Elevated Neutral to Earth Voltages Due to Harmonics – A T&D Update

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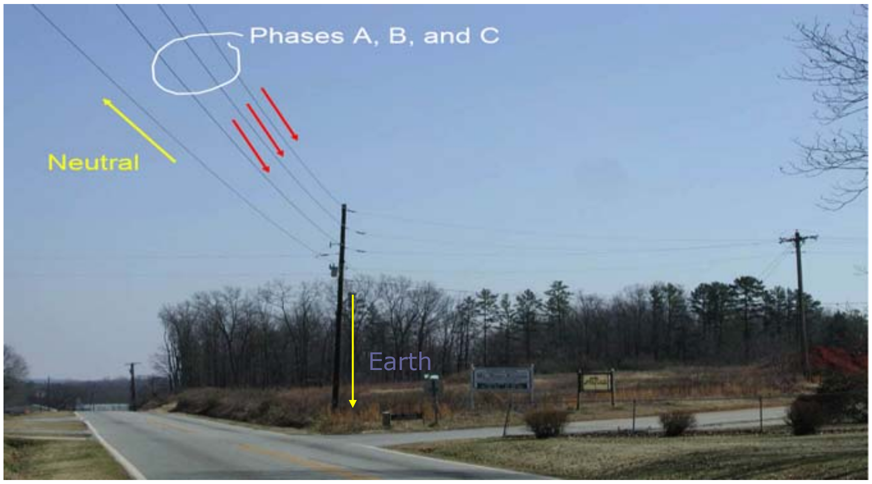
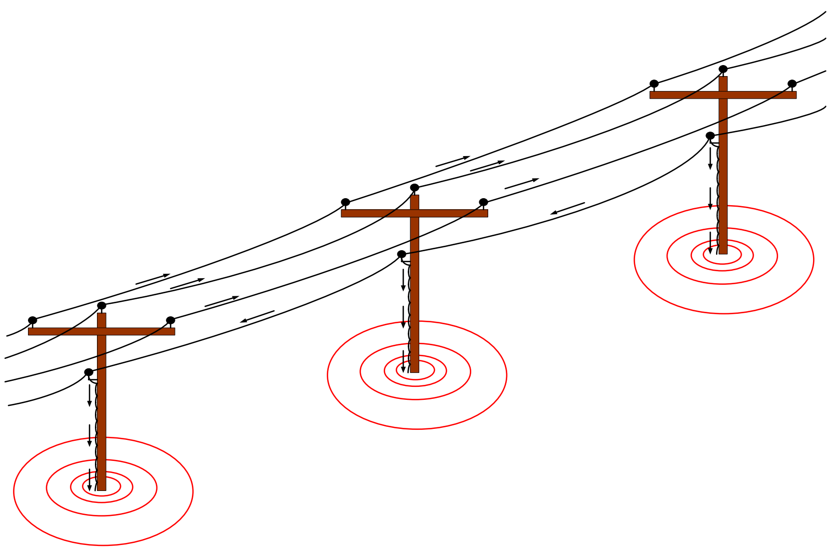
Two Publications of Interest

- *"Analysis of Elevated Neutral-to-Earth Voltage in Distribution Systems with Harmonic Distortion"* to appear in 2008, IEEE Trans. on Power Delivery, Paper TPWRD-00652-2006 by Randy Collins and Jian Jiang.
- *"Elevated Neutral-To-Earth Voltage In Distribution Systems With Harmonic Distortion,"* PhD Dissertation, Clemson University, by Jian Jiang, 2007.

Three Phase Distribution Feeder with Single Phase Lateral



Equipotentials surround ground rods



What do we mean by NEV and how does this relate to stray voltage?

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- Neutral-to-earth voltage is the neutral conductor voltage referred to remote earth.
- The NEV can be much higher than the "stray voltage" that can be contacted by humans or animals, so the results must be tempered with this understanding.
- Knowledge of NEV under different system conditions is extremely important in analyzing and mitigating stray voltage problems arising from NEV.

