Impact of DC Currents and Associated Harmonics on Substation Transformers, Distribution Feeders, and Customer Loads

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Our Tests - Instantaneous Voltages and Currents are Measured on Both Sides. Then, Off-Line, Instantaneous and Average Powers are Calculated and Analyzed.

Pin = Va*Ia + Vb*Ib + Vc*Ic

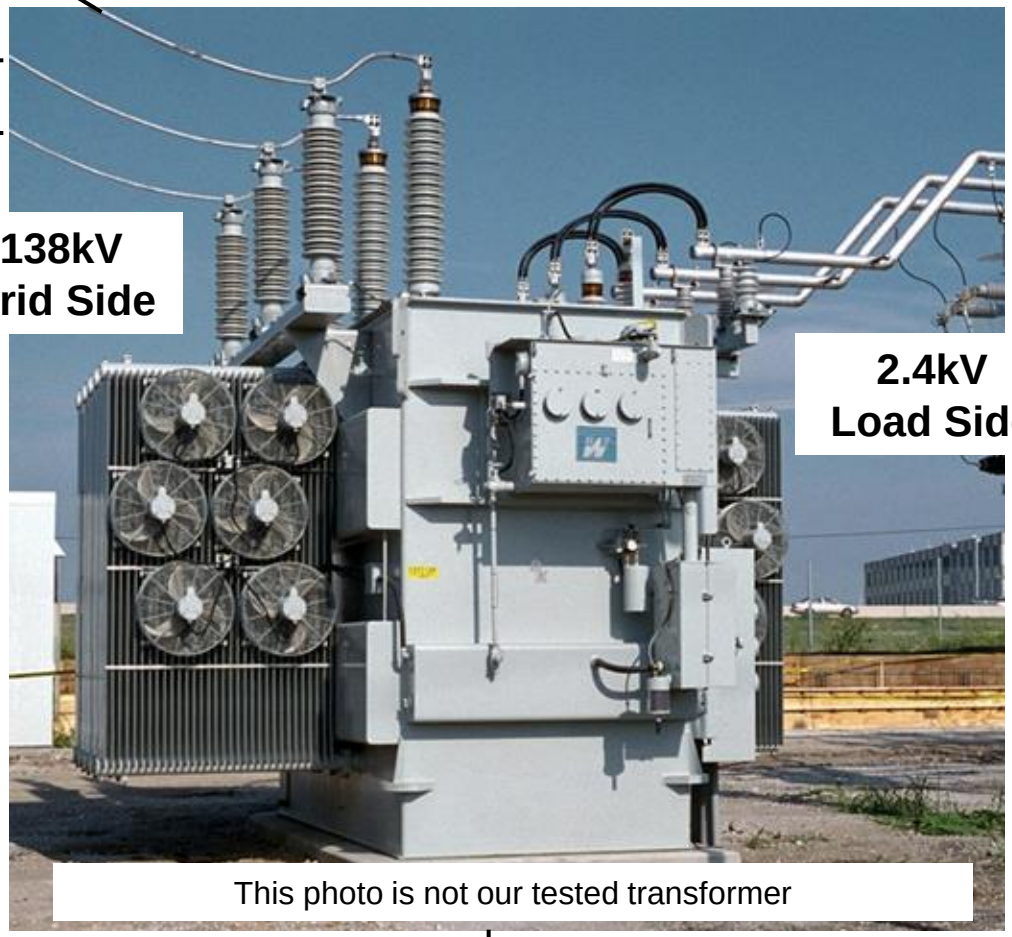
Pout = va*ia + vb*ib + vc*ic

Ploss = Pin – Pout

+Va Ia

+Vb Ib

+Vc Ic



+va, +vb, +vc,
ia, ib, ic

Voltage Reference is Ground

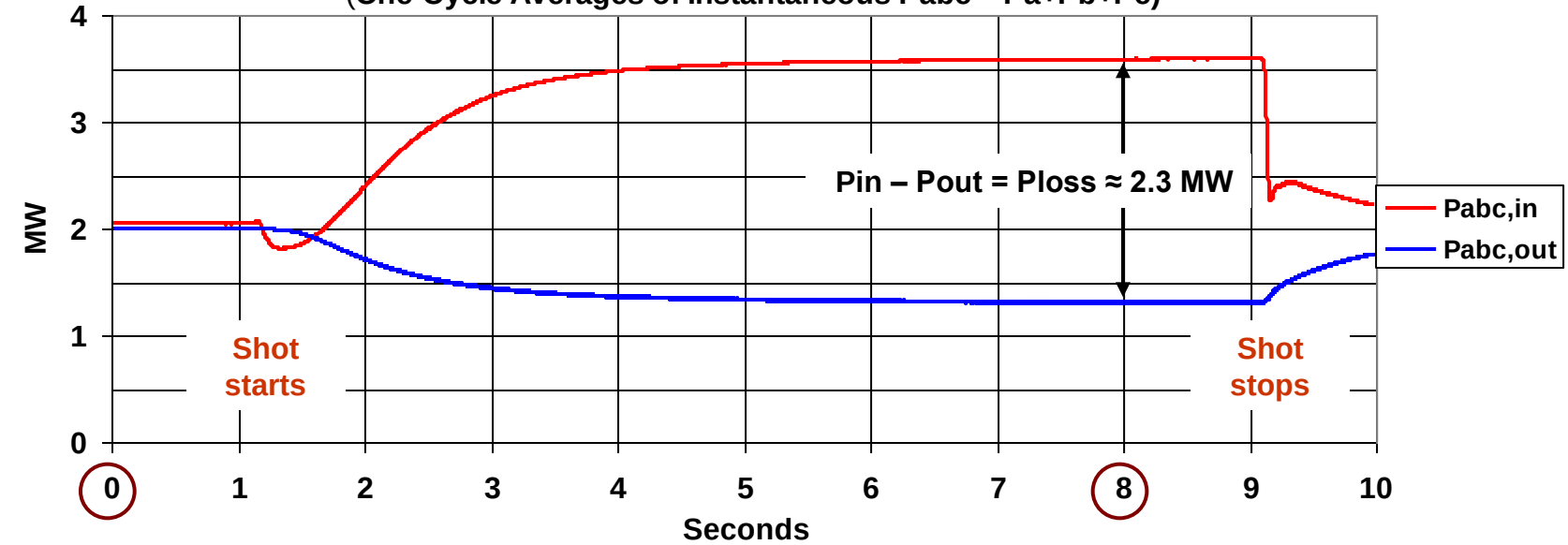
One-cycle averages of pabc INTO transformer

