_{ab}}{\sqrt{3}}\left(\frac{I_{FN}}{3}\right) = 0.577\, V_{ab} I_{FN}$$

Zig-Zag Transformer for Neutral Current Reduction

Disadvantages

Zero sequence impedance of the Zig-Zag transformer must be low. This requires special design.

The effectiveness of the Zig-Zag transformer to divert 3rd. harmonic current is highly dependent on the distribution system impedance. In most cases only 50% reduction can be guaranteed.

Lower zero-sequence impedance increases the single-phase fault current level. Therefore, fusing and circuit breaker re-sizing may be necessary.

The specially designed low impedance Zig-Zag transformer becomes a low impedance path for zero sequence currents from other parts of the system

Due to the reasons mentioned above the passive Zig-Zag transformer approach is larger in size and weight.

Solutions. Passive Approach

Acme's I-Trap™ Reduces Excessive Neutral Currents Caused by Harmonic Distortion

Acme has introduced a product that provides a cost effective solution to high neutral currents that result from zero sequence harmonics and unbalanced loads.

The I-TRAP™ units are designed for use on 208Y/120V three phase 60Hz systems. They provide electrical contractors, system designers and specifying engineers with an economical alternative to replacement of overheated system neutral conductors. The I-TRAP™ can be installed adjacent to distribution panels that will feed non-linear loads in plants, offices, hi-rises and other locations. This permits the use of smaller, less expensive neutral cable and provides protection to distribution transformers that may overheat due to harmonic loads.

The I-TRAP™ is for use on systems with maximum neutral currents of 100A, 150A, 300A and 450A. Each unit includes a built-in ammeter to provide constant reading of the neutral current.

Installation is accomplished by four simple terminal connections and the units can be floor or wall mounted and require minimal maintenance.
All I-TRAP™ units are UL listed and CSA certified, rated for 115 deg. C temperature rise and 220 deg. C insulation class, and are covered under Acme's exclusive 10 year warranty.
The I-TRAP™ and Acme's full line of dry type distribution transformers are available through a network of reps and electrical distributors in the United States and Canada.

Acme Electric Corporation
Power Distribution Products Division
Building products to serve a wide range of electrical power distribution and control applications
Lumberton, NC
Phone: 1-800-334-5214
910-738-1121
Fax: 910-739-0024

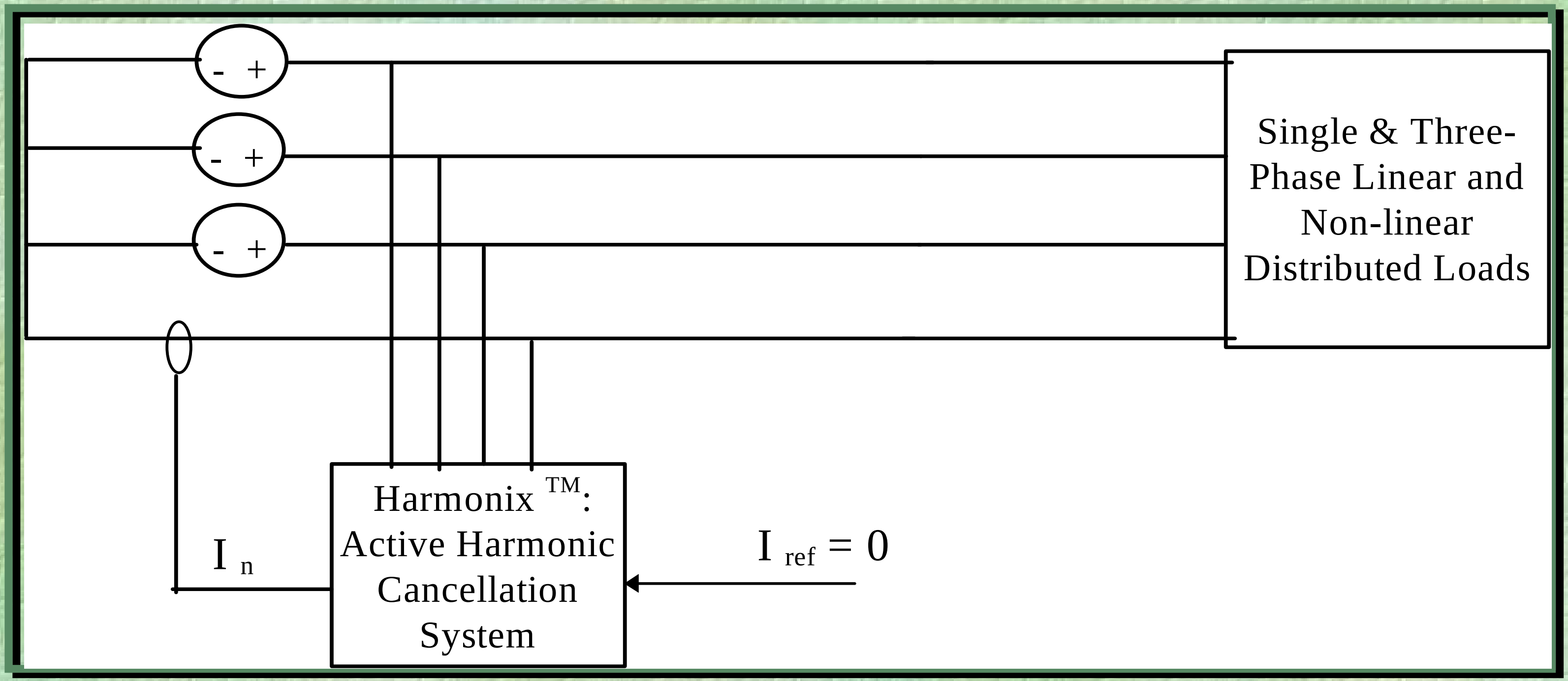
Solutions:

