Elevated NEV Due to Triplen Harmonics

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Panel Session PN-29 Stray Voltage: Causes, Impacts and Mitigation
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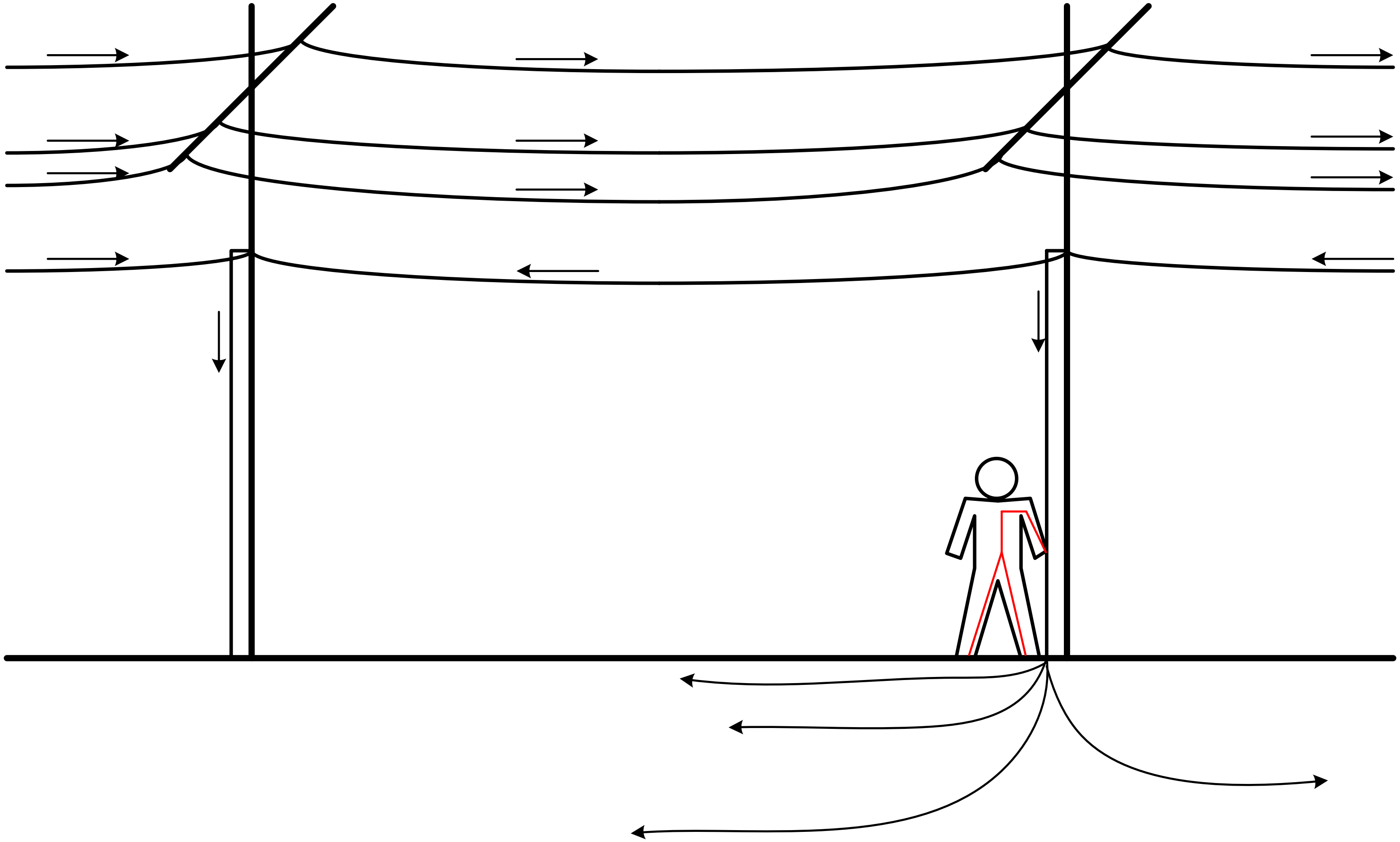
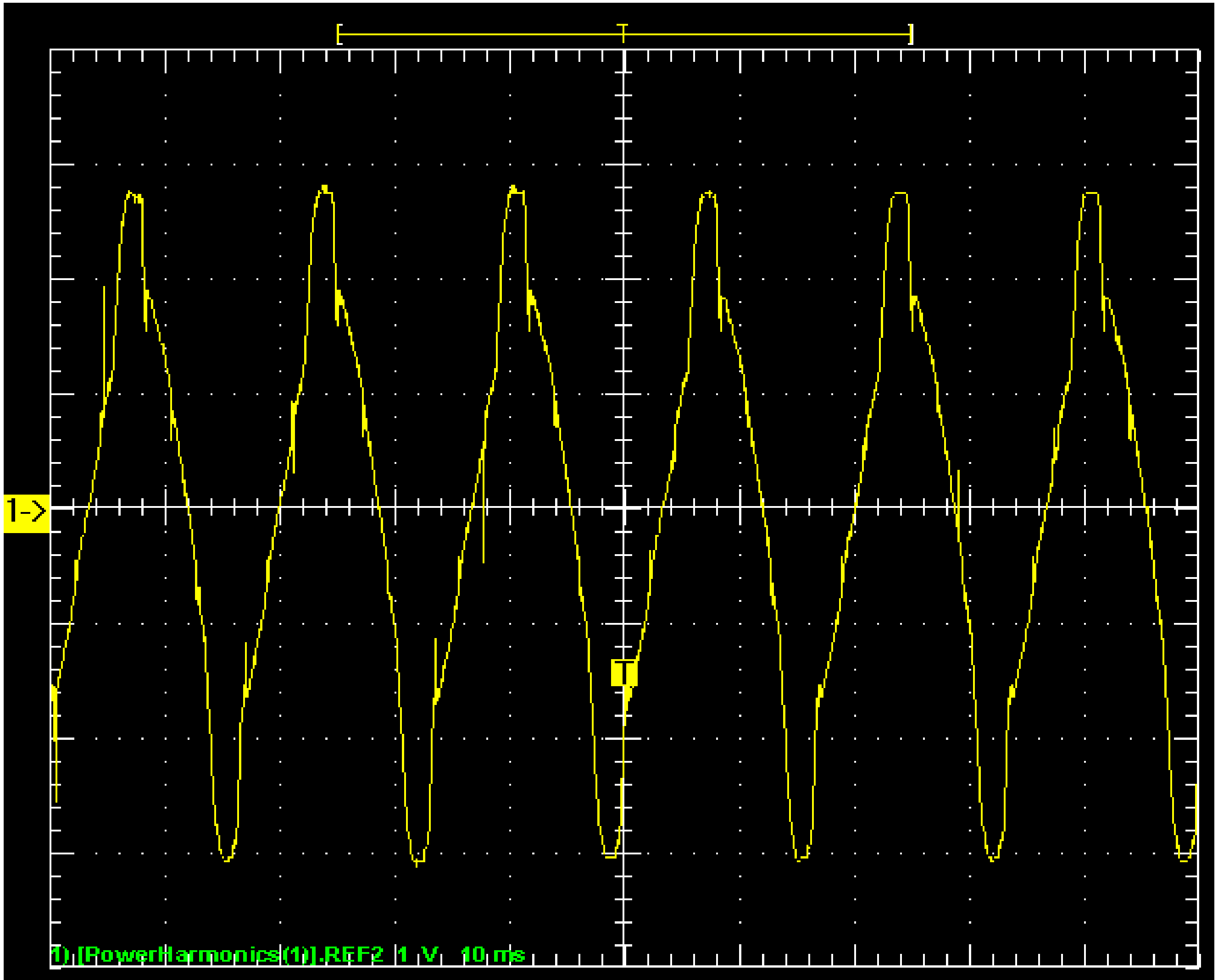
Neutral-to-Earth Voltage