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Common Sources and Conventional Resolutions for Elevated NEV and Stray Voltage

- Sources
  - Power system grounding
  - Load unbalance
  - Transformer connections
  - Neutral conductor impedance
- Alleviation methods
  - Balance the loads
  - Three-phase single phase laterals
  - Increase the neutral conductor size
  - Improve grounding connection
  - Repair bad neutral connections and splices

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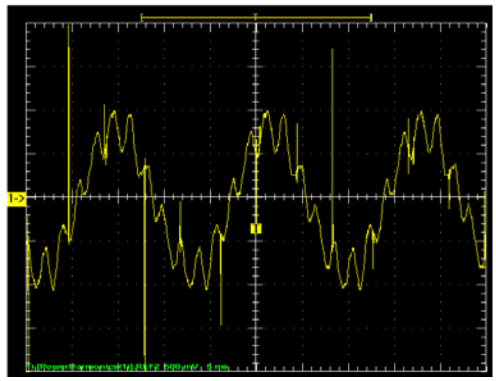
Trends of Consumer Electronics and Their Impact on NEV

- Proliferation of single phase nonlinear power supplies in electronic appliances
- Non-linear response of single-phase motors to voltage distortion
- Increased triplen harmonic distortion
- Elevated neutral conductor current



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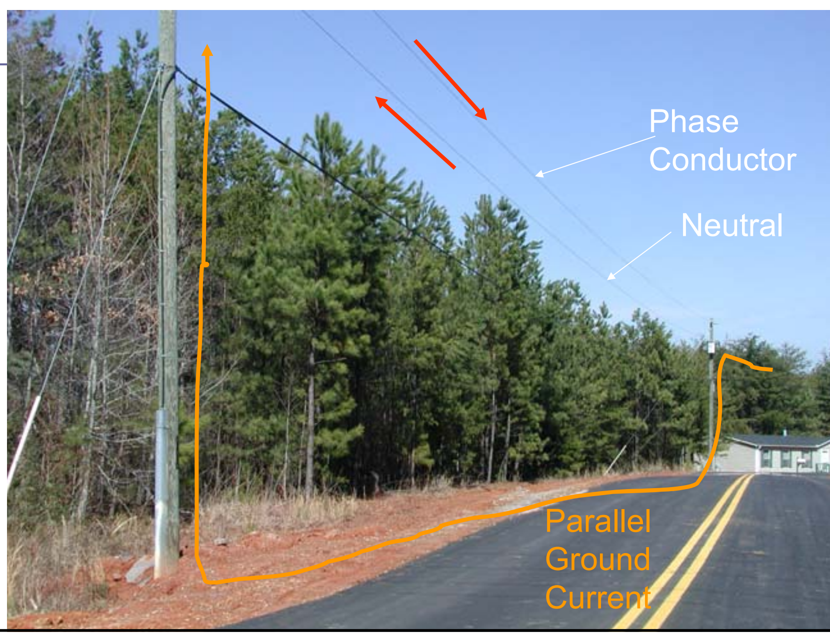
Our Research Objectives

- Develop means for systematic analysis of NEV in distribution power systems including harmonic distortion
- Develop procedures to predict NEV for planning and assessment, and to troubleshoot existing problems
- Assess the effects of NEV mitigation techniques in an environment with harmonic distortion

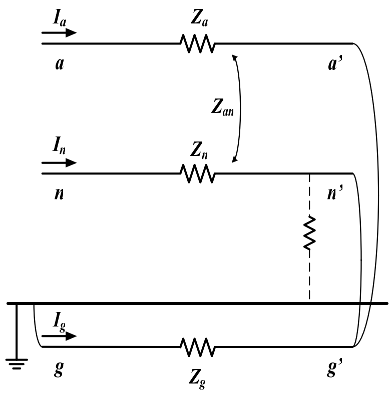
Steps of This Project

- Develop detailed power system models, including the nonlinear loads, for NEV analysis.
- Construct a multiphase harmonic load flow algorithm to calculate NEV.
- Test the algorithm accuracy by comparing with the actual field measurement.
- Examine the algorithm capabilities using a standard IEEE example system.
- Develop procedures for locating sources of elevated NEV and assess common methods in reducing NEV with nonlinear loads.

Single-Phase Distribution Feeder Modeling



Conventional Transmission Line Model (Carson's Line)



$$Z_{ii} = r_i + 4\omega P_{ii} G + j\left(2\omega \ln\left(\frac{S_{ii}}{D_{ii}}\right) + 4\omega Q_{ii}\right)G$$

$$Z_{ij} = 4\omega P_{ij} G + j\left(2\omega \ln\left(\frac{S_{ij}}{D_{ij}}\right) + 4\omega Q_{ij}\right)G$$