-Derating

-Passive Approach

-Active Approach

Active Neutral Current Filtering Scheme



Circulates excessive triplen harmonics through the filter and back to the load.

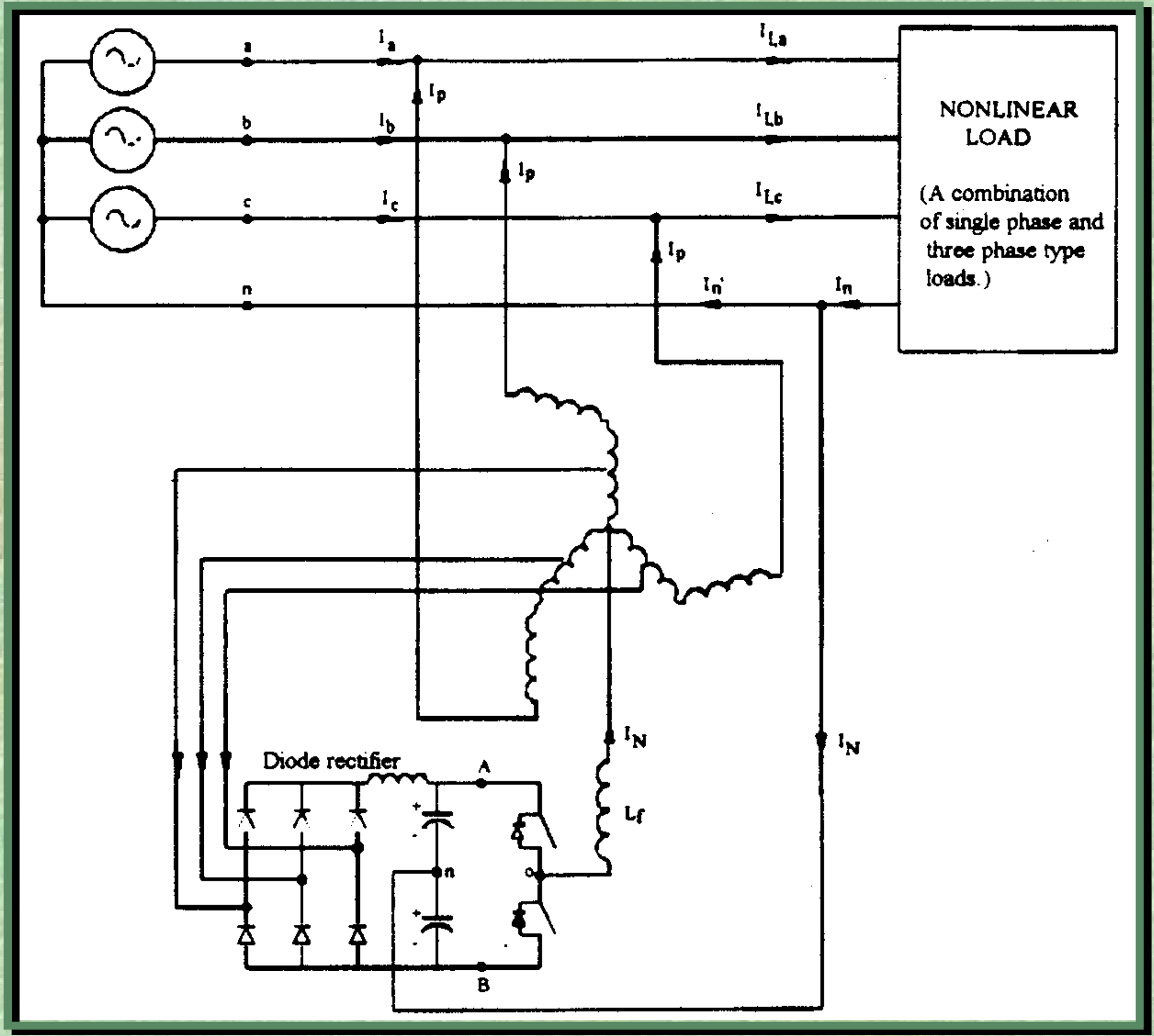
Protects the distribution transformer and neutral conductor from excessive neutral currents.