One-cycle averages of pabc OUT OF transformer

Impact of 120Adc Shot (40Adc each phase) Into the 138kV Windings

Three-Phase Power Flowing Into and Out of a 3.75 MVA, 138kV Wye / 2.4 kV Delta Transformer Subjected to a 120Adc Shot

(One-Cycle Averages of Instantaneous Pabc = Pa+Pb+Pc)

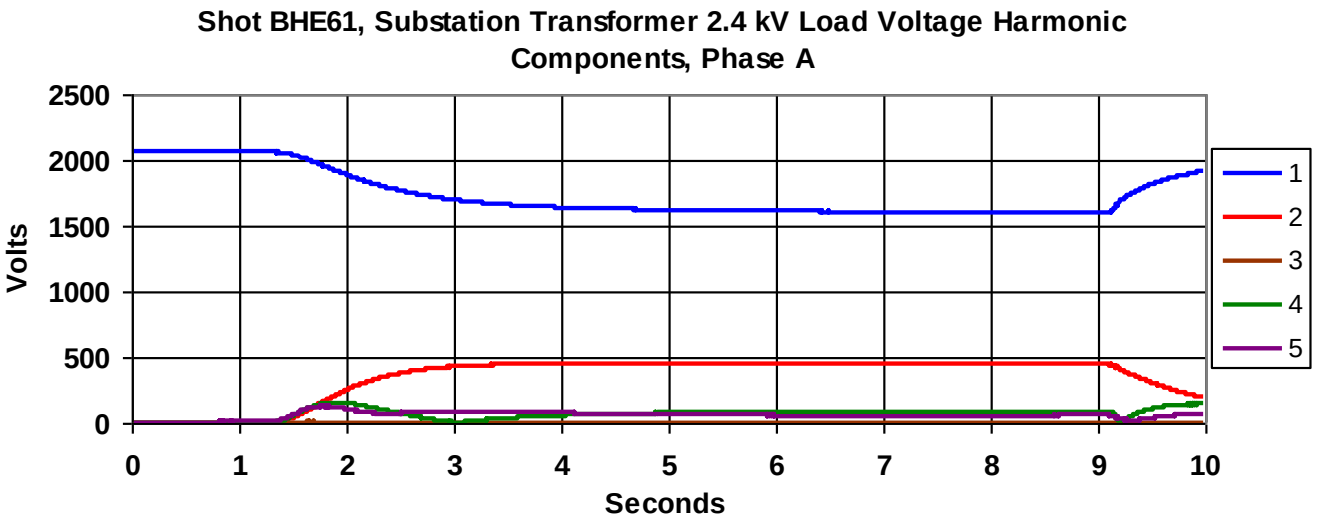


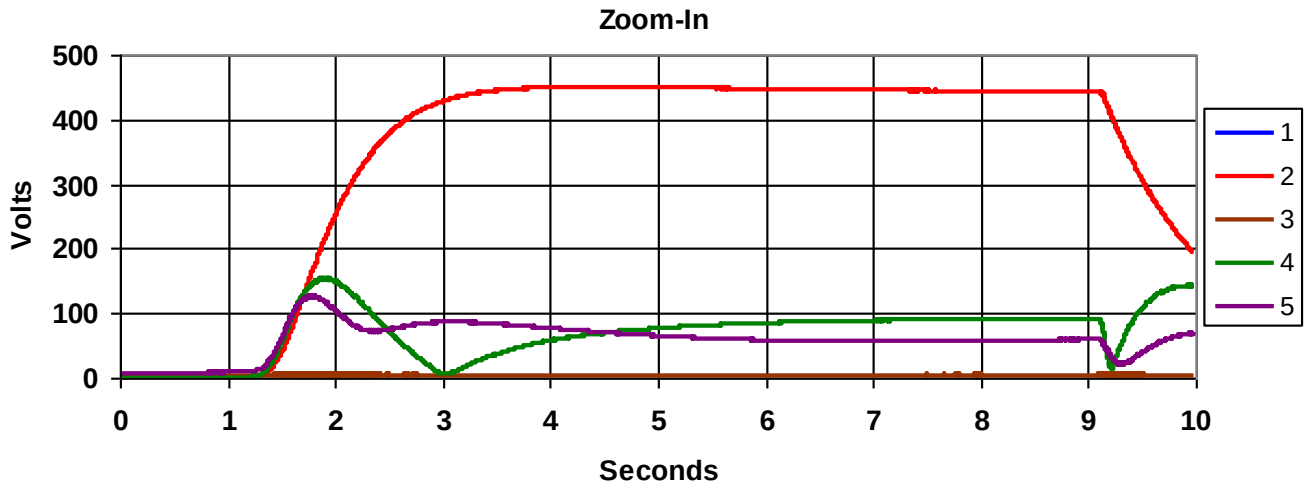
Pre-Shot (t = 0 sec)

Deep-Shot (t = 8 sec)

Transformer losses during the shot are approximately 60% of transformer rated power, and about 60-to-100 times normal losses