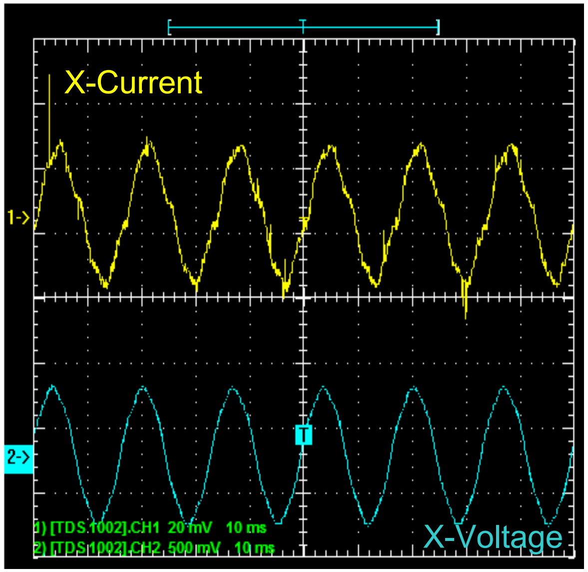
Factors Affecting NEV

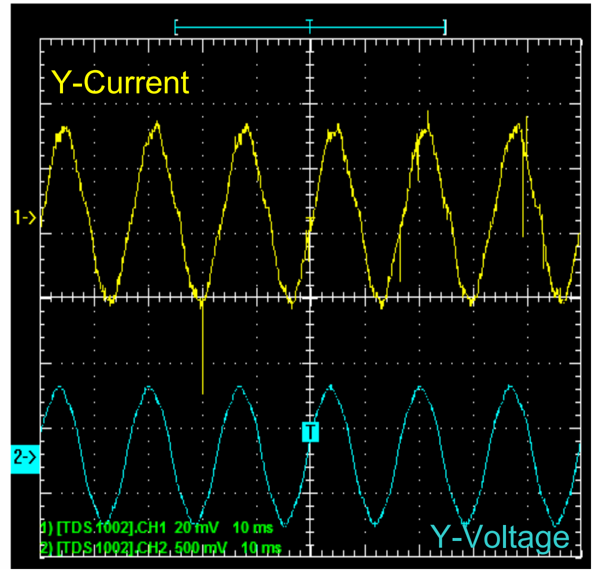
- Power system grounding
- Load balancing
- Transformer connection
- Primary circuit voltage level
- Neutral conductor impedance
- Neighboring ground fault
- Parallel utilities with common bonds