Improves transformer power factor.

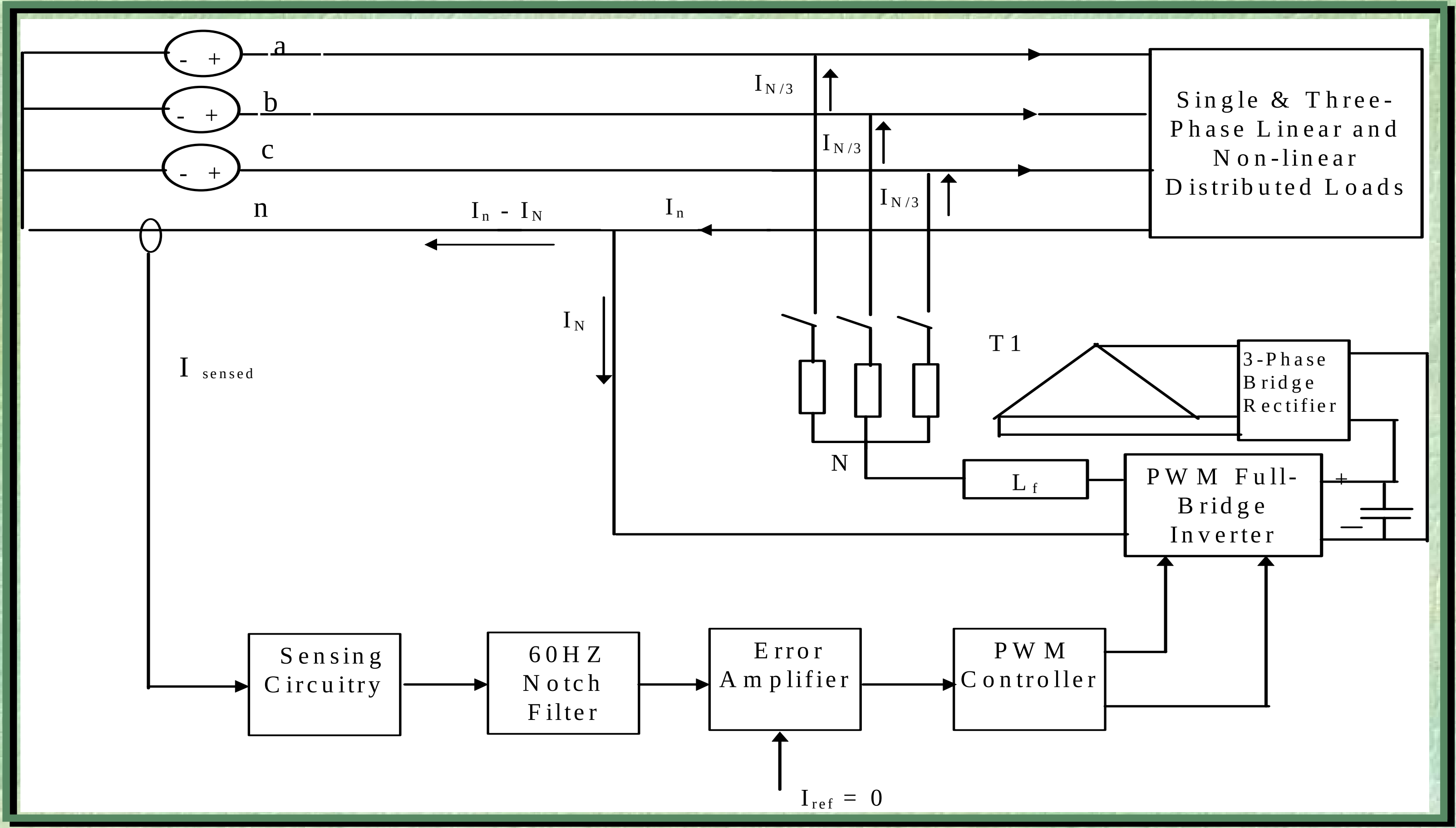
Active Neutral Current Filtering Scheme

- Developed by Texas A&M University, College Station & Current Technology, Inc. Dallas, Texas.
- Design to Cancel Zero Sequence Harmonic Current from a 3-Phase 4-Wire Distribution System.
- Patented Technology.

Active Neutral Current Filtering Scheme



Active Neutral Current Filtering Scheme. Functional Block Diagram.