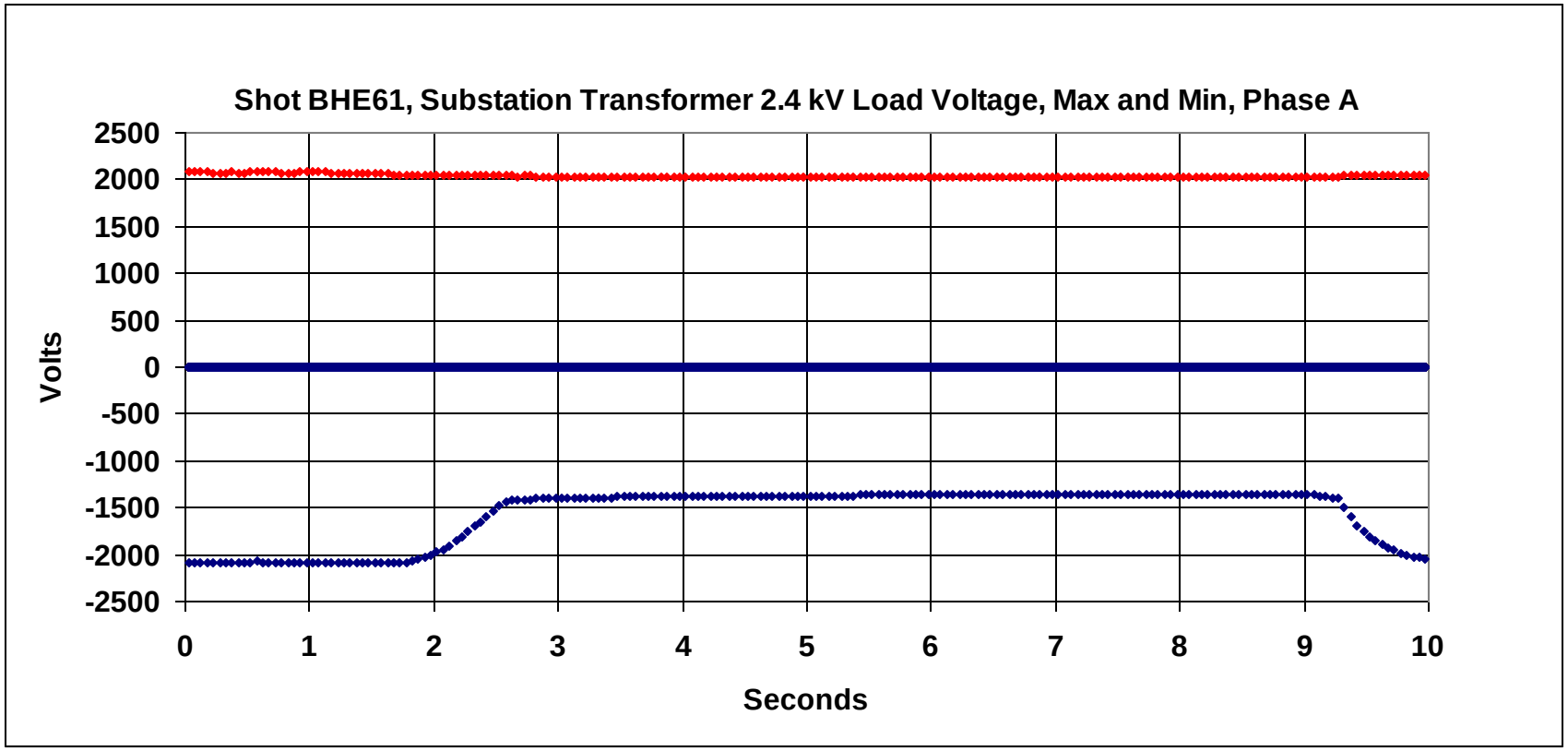
Load-Side Voltage Harmonics



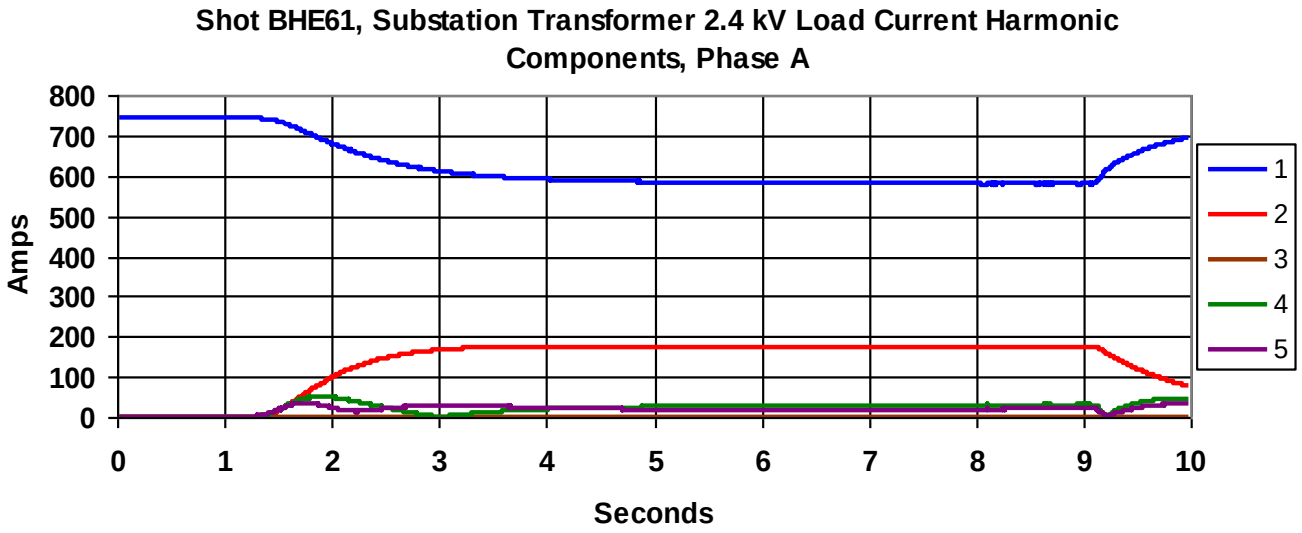


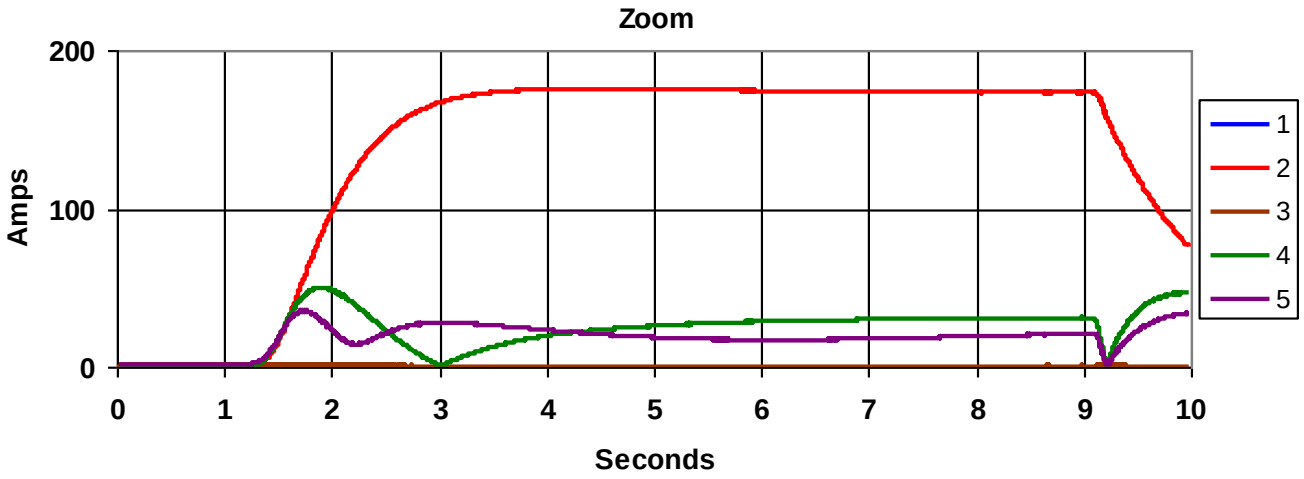
Load-Side Peak Voltage

- 60 Hz rms load voltage (previous graph) dropped 20%, but as shown below, peak load voltage was steady
- Power electronic loads (power supplies, computers, backup systems) are damaged by peak voltage
- Can power distribution systems resonate with harmonic excitation to raise peak voltages down feeders?