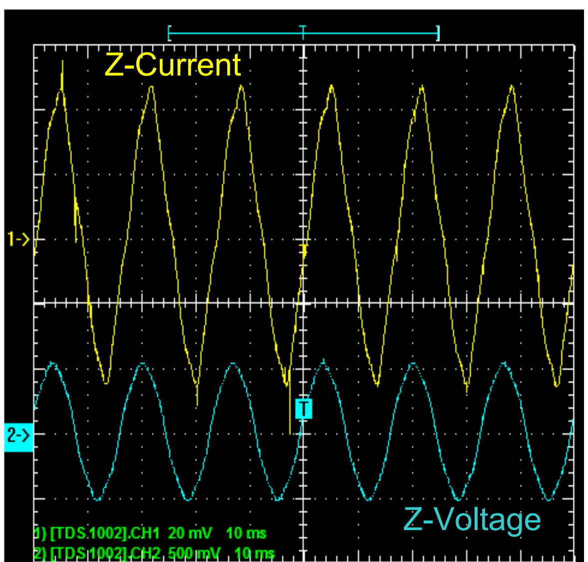
NEV at Three-Phase Pole

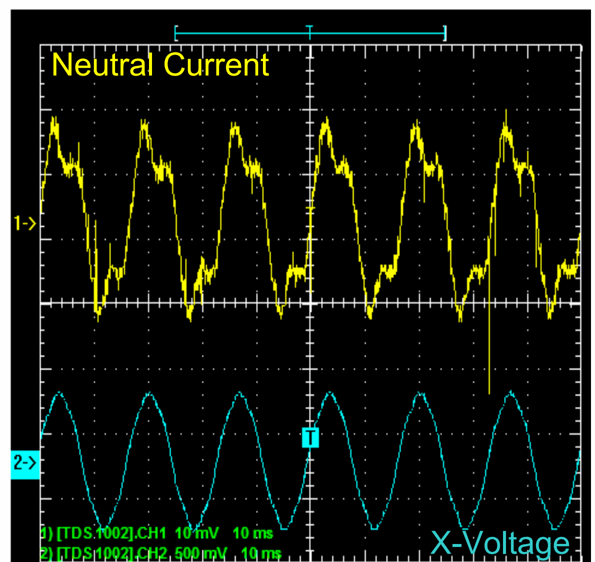


Distribution Feeder Measurements

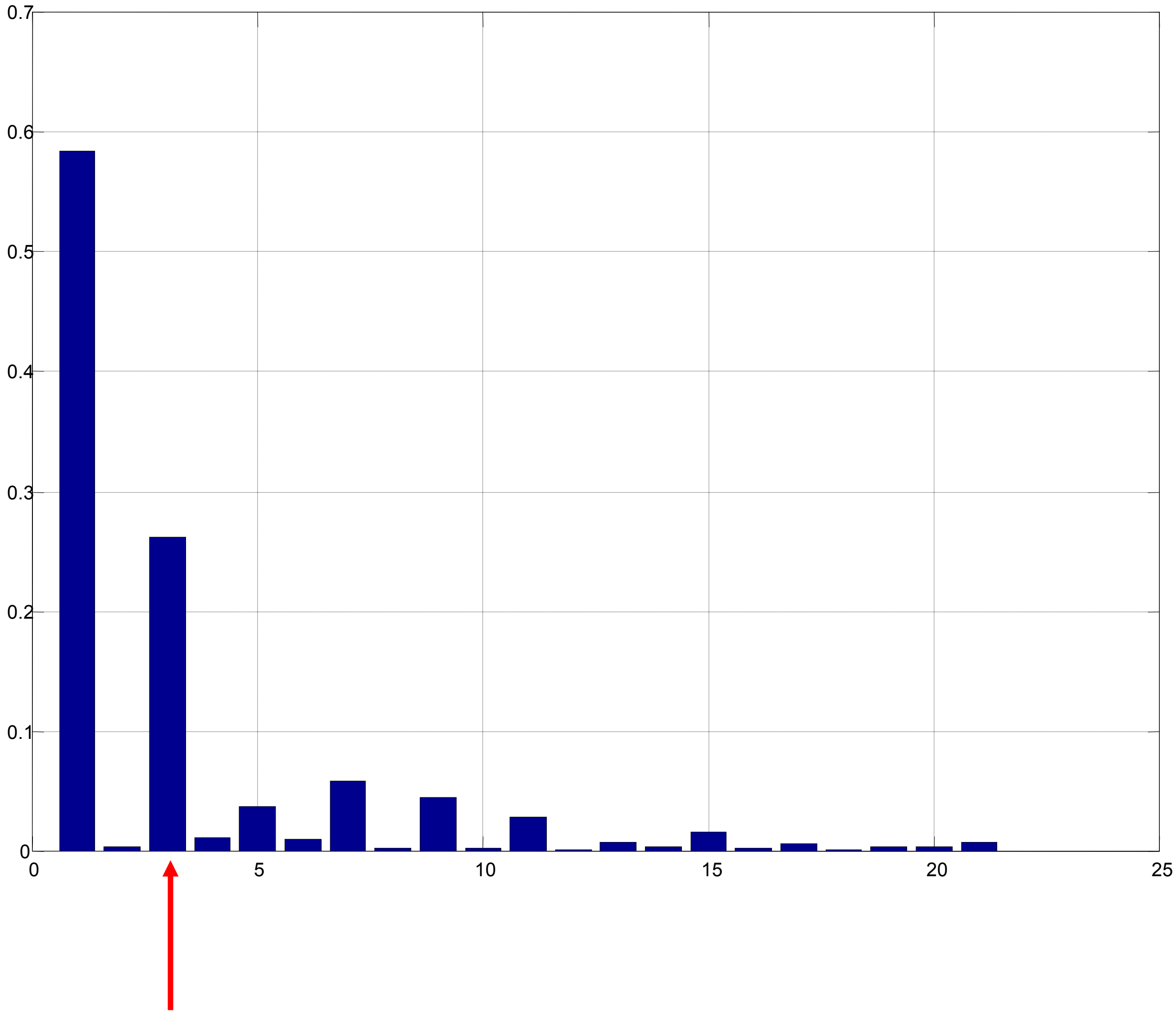








NEV Spectrum



Third Harmonic is 40% of the Fundamental

Non-Linear Loads and Their Impact on NEV

- Proliferation of single phase nonlinear residential loads
  - Rectifiers/Power Electronics
  - Magnetics (e.g., single-phase motors)
- Increased triplen harmonic distortion
- Elevated neutral conductor current
- Interference with capacitors and harmonic filters

Some typical loads drawing 3rd harmonic currents

- Rectifiers
  - Power supplies in all consumer electronics, motor drives, lighting, etc.

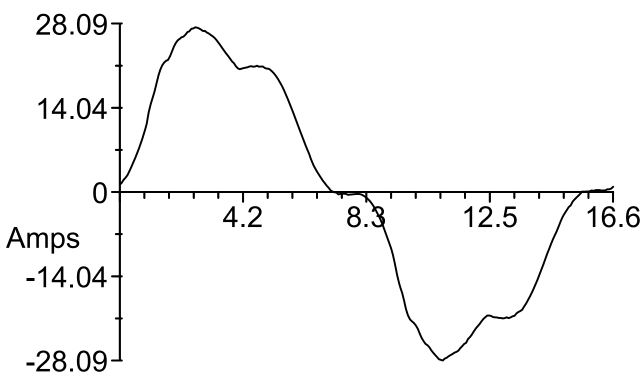
- Single-phase induction motors
  - Used in almost every motorized application in with single-phase service: Compressors (HVAC, Freezers, Refrigerators), Fans, Pumps, Washers and dryers, etc.

  - Several types: Cap start, Cap-start and run, Split-phase, Shaded pole

Residential Load: *L1*

Event: 150 Of 425 | Event Triggered by Time
Duration: 1 Cycles | Event Trigger Cycle 1

Time: 09/25/2004 09:38:49.000
Input: Ia Amps
Cycle: 1

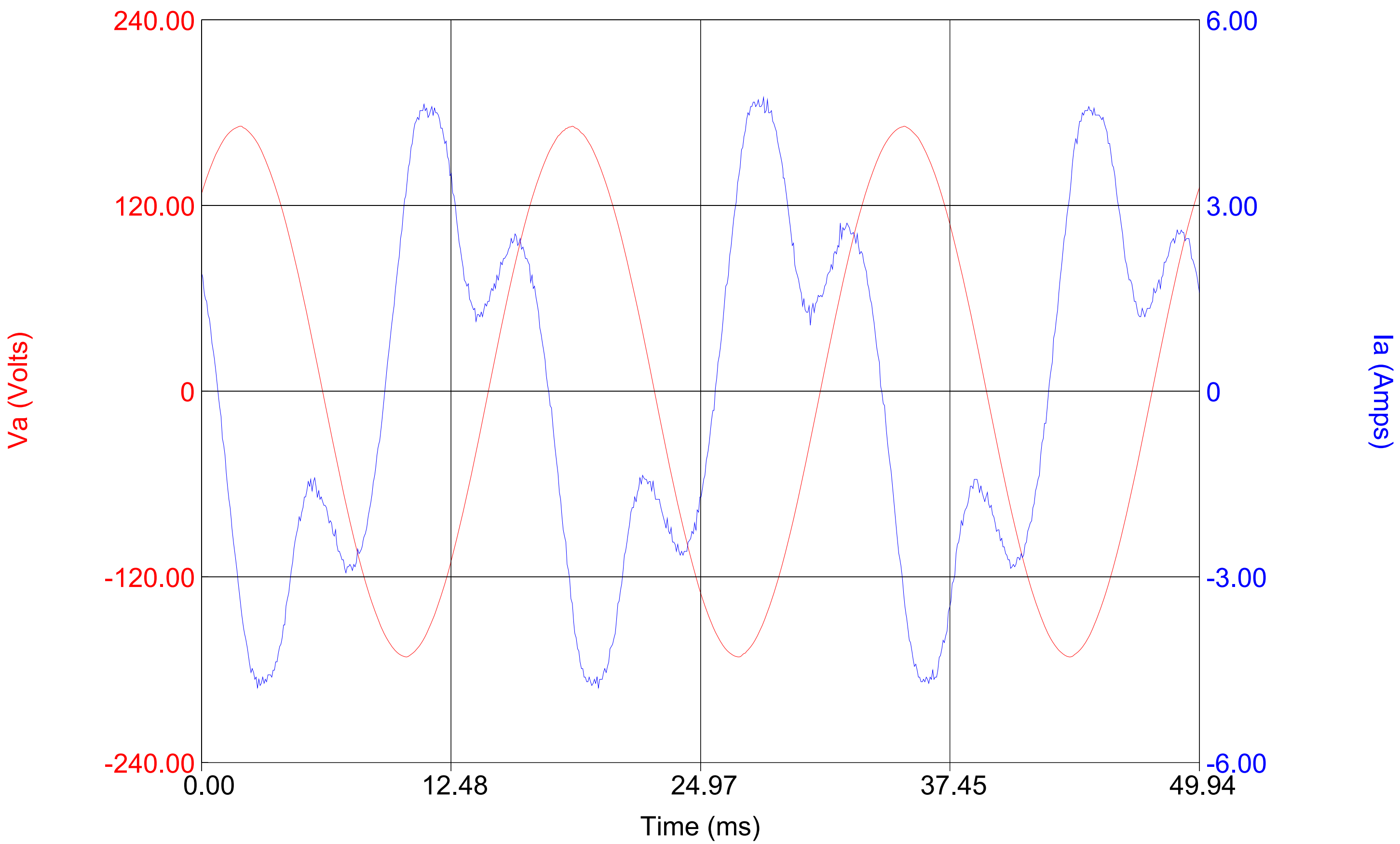


Cycle Waveform

Total Harmonic Distortion	19.52 %
Odd Contribution	19.52 %
Even Contribution	0.51 %
RMS Of Fundamental	17.13 A
RMS Of Fund + Harm	17.45 A
K Factor	1.75