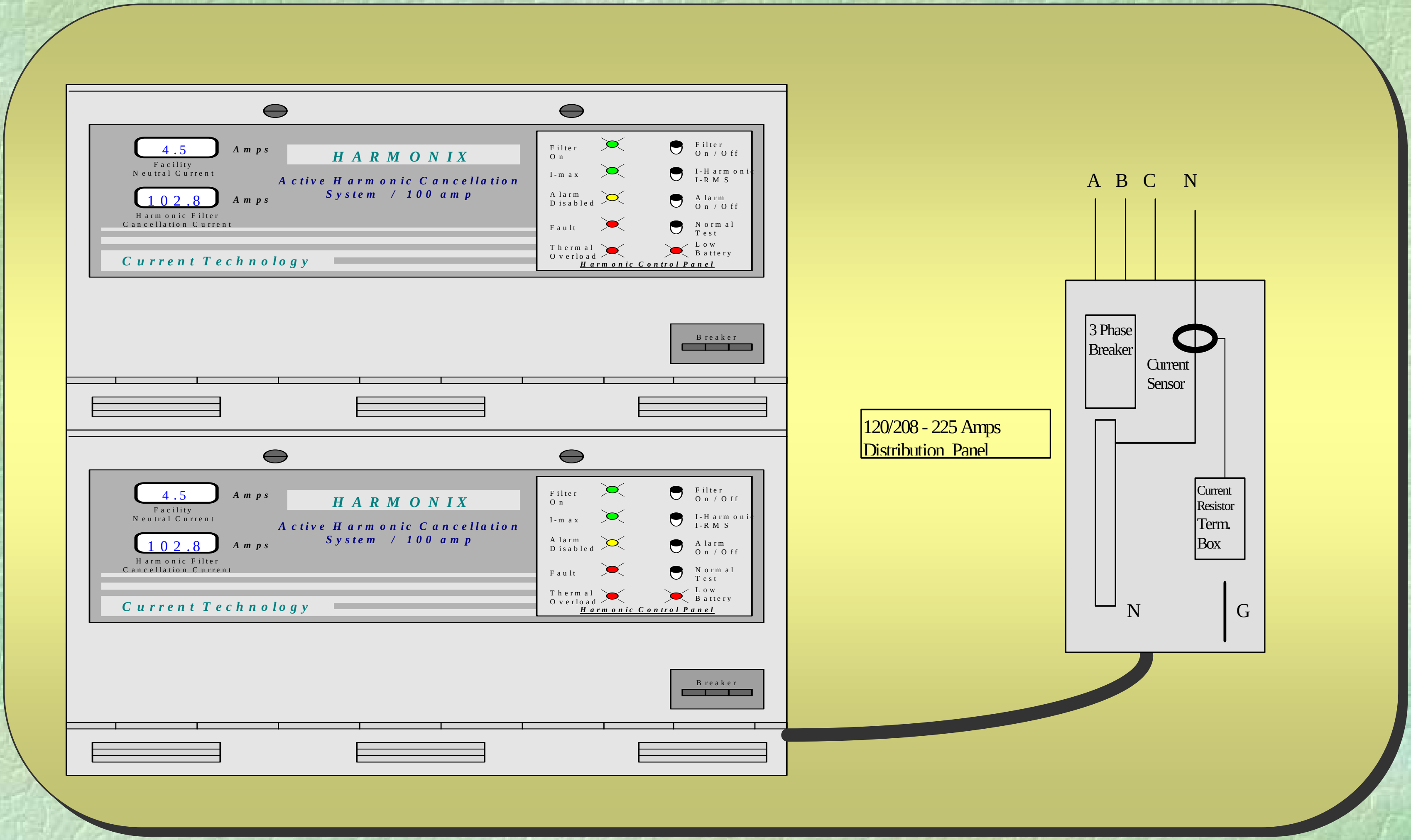


Active Neutral Current Filter