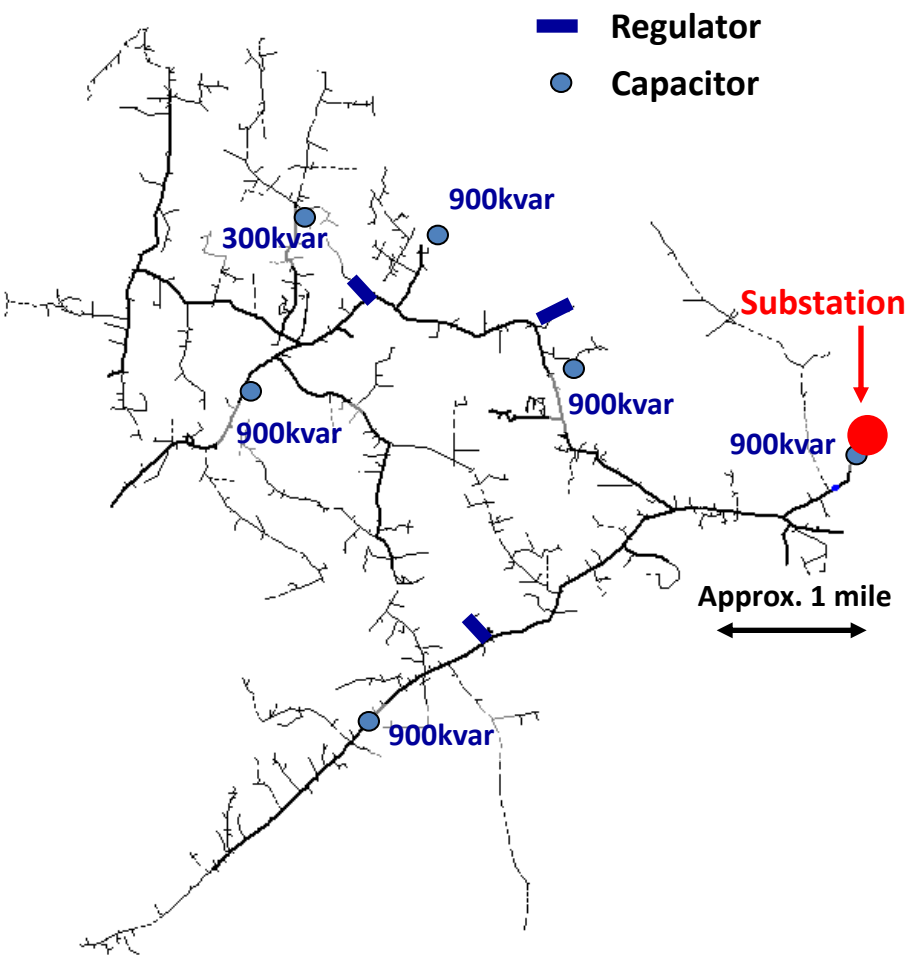
Load-Side Current Harmonics





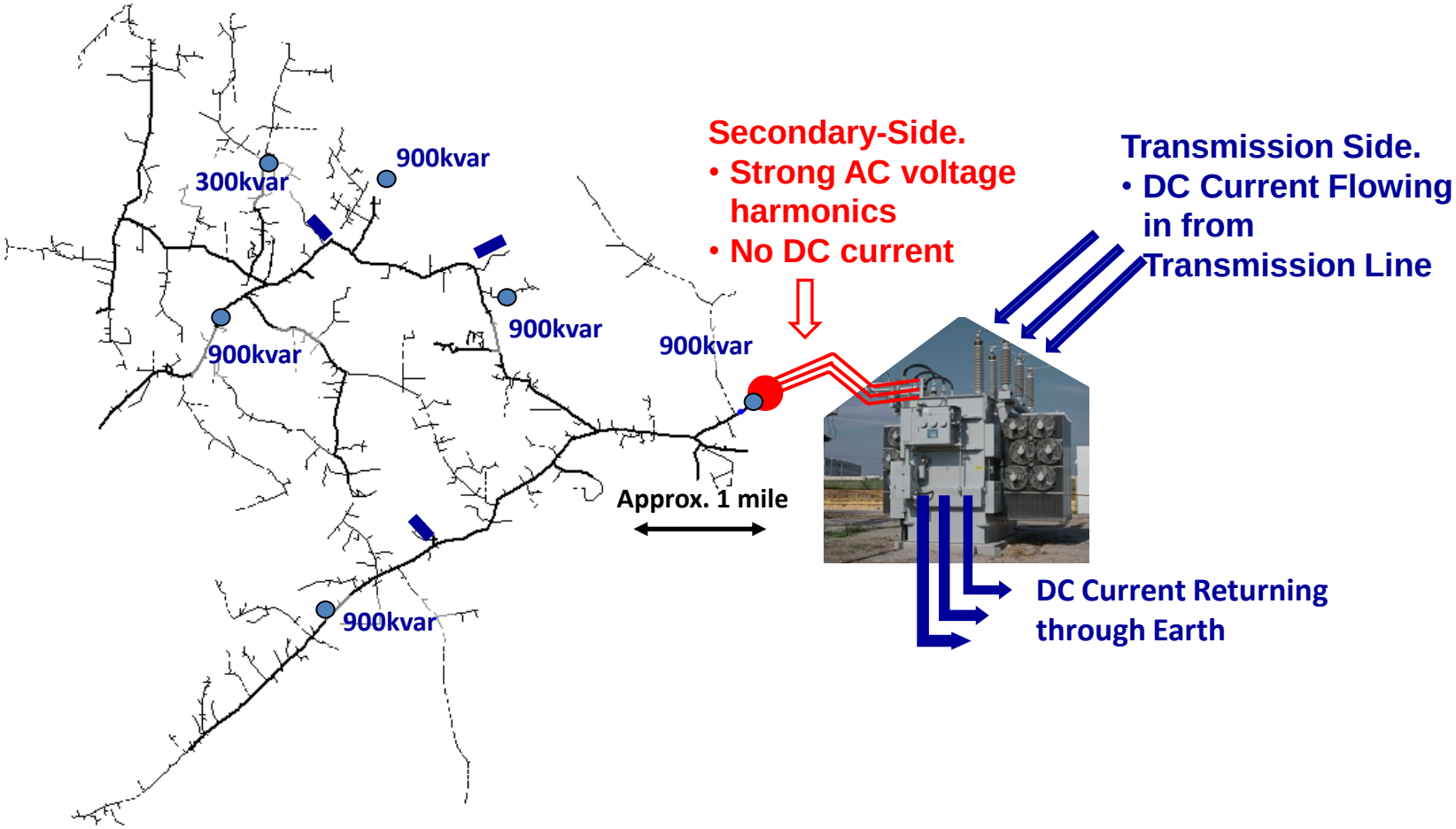
Representative Distribution Feeder Circuit

One of Dozens of Actual Utility Distribution Systems Studied by EPRI to Determine Precise Division of Feeder Losses (wires, transformer I^2R, transformer cores)