Harm	% Of Fund	Amps	Angle	Harm	% Of Fund	Amps	Angle
Fund	100.00	17.1	0°	2	0.19	0.0	129°
3	12.78	2.2	211°	4	0.33	0.1	319°
5	14.42	2.5	147°	6	0.12	0.0	297°
7	1.92	0.3	189°	8	0.14	0.0	55°
9	1.93	0.3	38°	10	0.12	0.0	270°
11	0.67	0.1	281°	12	0.13	0.0	152°
13	0.43	0.1	228°	14	0.07	0.0	15°
15	0.76	0.1	132°	16	0.10	0.0	194°
17	0.57	0.1	6°	18	0.04	0.0	68°
19	0.16	0.0	312°	20	0.06	0.0	342°
21	0.32	0.1	235°	22	0.05	0.0	174°
23	0.17	0.0	155°	24	0.04	0.0	55°
25	0.16	0.0	70°	26	0.03	0.0	292°
27	0.34	0.1	293°	28	0.06	0.0	177°
29	0.18	0.0	179°	30	0.02	0.0	316°
31	0.18	0.0	352°	32	0.05	0.0	275°
33	0.15	0.0	296°	34	0.02	0.0	42°
35	0.22	0.0	170°	36	0.01	0.0	67°
37	0.19	0.0	61°	38	0.05	0.0	330°
39	0.13	0.0	354°	40	0.01	0.0	117°
41	0.20	0.0	252°	42	0.03	0.0	82°
43	0.16	0.0	174°	44	0.06	0.0	305°
45	0.09	0.0	49°	46	0.06	0.0	302°
47	0.12	0.0	349°	48	0.02	0.0	159°
49	0.09	0.0	246°	50	0.02	0.0	133°
51	0.06	0.0	230°	52	0.02	0.0	13°
53	0.08	0.0	132°	54	0.08	0.0	47°
55	0.06	0.0	64°	56	0.01	0.0	357°
57	0.04	0.0	345°	58	0.05	0.0	56°
59	0.07	0.0	248°	60	0.01	0.0	344°
61	0.05	0.0	175°	62	0.03	0.0	138°
63	0.03	0.0	106°				

1/3 hp Capacitor-Run Motor



The voltage THD is 0.7% but the current THD is 49%, almost all third!

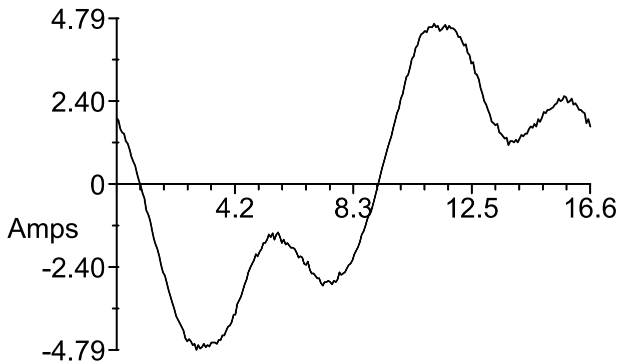
Event: 1 Of 64 — Event Triggered by Time

Duration: 3 Cycles — Event Trigger Cycle 1

Time: 10/28/2003 18:32:36.950

Input: Ia Amps

Cycle: 1

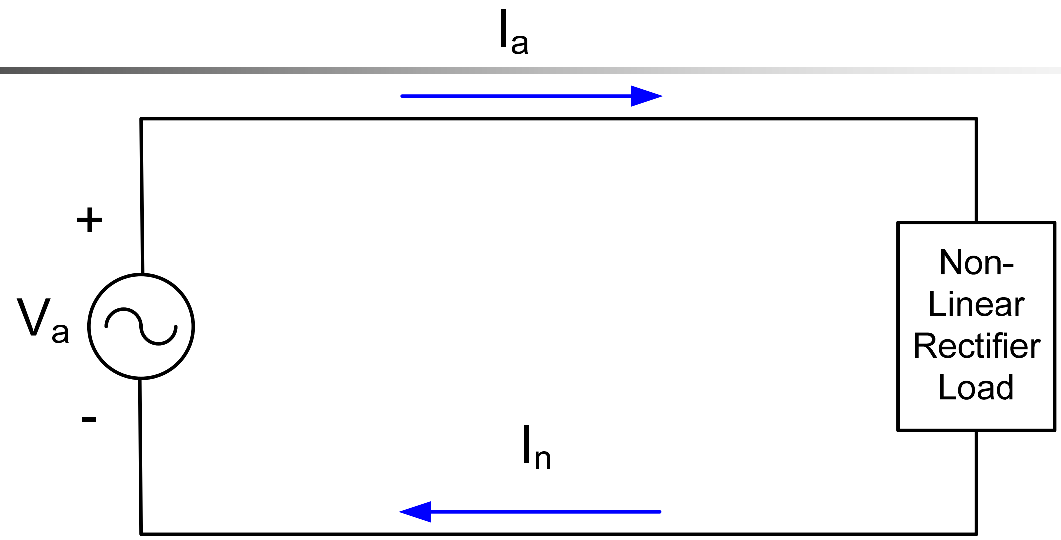


Cycle Waveform

Total Harmonic Distortion	49.04 %
Odd Contribution	48.96 %
Even Contribution	2.81 %
RMS Of Fundamental	2.55 A
RMS Of Fund + Harm	2.84 A
K Factor	2.93

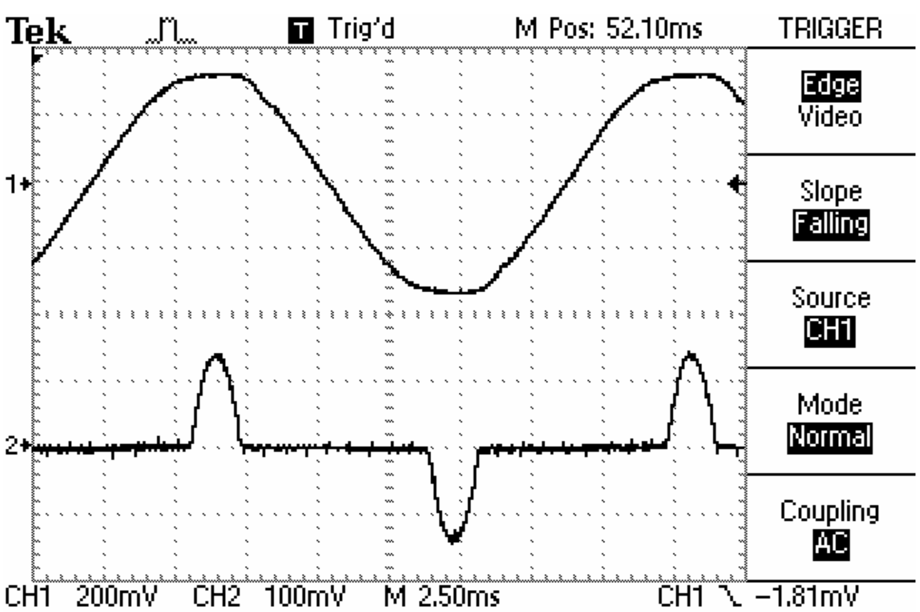
Harm	% Of Fund	Amps	Angle	Harm	% Of Fund	Amps	Angle
Fund	100.00	2.5	0°	2	2.20	0.1	3°
3	48.74	1.2	292°	4	1.02	0.0	338°
5	3.24	0.1	86°	6	0.70	0.0	32°
7	2.65	0.1	206°	8	0.31	0.0	61°
9	1.39	0.0	75°	10	0.49	0.0	31°
11	1.02	0.0	263°	12	0.29	0.0	342°
13	0.73	0.0	209°	14	0.08	0.0	88°
15	0.24	0.0	332°	16	0.45	0.0	80°
17	0.26	0.0	64°	18	0.09	0.0	102°
19	0.26	0.0	255°	20	0.27	0.0	115°
21	0.38	0.0	36°	22	0.21	0.0	85°
23	0.15	0.0	228°	24	0.10	0.0	35°
25	0.19	0.0	353°	26	0.23	0.0	59°
27	0.16	0.0	355°	28	0.13	0.0	80°
29	0.25	0.0	317°	30	0.30	0.0	197°
31	0.13	0.0	89°	32	0.15	0.0	178°
33	0.14	0.0	312°	34	0.16	0.0	332°
35	0.04	0.0	284°	36	0.19	0.0	208°
37	0.17	0.0	244°	38	0.25	0.0	242°
39	0.25	0.0	13°	40	0.05	0.0	216°
41	0.21	0.0	16°	42	0.19	0.0	1°
43	0.08	0.0	178°	44	0.09	0.0	229°
45	0.38	0.0	77°	46	0.08	0.0	209°
47	0.09	0.0	93°	48	0.28	0.0	213°
49	0.18	0.0	178°	50	0.22	0.0	285°
51	0.15	0.0	140°	52	0.08	0.0	246°
53	0.16	0.0	103°	54	0.15	0.0	318°
55	0.25	0.0	177°	56	0.26	0.0	40°
57	0.14	0.0	357°	58	0.08	0.0	330°
59	0.29	0.0	157°	60	0.37	0.0	277°
61	0.12	0.0	290°	62	0.06	0.0	261°
63	0.38	0.0	31°				