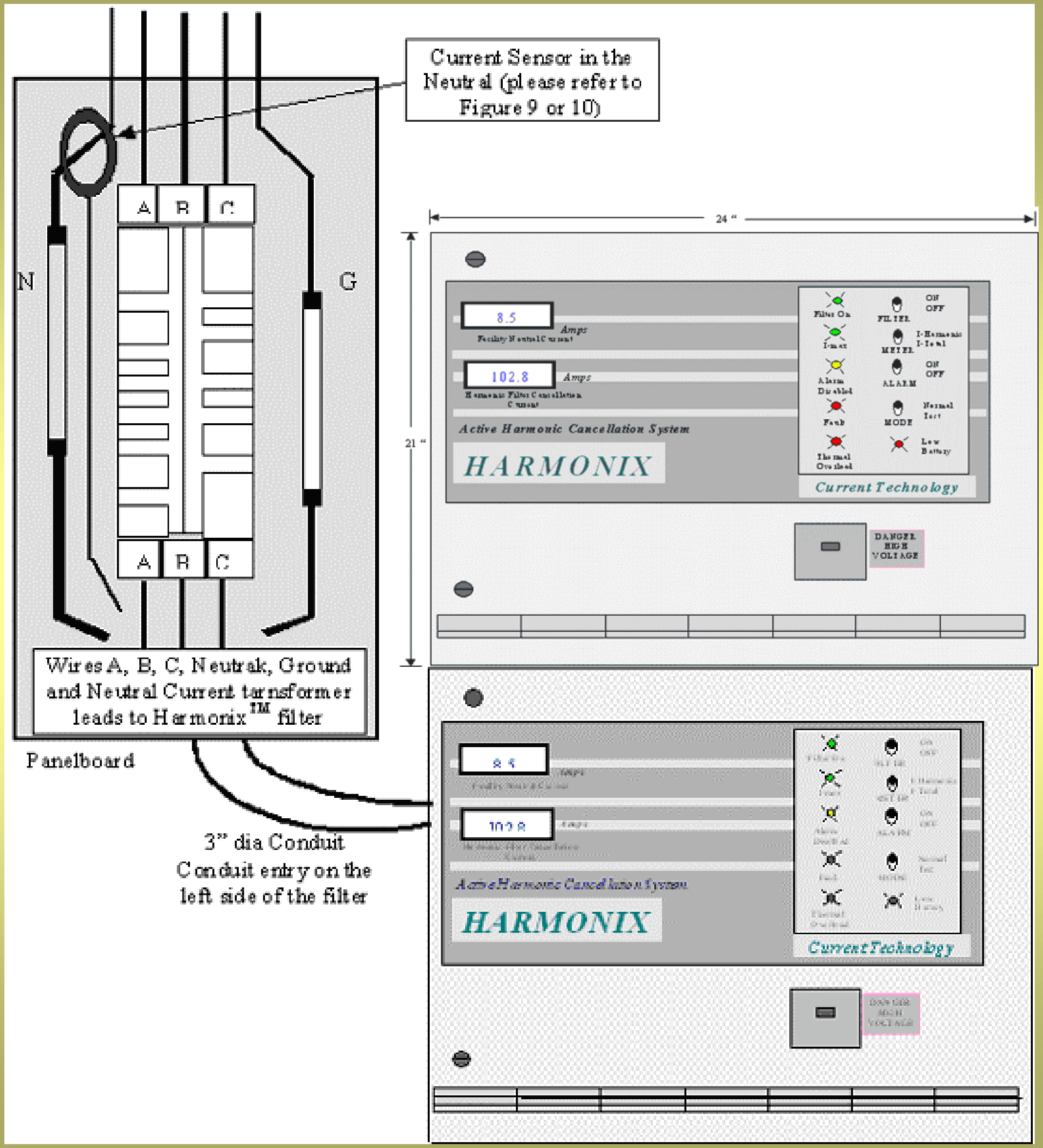
Active Neutral Current Filter. Features.