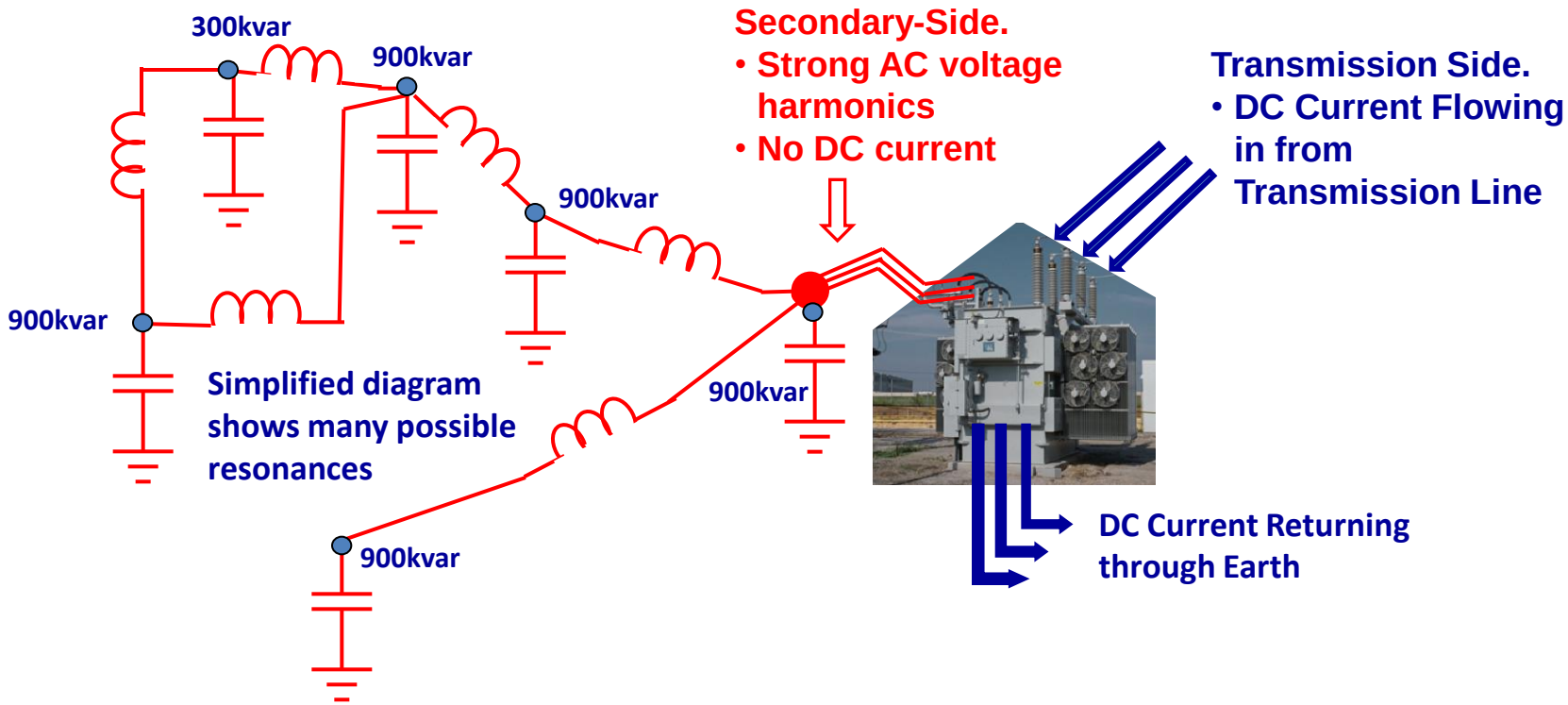


- 12.47 kV circuit.
  - 24 miles primary lines (three-phase),
  - 80.8 miles non-primary lines
- Load.
  - 10.5 MW max
- Voltage Regulation,
  - Linear tap changer at substation transformer,
  - Three other regulating transformers downstream,
  - Five fixed capacitor banks, 3.9 Mvar,
  - One controlled capacitor bank 0.9 MVAr.

Within a Few Seconds, DC Current Flowing in from the Transmission Grid Saturates the Core, Converting the Substation Transformer into a Strong Low-Frequency Harmonic Voltage Source

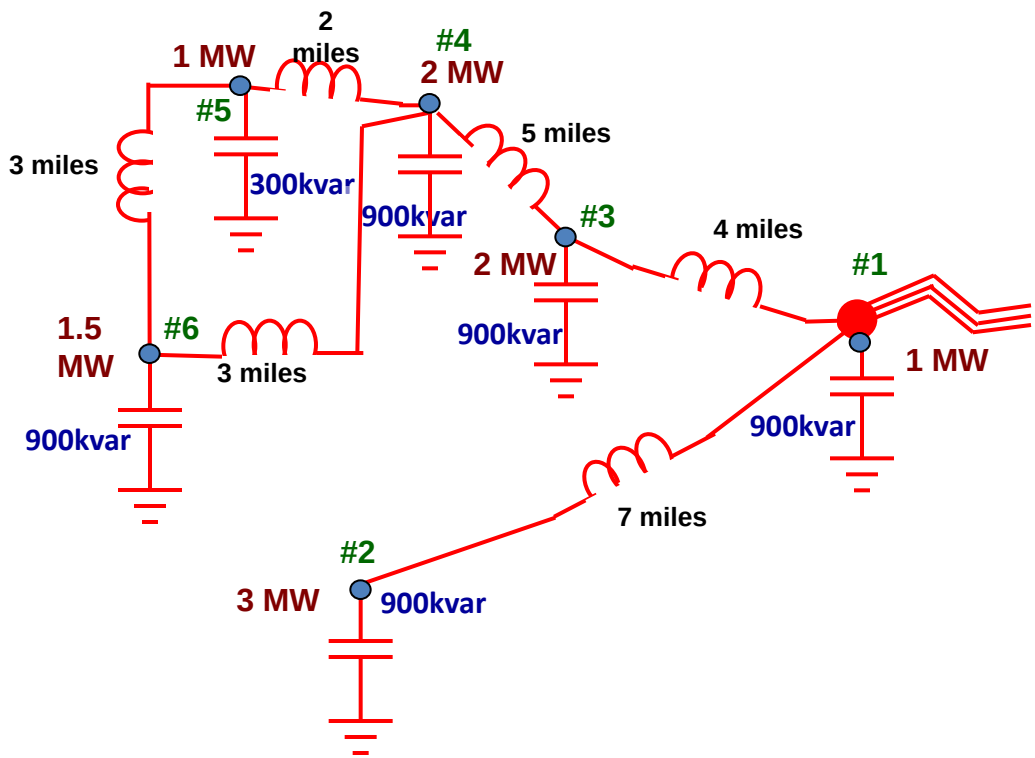


The Combination of Feeder Inductances and Shunt Capacitors Places Most Distribution Feeder in the 3rd Harmonic of 60 Hz (i.e., 180 Hz) Resonance Range



Why resonance in distribution at such low frequencies (120 Hz, 360 Hz, 720 Hz, etc.)?