Single-Phase PC Load

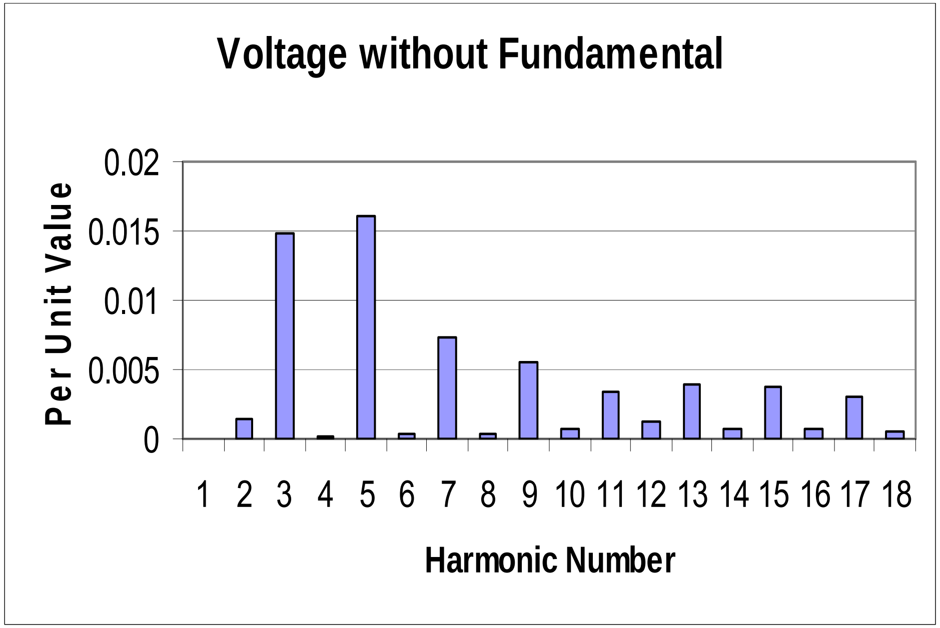


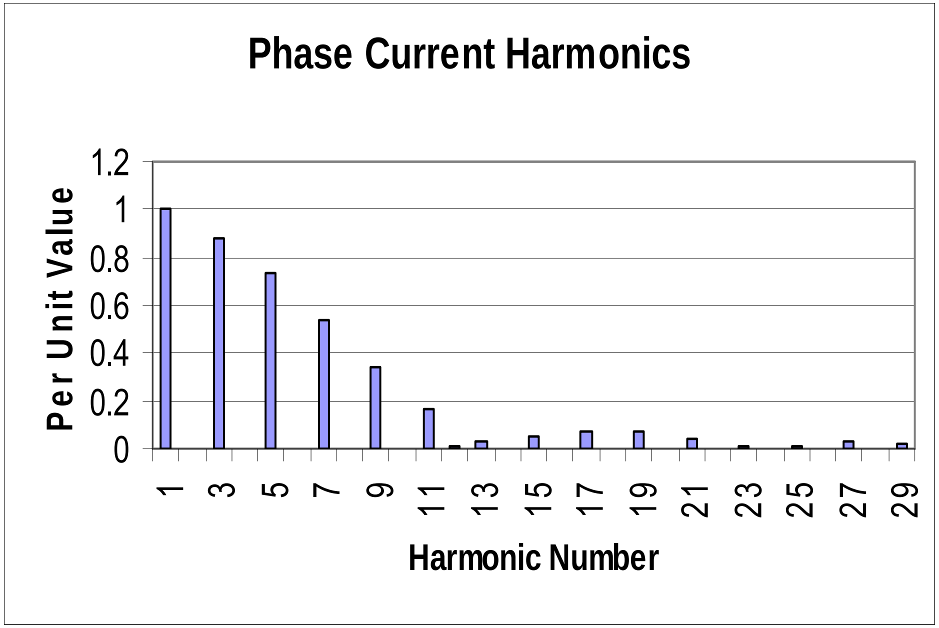
Voltage (notice the distortion near the peaks)