- High Cancellation Effectiveness : 90 - 95%.
- Performance independent of System Impedance.
- Cancels neutral current harmonics by measurement and close-loop control.
- No low-impedance path for Zero-Sequence 60 Hz.
- Built-in pulse-pulse current limit (No Overloading).
- Significant improvement in Voltage and Current THD’s.
- Fast-response characteristics.

Active Neutral Current Filter. Connection.



Active Neutral Current Filter. Connection.



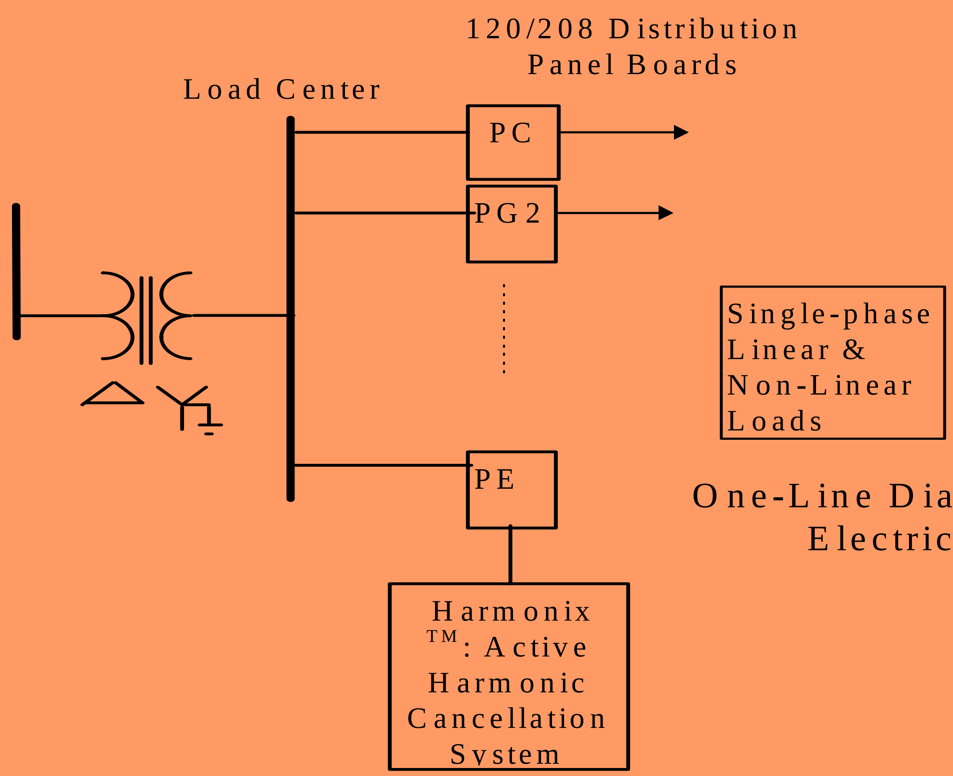
Filter Specifications

Voltage	120/208, 220/380, 277/480
Current	100 A rms per module
Frequency	50/60 Hz
Power Efficiency	90%
Cancellation Effectiveness	90-95%
Parallelability	Up to 4 filters can be connected in parallel
Topology	Parallel connection 3-Phase, 4-Wire

Filter Specifications. Contd.

Protection	Pulse-Pulse current protection Thermal shutdown Overcurrent protection
Monitoring	Facility current Filter current Harmonics or total rms current
Status Indication	Indicator lights, Audible alarm, Max current indicator, Dry contacts
Enclosure	21H x 24W x13D Floor mount stackable
Weight	200 lbs (approx.)

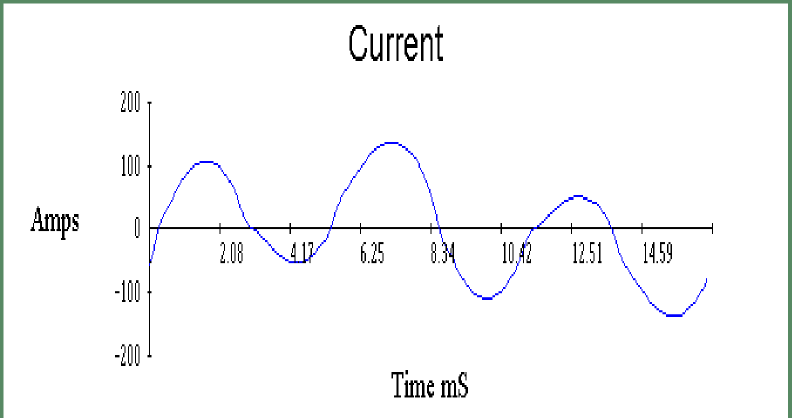
Active Neutral Current Filter. Test Results