- **4.8 MVAr of three-phase shunt capacitors on a 12.47 kV system corresponds to 81.9 μF per phase.**
- **24 miles of distribution three-phase feeder @ 1 μH/meter (each-phase) corresponds to 38.6 mH series inductance per phase.**
- **If entire L and C for each circuit were lumped together, the resonant frequency would be 89.5 Hz.**

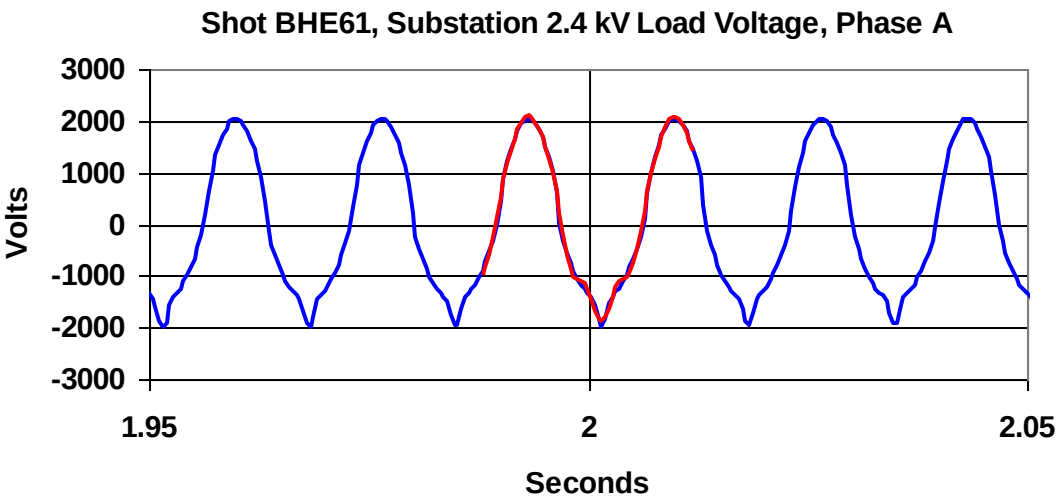


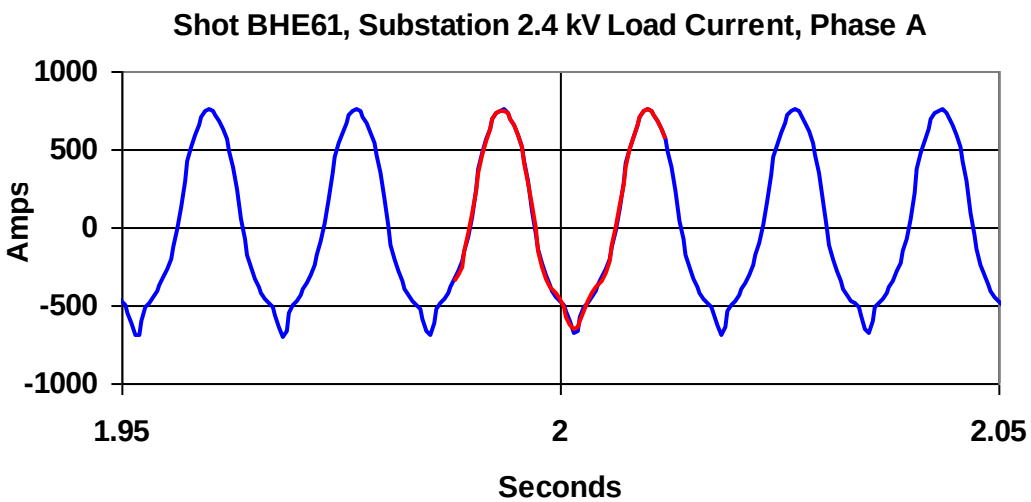
Reasonable Assumptions for Today's GMD Impact Analysis

- Balanced power and distortion (as expected from DC saturation and as observed in 2012 E3 tests)
- Feeder R = 0.05 ohms/kilometer
- Feeder L = 1 microH/meter
- Feeder C = 12 picoF/meter (not significant compared to power factor correction capacitors)

Actual Load Voltage and Current Waveforms During Test

(t = 2 seconds, blue is actual, red is Fourier series curve fit, Fourier coefficients are computed for each 3-cycle window of 60 Hz)





Fourier Cosine Series for Red Voltage and Current Waveforms

Harm.	Vmag	Vang	Imag	Iang
1	1888.6	146.8	679.7	142.5
2	251.9	-70.2	98.3	-83.8
3	4.6	8.1	0.4	85.0
4	149.0	40.4	48.5	22.6
5	103.6	21.5	22.8	-0.1

PCFLO Bus Data

:GMD_Example. Base = 12.47kV,100 MVA.								
:								
:			Linear	Linear	Linear	Linear		Shunt
:			P	Q	P	Q	Desired	Reactive
:Bus	Bus	Bus	Generation	Generation	Load	Load	Voltage	Q Load
:Number	Name	Type	(%)	(%)	(%)	(%)	(pu)	(%)
:(I)	(A)	(I)	(F)	(F)	(F)	(F)	(F)	(F)
1	Bus1	3			1	0.5		-0.9
2	Bus2	3			3	1.5		-0.9
3	Bus3	3			2	1		-0.9
4	Bus4	3			2	1		-0.9
5	Bus5	3			1	0.5		-0.3
6	Bus6	3			1.5	0.75		-0.9
7	SWING	1					0.9	

Positive	Positive	Negative	Negative	Zero
Sequence	Sequence	Sequence	Sequence	Sequence
Subtransie	Subtransie	Subtransie	Subtransie	Subtransie
R	X	R	X	R
(pu)	(pu)	(pu)	(pu)	(pu)
(F)	(F)	(F)	(F)	(F)
100		100		100