Phase current



Harmonic Analysis

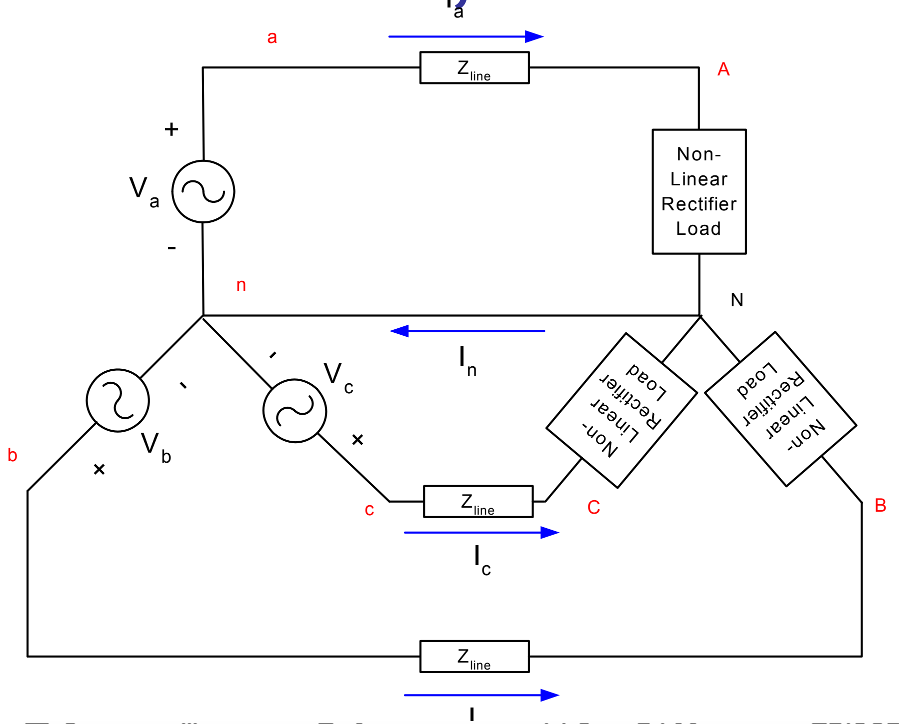




Voltage THD = 2.5%

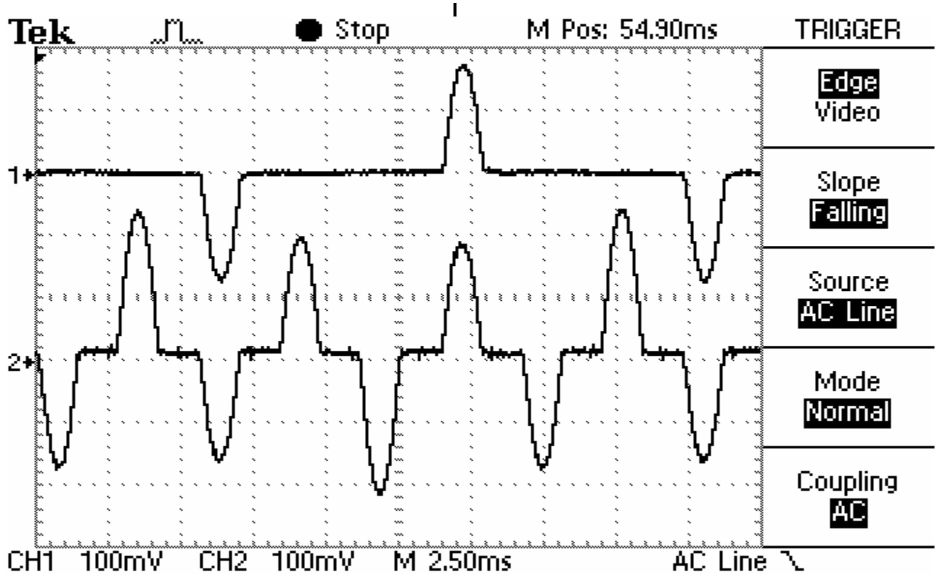
Current THD = 133%

Three PC's, connected in Y



Phase B Current

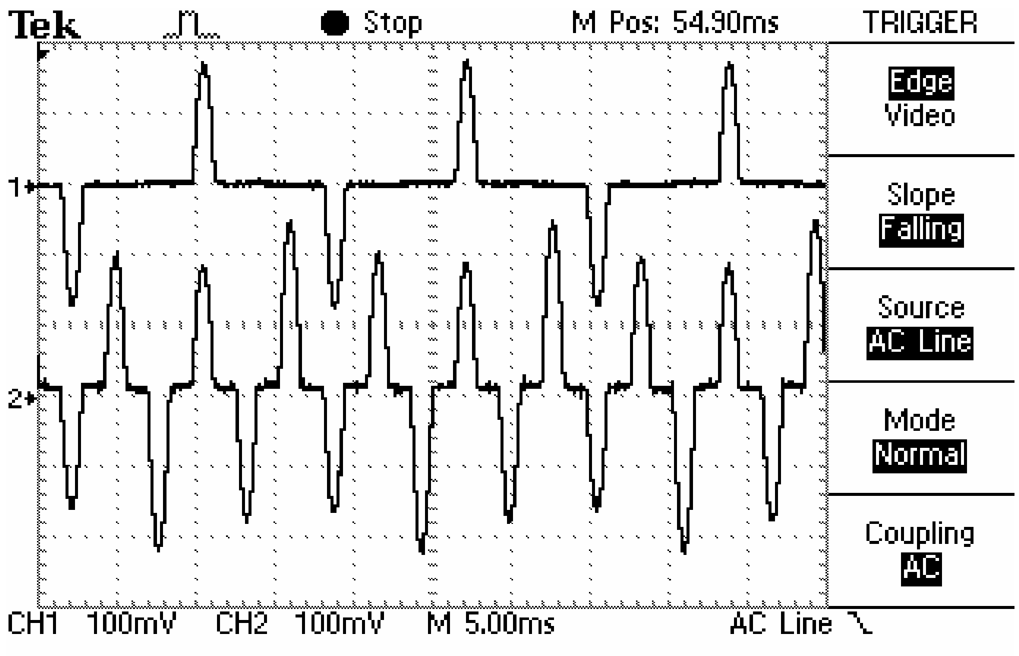
Neutral Current

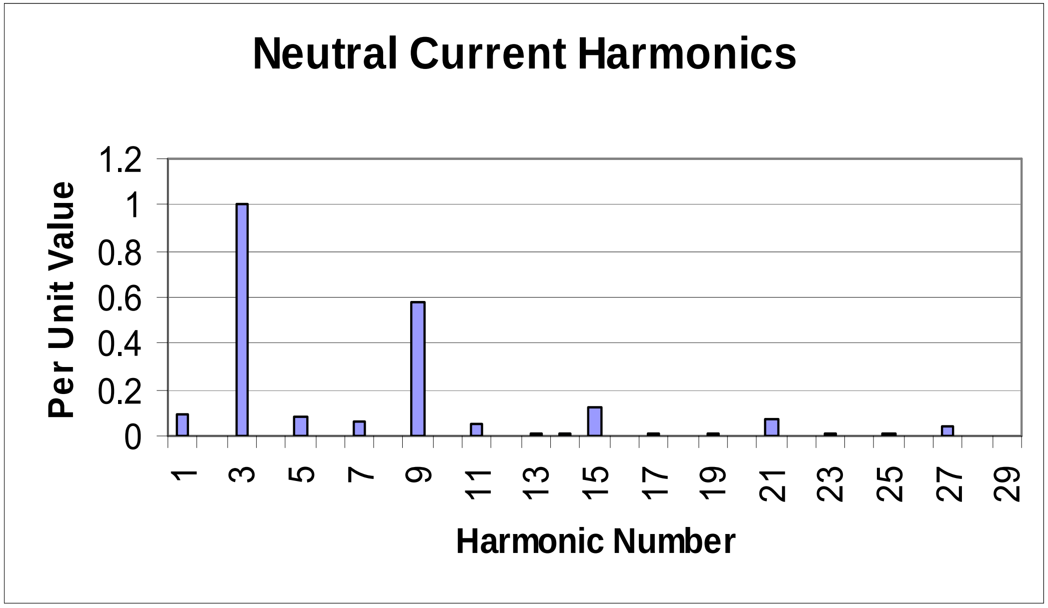


Harmonic Analysis

Phase A

Neutral

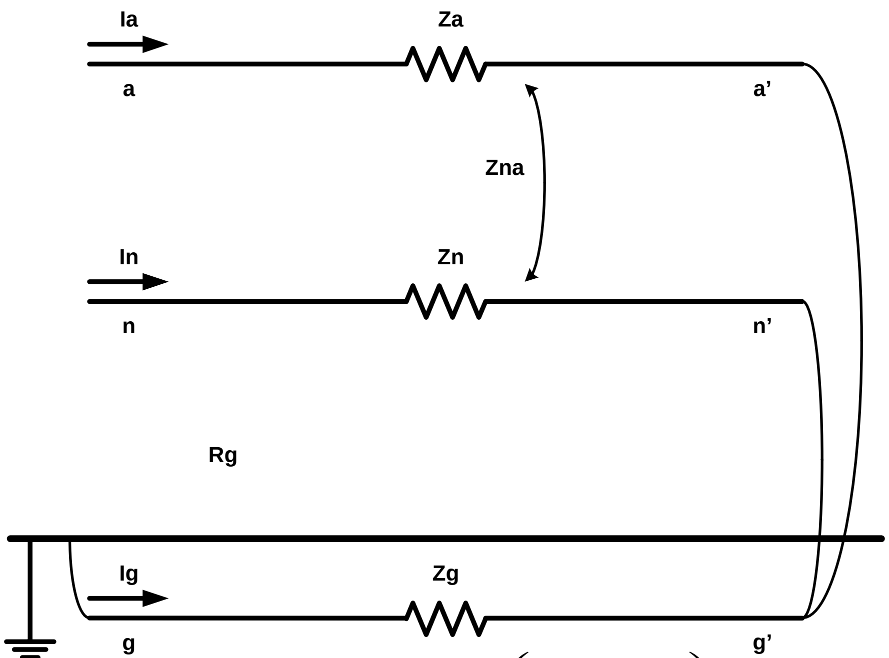




Research Objectives

- Develop detailed models for power system components, including nonlinear devices, tailored for NEV analysis
  - Need a 4-wire model
- Construct a multiphase harmonic load flow algorithm to obtain the NEV directly
  - The elevated NEV is due to load current, not fault current
- Analyze NEV problem in distribution systems with a large number of nonlinear devices distributed within the network
  - The focus is on simple distribution networks without parallel bonded utilities to get an understanding of the problem.