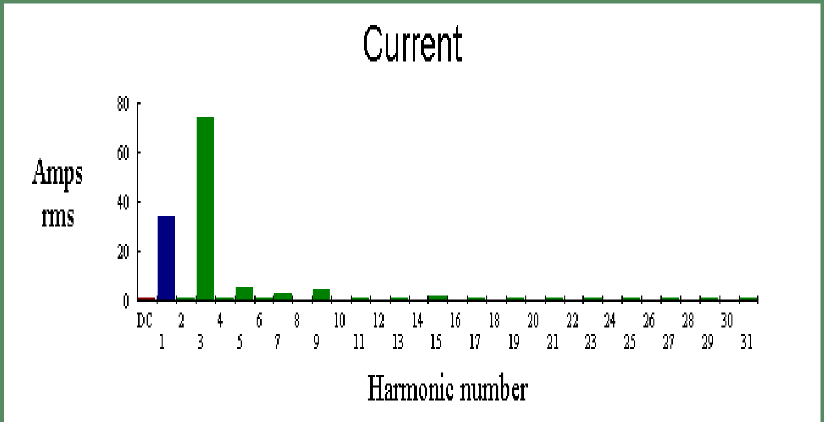


One-Line Diagram - Beta Site
Electric Room 103

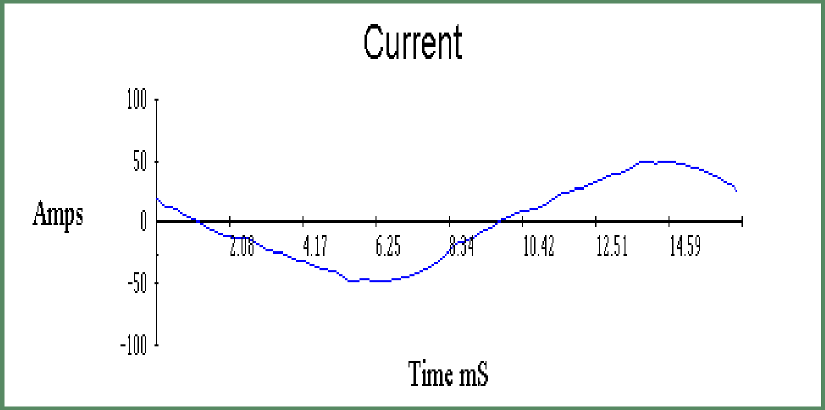
Active Neutral Current Filter. Test Results

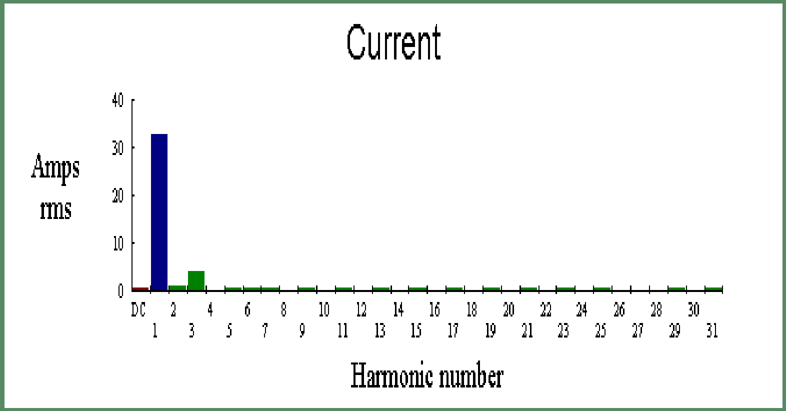
Neutral Current without Active Harmonic Cancellation System