$$i, j = a, n$$

$$P_{ij} = \frac{\pi}{8} - \frac{1}{3\sqrt{2}} k_{ij} \cos\theta_{ij} + \dots$$

$$Q_{ij} = -0.0386 + \frac{1}{2}\ln\frac{2}{k_{ij}} + \dots$$

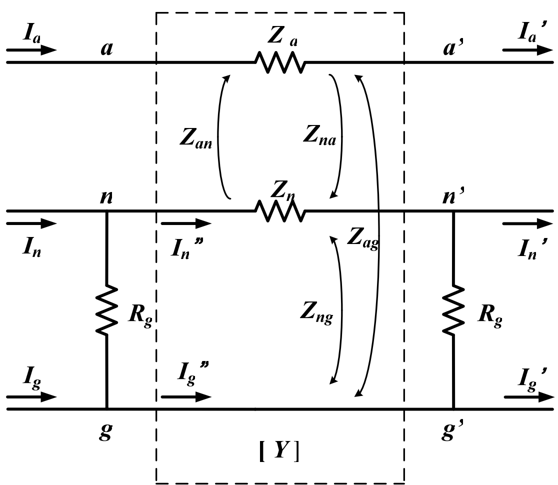
$$k_{ij} = 8.65 \times 10 \left(S_{ij}\sqrt{f/\rho}\right)$$

$$G = 1.60935 \times 10^{-4}$$

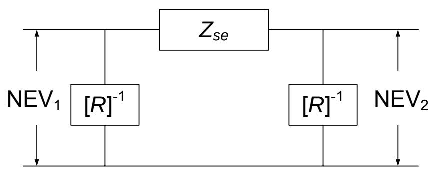
$$\begin{bmatrix} V_{aa'} \\ V_{nn'} \end{bmatrix} = \begin{bmatrix} Z_{aa-g} & Z_{an-g} \\ Z_{na-g} & Z_{nn-g} \end{bmatrix} \begin{bmatrix} I_a \\ I_n \end{bmatrix}$$

S — *Distance between conductors and the images*
D — *Distance between conductors*

Practical Distribution Feeder with Non-zero Grounding Resistance



Equivalent PI Model



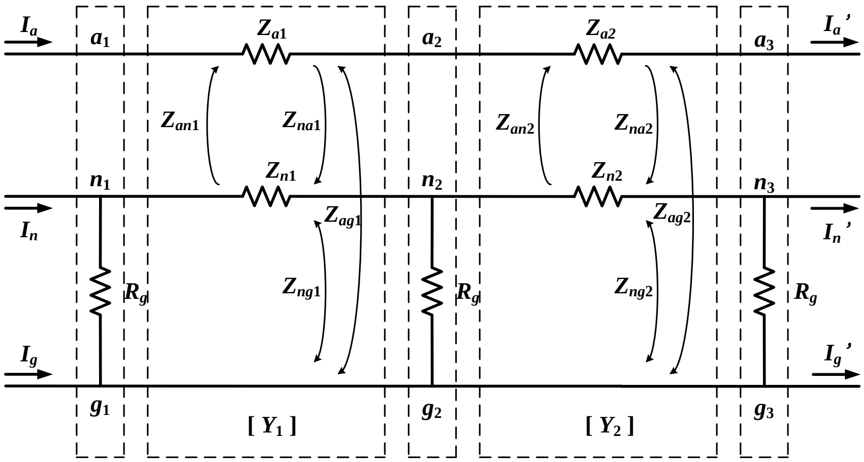
- The series impedance is the same as in Carson's line

$$[Z_{se}] = \begin{bmatrix} Z_{aa} & Z_{an} \\ Z_{an} & Z_{nn} \end{bmatrix}$$

- The shunt admittance matrix is obtained from the grounding resistance

$$[R]^{-1} = \begin{bmatrix} 0 & 0 \\ 0 & \frac{1}{R_g} \end{bmatrix}$$

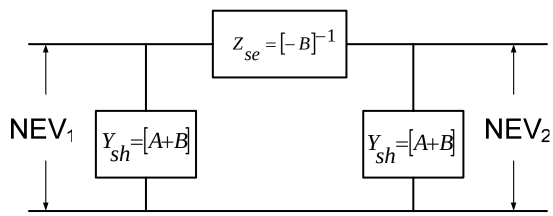
Multiple Segments Assembling



Equivalent PI Model

- Apply Kron reduction to Ybus to eliminate the nodes in the middle of the feeder
- Derive the equivalent pi model from the resultant matrix

$$\left[Y_{bus}^{new} \right] = \begin{bmatrix} [A] & [B] \\ [B] & [A] \end{bmatrix}$$