Transmission Line Model I

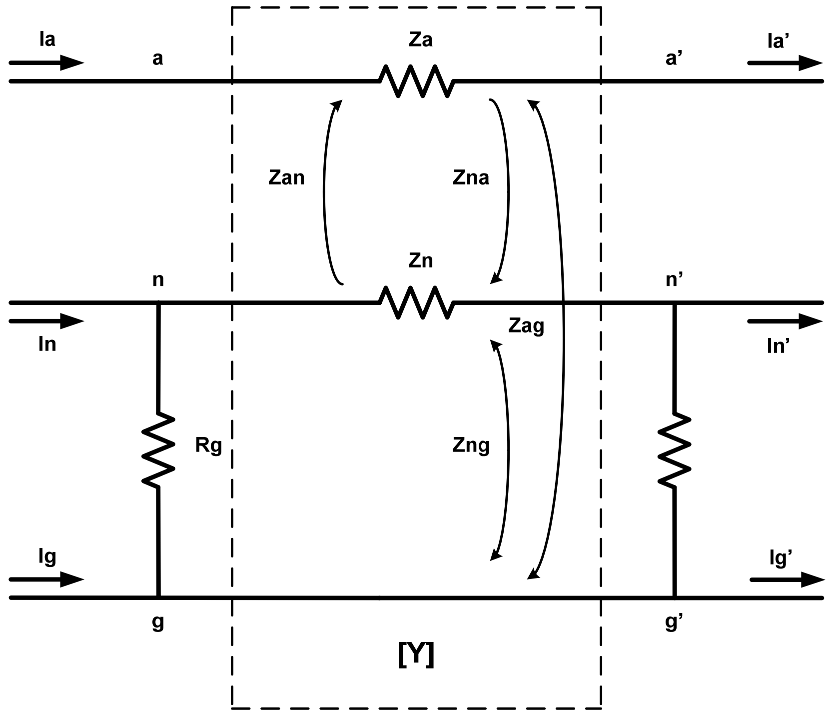


Carson's Line

$$Z_{ii-g} = R_i + j2\omega T \ln\left(\frac{S_{ii}}{GMR_i}\right) + \left(4\omega P + j4\omega Q\right)T \ \Omega/\text{mi}$$

$$Z_{\text{ij-g}} = j2\omega T \ln\left(\frac{S_{ij}}{d_{ij}}\right) + \left(4\omega P + j4\omega Q\right)T \ \Omega/\text{mi}$$

Transmission Line Model II



Practical Distribution Line

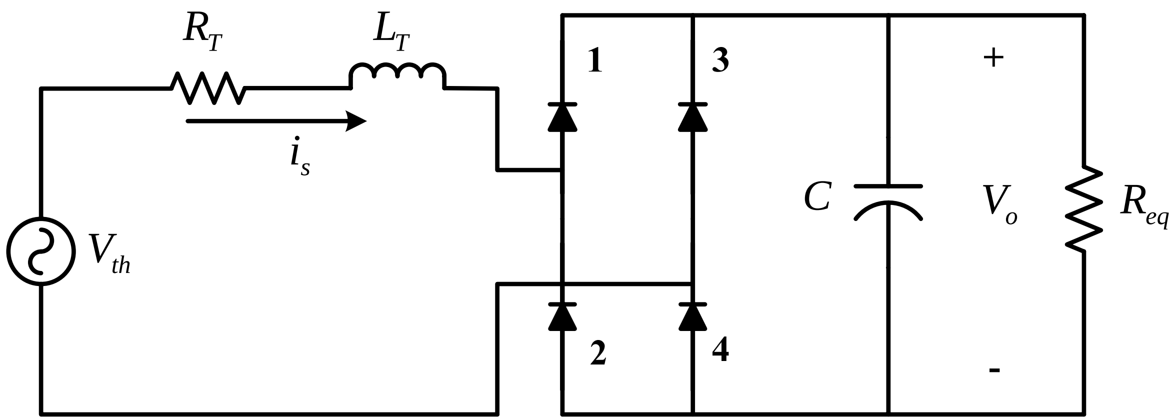
$$I_a + I_n + I_g = 0$$

$$V_{ii'} + V_{g'g} = V_i - V_{i'} + V_{g'} - V_g$$
$$= V_{ig} - V_{i'g'}$$

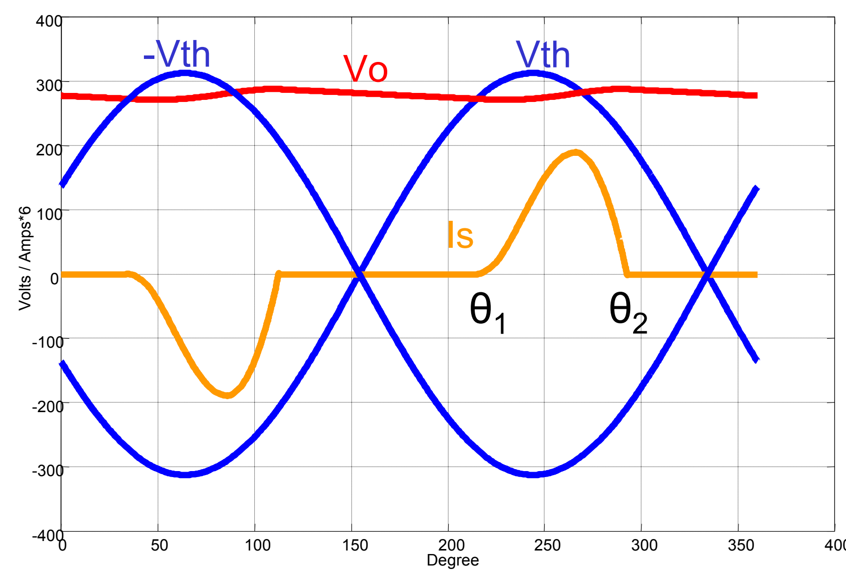
$$\begin{bmatrix} V_{ag} \\ V_{ng} \end{bmatrix} - \begin{bmatrix} V_{a'g'} \\ V_{n'g'} \end{bmatrix} = \begin{bmatrix} Z_{aa-g} & Z_{an-g} \\ Z_{an-g} & Z_{nn-g} \end{bmatrix} \begin{bmatrix} I_a \\ I_n \end{bmatrix}$$

By taking advantage of the Kirchhoff Current Law, loop voltage equations can be converted to branch voltage equations using the same loop impedances. Thus, we can solve for the phase-to-ground and neutral-to-ground voltage directly.

Single Phase Rectifier Waveform



The input current to the rectifier is a function of the input voltage waveshape and circuit parameters. An iterative procedure is used to find θ_1 and θ_2. These are used to determine the current spectrum.