Neutral Current with Active Harmonic Cancellation System

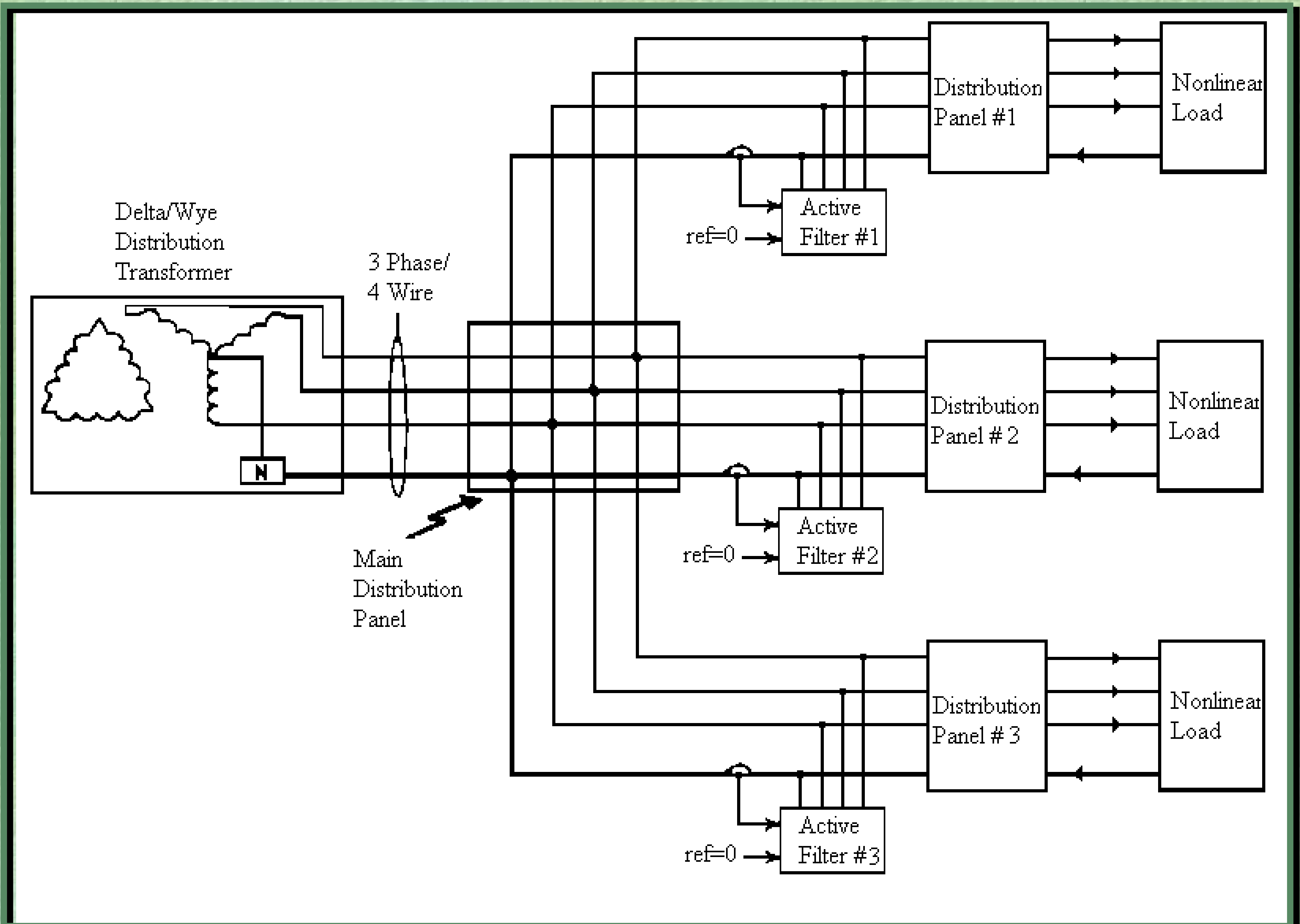




Active Neutral Current Filter. Test Results

Variable	Without Filter	With Filter
Neutral Current (A rms)	82.1	33.0
Zero-Sequence Harmonic Current in Neutral (A rms)	71.5	4.14
60 Hz Zero-Sequence Current in Neitral (A rms)	34.3	32.7
Voltage THD (% Fundamental)	3.3	2.9
Current THD (% Fundamental)	67.2	33.3
Cancellation Effectiveness	-	94.2

Neutral Current Filtering Scheme



Conclusions

The active filter employs a conventional zig-zag transformer (not optimized for low zero sequence impedance) and cancels the neutral current harmonics by measurement and closed loop current control.

The performance of the active filter is independent of the system impedance, hence is not location sensitive.

The active filter compensates only for harmonic currents in the neutral and does not become a low impedance path to unbalanced 60Hz currents.

The active filter has an electronic built in current limit and does not overload.

The proposed active filter is rugged and stable in operation. Notice the power electronic components are not subjected to line disturbances such as over voltages, voltage spikes etc.

The kVA of the power electronic active current source in low as the voltage between the neutral of the zig-zag transformer and the system neutral is near zero.