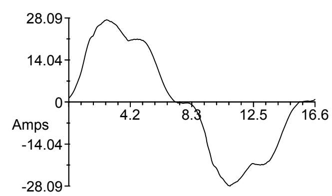


Step of This Project

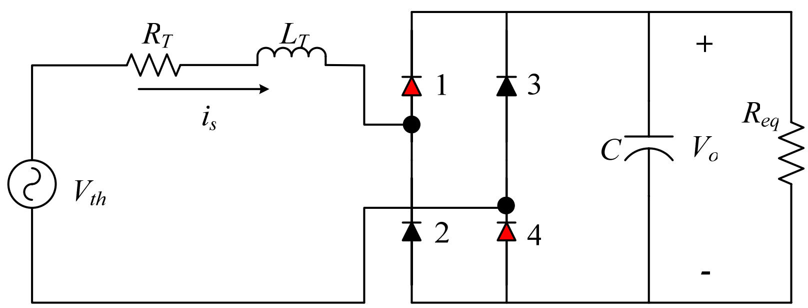
- ☑ Linear modeling
- ❑ Nonlinear modeling
- ❑ Multiphase harmonic load flow
- ❑ Examine algorithm capability using IEEE example system
- ❑ Test algorithm accuracy by comparing with actual field measurements
- ❑ Assess three-phasing method with harmonic distortion present

Typical Non-Linear Loads in Distribution Systems

- Three phase AC/DC converter
- ☑ Single phase load with uncontrolled rectifier front end
- Single phase induction motor
- Fluorescent lighting



Single Phase Rectifier



$$V_{th} = R_T i_s + \omega L_T \frac{di_s}{d\theta} + V_o$$

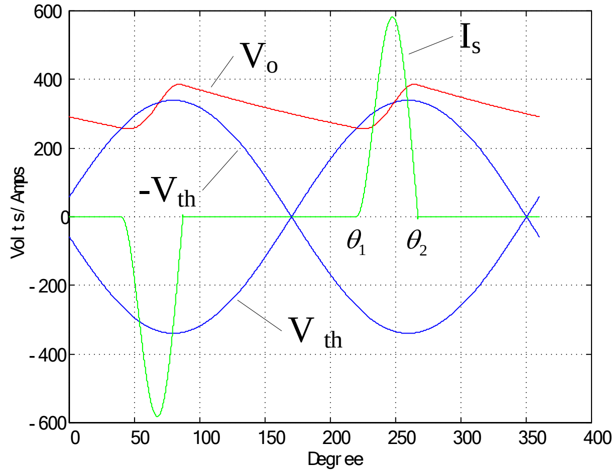
$$i_s = \omega C \frac{dV_o}{d\theta} + \frac{V_o}{R_{eq}}$$

$$\Longrightarrow$$

$$\frac{d^2V_o}{d\theta^2} + (\alpha_1 + \alpha_4)\frac{dV_o}{d\theta} + (\alpha_1\alpha_4 + \alpha_2\alpha_3)V_o = \alpha_2\alpha_3 V_{th}$$

$$\frac{d^2 i_s}{d\theta^2} + (\alpha_1 + \alpha_4)\frac{di_s}{d\theta} + (\alpha_1\alpha_4 + \alpha_2\alpha_3)i_s = \alpha_2\alpha_4 V_{th} + \alpha_2 \frac{dV_{th}}{d\theta}$$

Typical Waveforms of a Single Phase Rectifier



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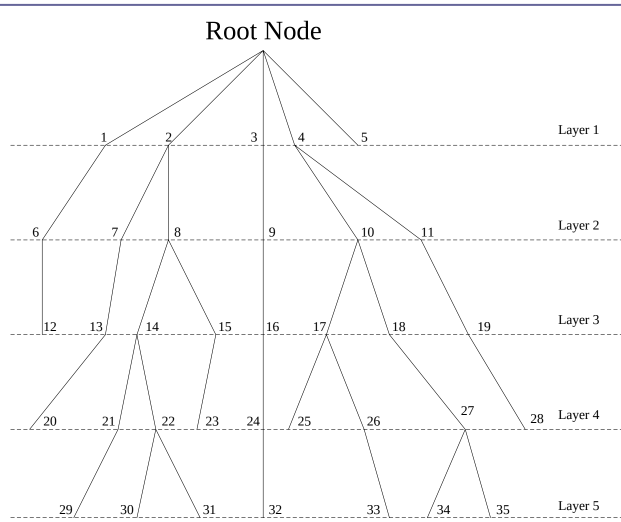
Multiphase Harmonic Load Flow for NEV Analysis