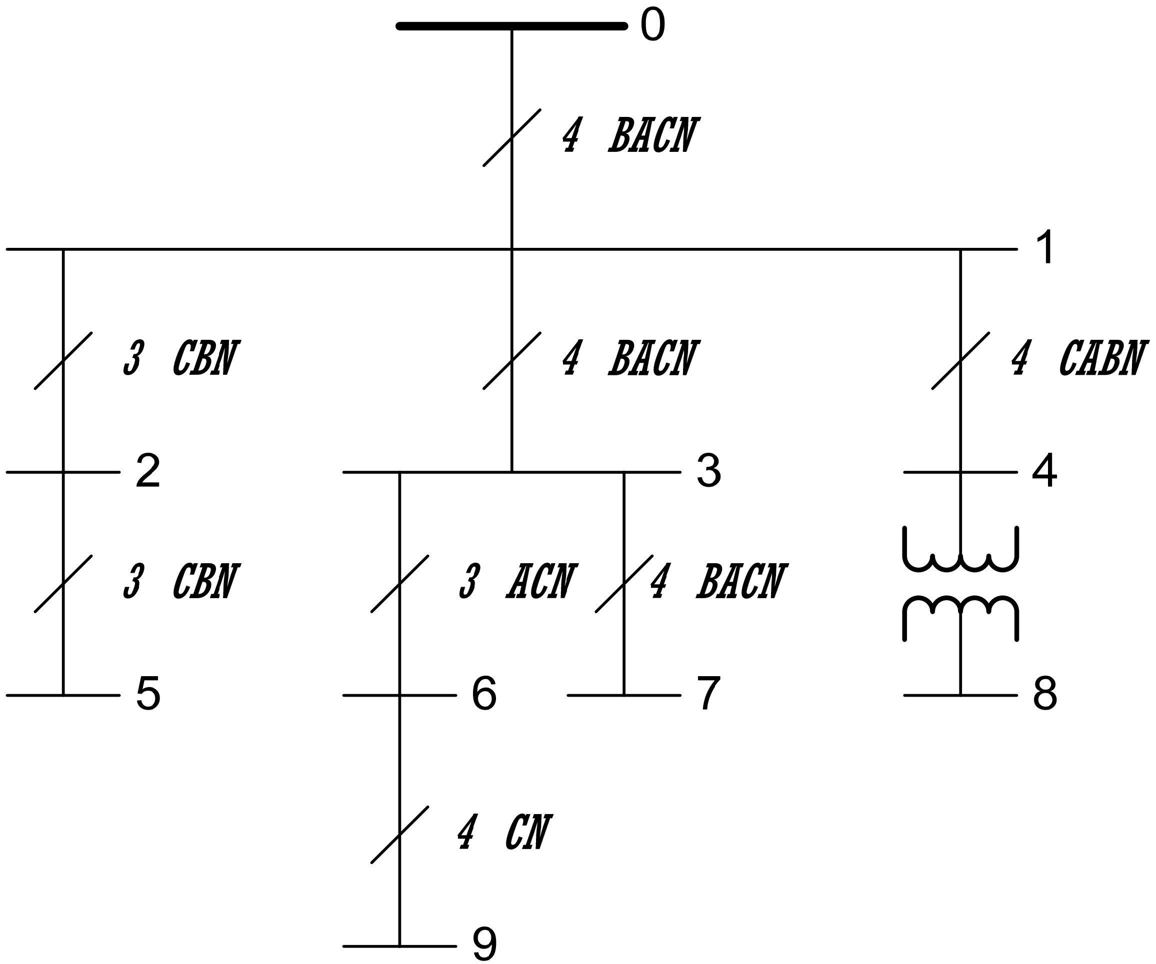
Multiphase Harmonic Load Flow

This is used to determine the voltage spectra at all nodes, including the neutral, with respect to local earth.

- Given the node voltages from initial guess or previous iteration results, calculate the nodal current injections
- Add up all the branch currents, starting from branch farthest away from source back to the root node
- Calculate voltage drop across each branch using the branch currents, and update nodal voltage from source out to the ends of network
- Compare with previous iteration's node voltages for convergence

Test on IEEE Example Distribution System

IEEE TEST SYSTEM



Test Scenarios

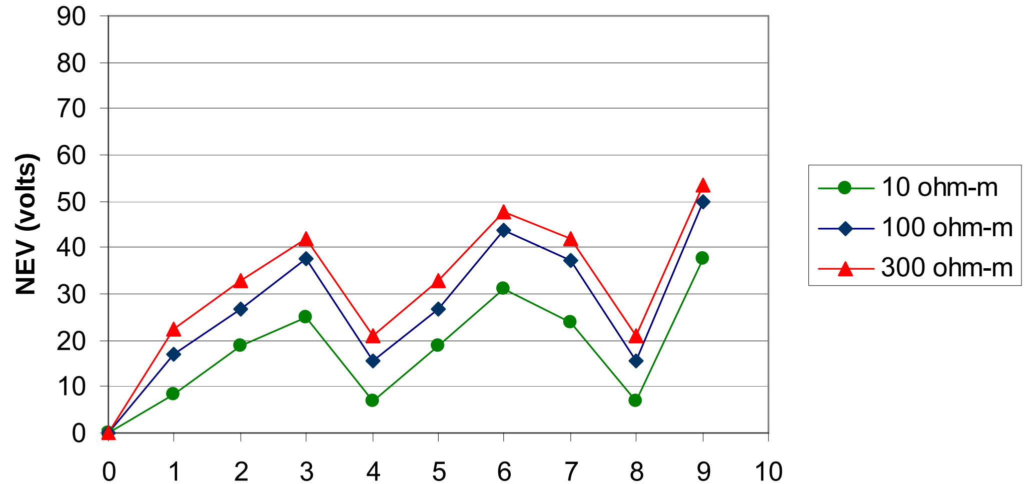
- Regular loads at different earth resistivities

  ρ = 10, 100, 300 Ω-m

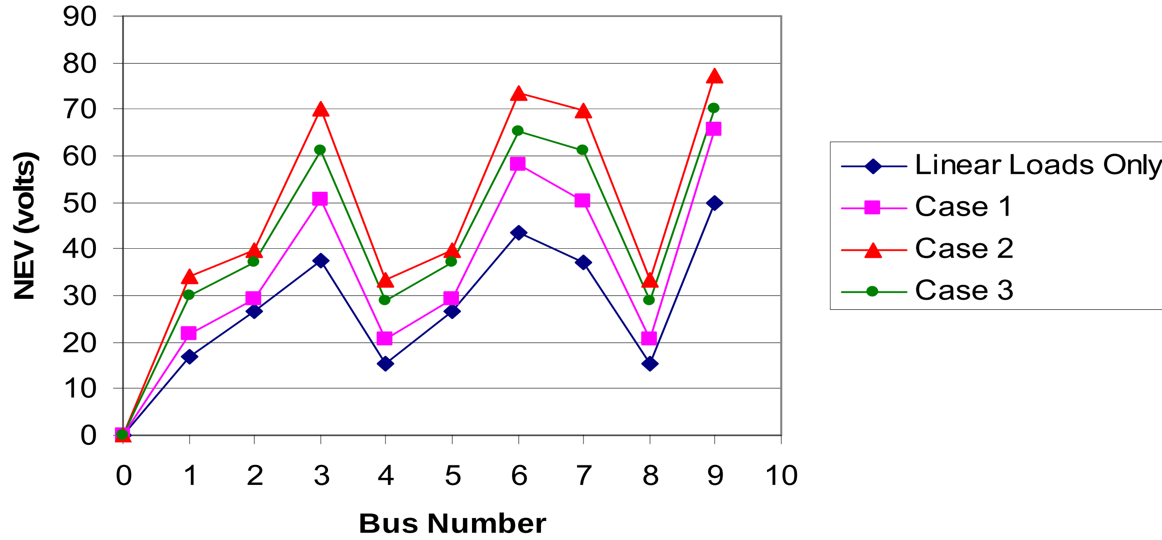
- Harmonic loads with different phasing using ρ = 100 (corresponds to $R_g = 30\Omega$)
  - Case 1: single rectifier @ 1ϕ bus
  - Case 2: balanced rectifiers @ 3ϕ bus
  - Case 3: unbalanced rectifiers @ 3ϕ bus

Test Results

Fundamental Load Test



Harmonic Load Test



Conclusion

- Triplen harmonics are present in 4-wire distribution networks, particularly those with residential loads.
- The traditional modelling techniques do not enable computation of the Neutral-to-Local Earth Voltage.
- A model has been developed which, in conjunction with a harmonic load flow, enables computation of the neutral-to-local earth voltage.
- Accurate load modeling will provide more accurate results, but the more-traditional and simple current injection models will provide reasonably accurate results.
- Future work will include longer feeders, models of other non-linear load types (e.g., motors), distributed loads, and field tests.