- The nature of NEV problems demands a multiphase load flow solution
- NEV problems are often more prevalent in radial distribution systems
- Simple load flow program with robust convergence is desired

A Typical Radial Distribution Topology



Multiphase Load Flow Algorithm - Iterative Solution

- Calculate the series impedance matrix for each branch and sum up the shunt admittance at every node except for the root node
- Assume the node voltages for initialization
- Find the nodal injection current using the node voltage in the previous iteration and determine the division between the neutral conductor and earth currents
- Back sweep the system to find the branch current from the last layer by applying KCL
- Forward sweep the system to find the voltage drop for each branch from the first layer and update the nodal voltage
- Check convergence and start a new iteration if necessary

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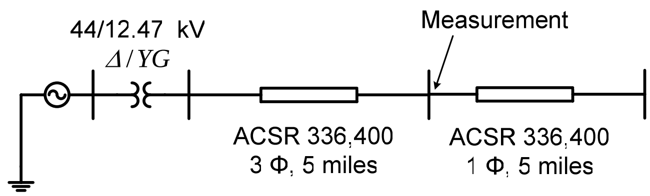
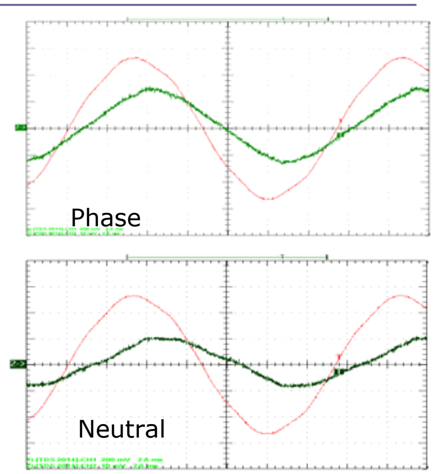
Algorithm Verification Using Actual System Measurement



- Three phase feeder with a single phase lateral (all conductor sizes are 336 kcmil)
- Transformer impedance: 7%
- Assume uniformly distributed loads after the measuring point and ignore any load before it

Actual Measurement



Meter ratios: Voltage (5000 V/div), Current (10 A/div)

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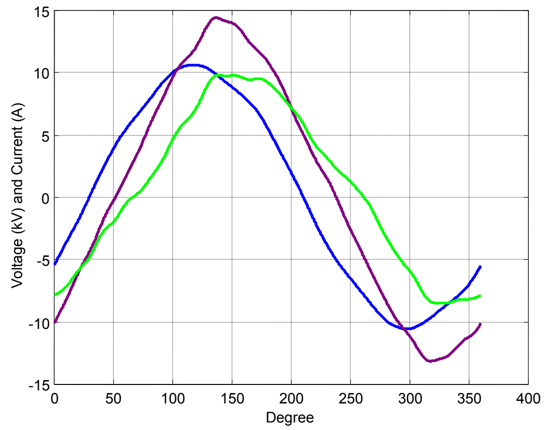
Synchronized Measurement Waveforms



- Phase voltage
- Phase current
- Neutral plus messenger current

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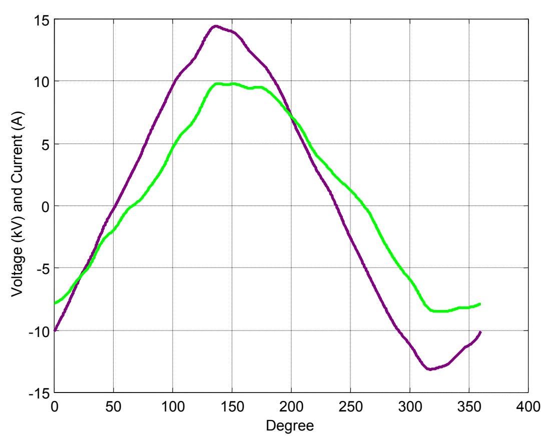
Synchronized Measurement Waveform



- Phase voltage
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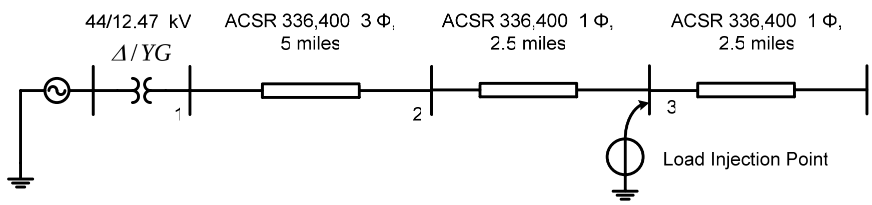
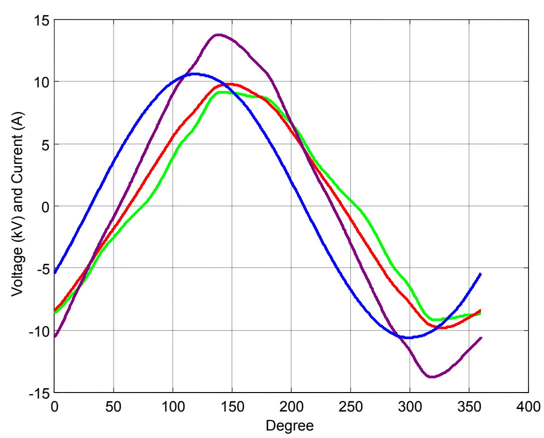
NEV Simulation



- The measured current is injected half way from the measuring point due to the uniform load distribution
- The calculated neutral current in the single phase lateral is compared with the measurement to check the modeling and algorithm accuracy

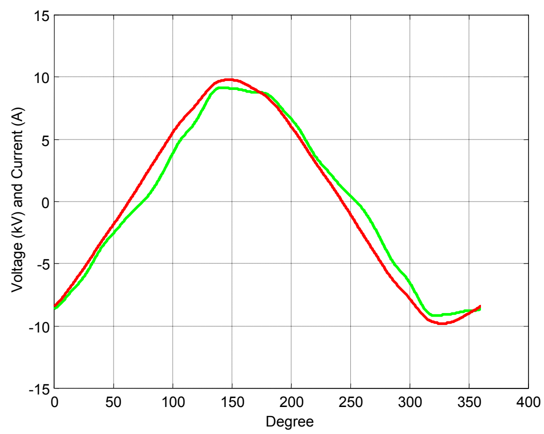
Waveform Comparison Using Simulation Results



- Phase voltage
- Phase current
- Calculated neutral current
- Measured neutral current

Close match-up between measurement and calculation

Comparison of Measurement and Simulation Results



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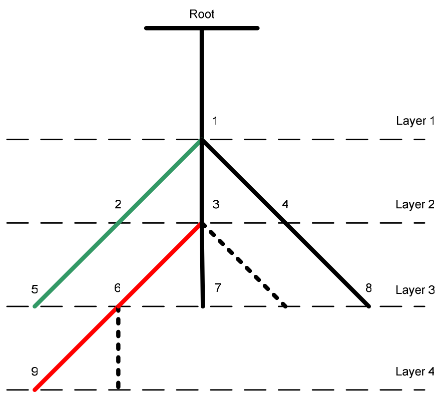
Test on IEEE Example Distribution System



Load flow algorithms test system

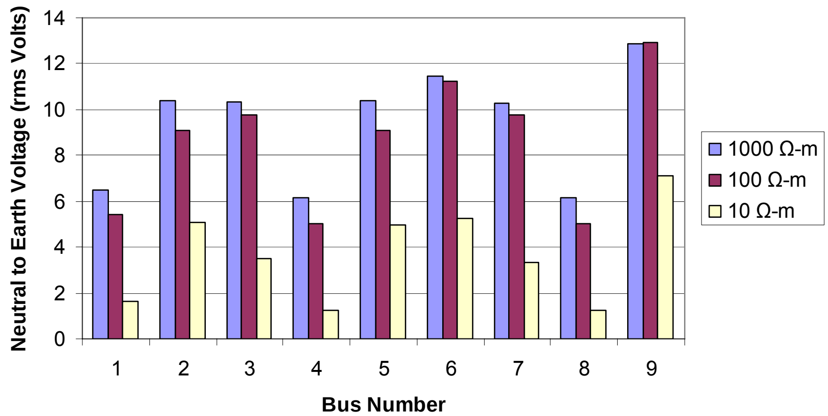
- Relative short feeder
- High loading level
- Various line configurations
- Different load connections

- Black – Three phase
- Green – Two phase
- Red – One phase

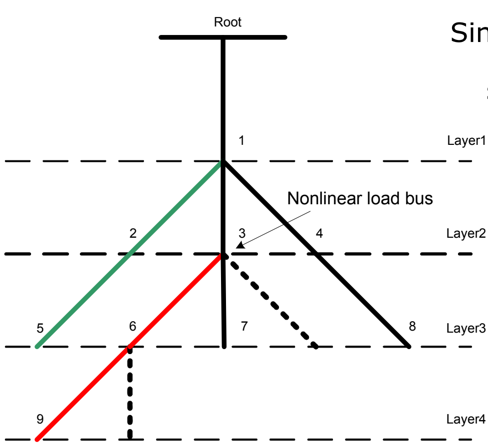
Linear Loads on The System

Load Type	Bus No.	Phase 1		Phase 2		Phase 3	
		kW	kvar	kW	kvar	kW	kvar
Y	8	160	110	120	90	120	90
Y	2	0	0	170	125	0	0
Δ	5	0	0	230	132	0	0
Δ	3	385	220	385	220	385	220
Δ	3	0	0	0	0	170	151
Y	9	0	0	0	0	170	80

NEV Test with Linear Loads at Different Earth Resistivities



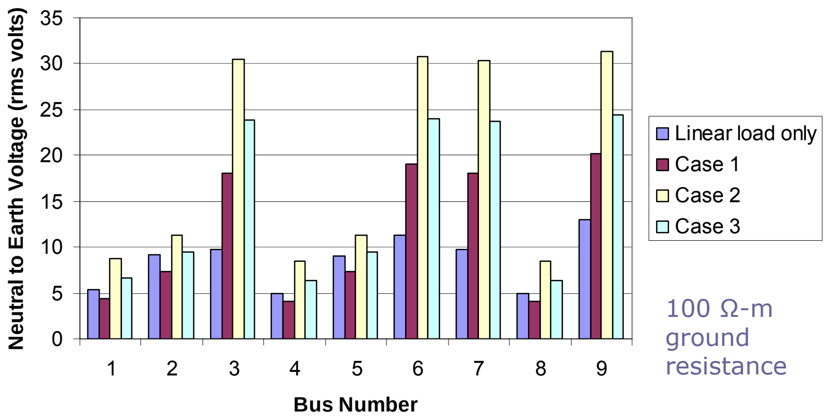
The Effect of Non-Linear Loads on NEV



Single-phase rectifier: 240V, 30kW with a 4200μF smoothing capacitor

- Case 1: A single rectifier on a single-phase line at bus 3
- Case 2: Three balanced rectifiers on a three-phase line at bus 3
- Case 3: Two identical rectifiers on two phases of a three-phase line at bus 3 to form an unbalanced load

NEV RMS Values with Different Nonlinear Load Combinations



100 Ω-m ground resistance

Case 2: Three identical single-phase rectifiers at bus 3

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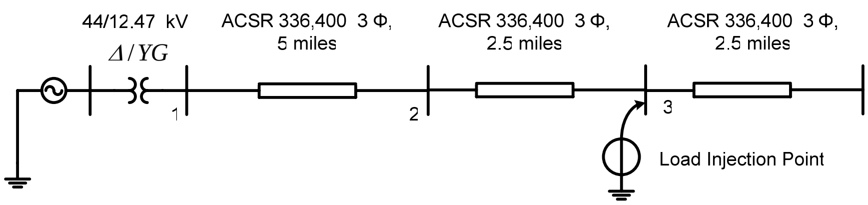
Three Phasing Single Phase Lateral

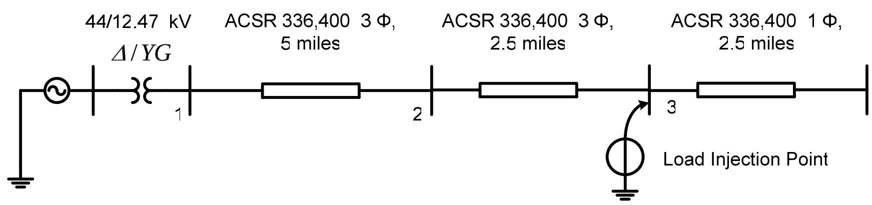


- A common practice for distribution system upgrade
- Simulation setup
  - Three phasing the single phase lateral
  - Evenly distribute the measured current among the three phases
  - Inject the currents half way from the measuring point

Detailed Results of Harmonic Components

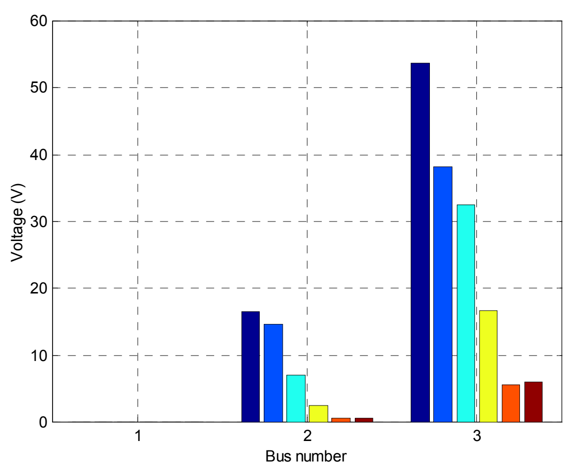
Harmonic Order	Single Phase				Three Phase			
	NEV (V)	Current (A)			NEV (V)	Current (A)		
		I_{ph}	I_n	I_E		I_{ph}	I_n	I_E
1	12.74	9.15	6.66	2.70	0.18	3.05	0.04	0.04
3	0.93	0.42	0.25	0.18	0.93	0.14	0.25	0.18
5	0.07	0.03	0.01	0.01	0.00	0.01	0.00	0.00
7	0.46	0.14	0.07	0.07	0.01	0.05	0.00	0.00
9	0.28	0.08	0.03	0.04	0.28	0.03	0.03	0.04
11	0.14	0.03	0.02	0.02	0.00	0.01	0.00	0.00
13	0.19	0.04	0.02	0.02	0.00	0.01	0.00	0.00
15	0.17	0.04	0.02	0.02	0.17	0.01	0.02	0.02
TOT RMS	12.8				1.05			

Assessing The Effect of Three Phasing with Nonlinear Loads



- Same system configuration
- The linear loads are modeled in constant power mode with its value doubled: 120kW @ 0.9 pf lagging
- Nonlinear load: single phase rectifier at 240V, 60kW with 6000 μF smoothing capacitors

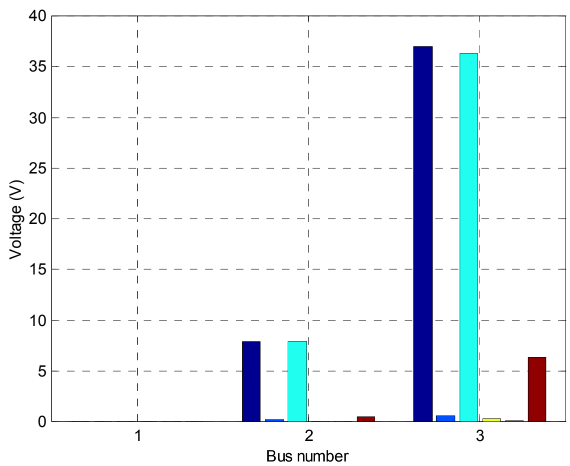
Single Phase Lateral NEV Spectrum with nonlinear load



At each bus, the NEV spectrum include the following components:

- Total RMS
- Fund.
- 3rd
- 5th
- 7th
- 9th

NEV Spectrum with Nonlinear load After Three Phasing



At each bus, the NEV spectrum include the following component:

- Total RMS
- Fund.
- 3rd
- 5th
- 7th
- 9th

Detailed Results for Harmonic Components with Nonlinear Load

Har-monic Order	Single Phase				Three Phase			
	NEV (V)	Current (A)			NEV (V)	Current (A)		
		I_{ph}	I_n	I_E		I_{ph}	I_n	I_E
1	38.21	27.44	20.00	8.09	0.55	9.69	0.12	0.12
3	32.56	14.54	8.86	6.44	36.34	5.42	9.86	7.19
5	16.68	5.84	3.07	3.00	0.25	2.40	0.06	0.04
7	5.58	1.67	0.80	0.91	0.13	0.62	0.03	0.02
9	5.94	1.58	0.72	0.87	6.35	0.56	0.78	0.93
11	2.93	0.71	0.32	0.39	0.05	0.31	0.01	0.01
13	3.18	0.72	0.32	0.40	0.07	0.25	0.01	0.01
15	1.83	0.39	0.18	0.21	2.24	0.16	0.22	0.26
RMS_{TOT}	57.2				37			

Conclusions

- Carson's line model is adapted for NEV analysis
- A multiphase harmonic load flow algorithm is developed for NEV analysis in distribution systems
- The simple current injection method used in harmonic analysis achieves similar accuracy as the detailed nonlinear device model
- It is possible to approximately predict the NEV profile and help locate potential stray voltage problems
- Triplen harmonics elevates the NEV due to their additive nature in the neutral
- Common methods for stray voltage mitigation, e.g. three phasing, may not be adequate when there is high harmonic distortion in the system

Future Research Opportunities

- More field measurements to validate model.
- Improve models to incorporate more complex situations
- Improve load flow program to handle large scale systems
- Better understand the human sensitivity to harmonic frequency voltages