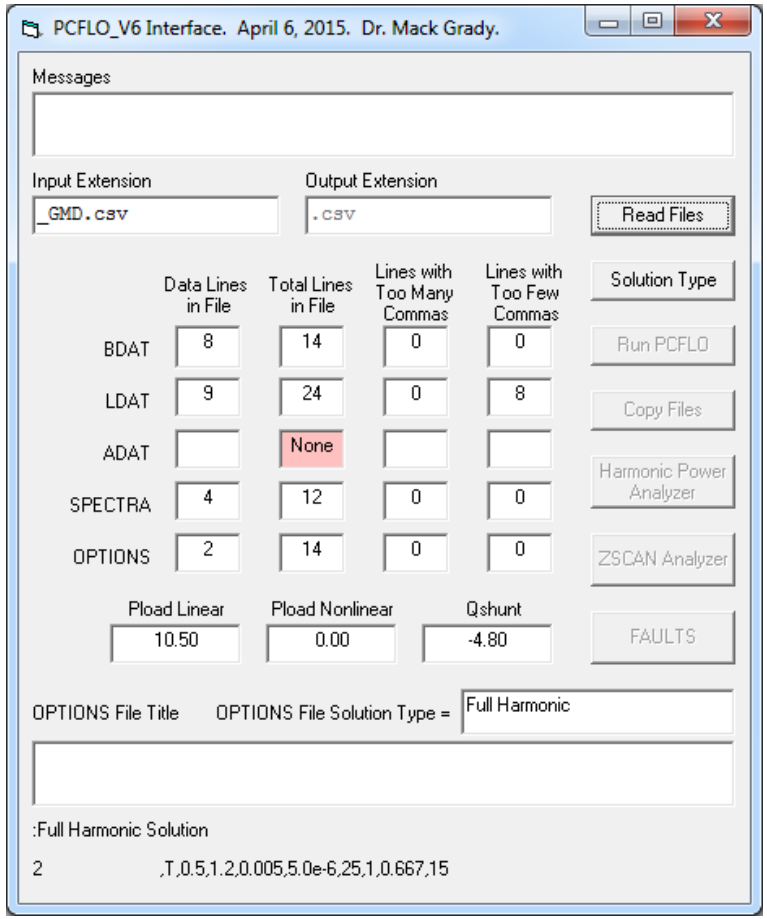
Nonlinear	Nonlinear	Nonlinear	
Device	Device	Device	
P	P	Displacem	Nonlinear
Gen	Load	Power Fac	Device
(%)	(%)	(pu)	Type
(F)	(F)	(F)	(I)
0.15		1	25
	0	0	0
	0	0	0
	0	0	0
	0	0	0
	0	0	0
	0	0	0

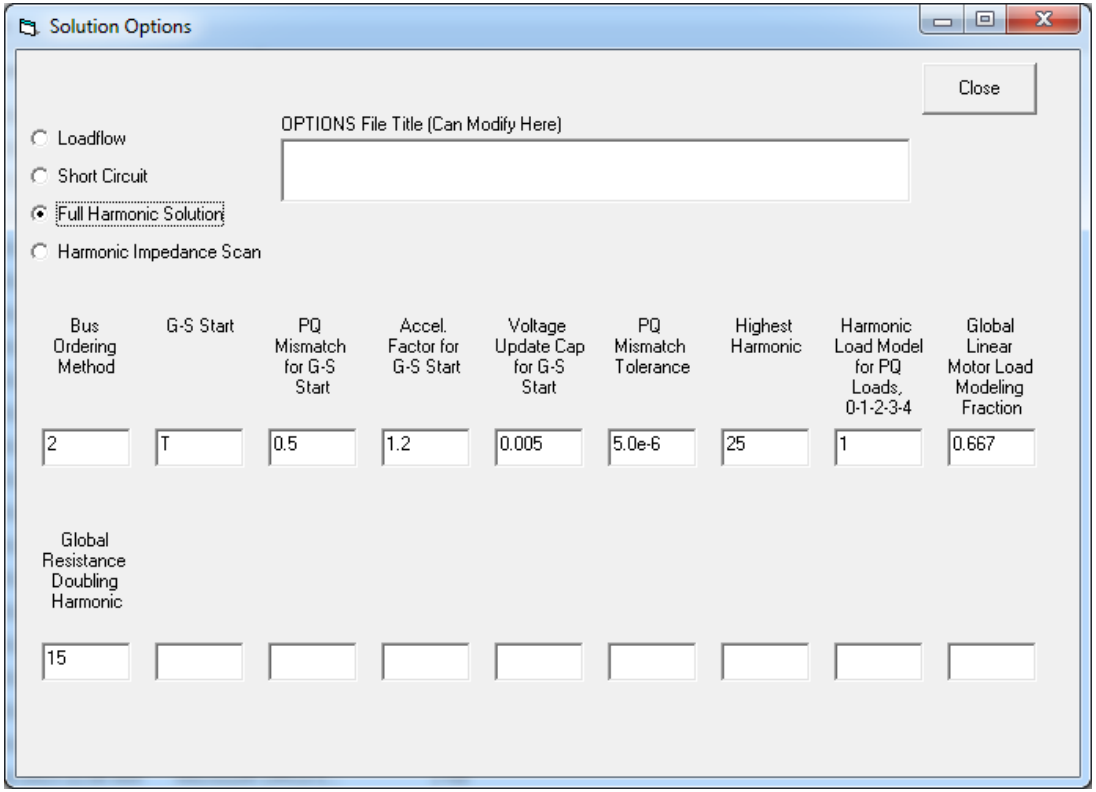
PCFLO Line Data

:GMD_Example. Base = 12.47kV,100 MVA. Zbase = (12.47*12.47)/100 = 1.555 ohms. Fbase = 60Hz.									
:Ibase = Sbase/sqrt(3)/Vbase = 4630 amps.									
:									
:									
:			Positive	Positive	Pos/Neg				
:			Sequence	Sequence	Sequence		Minimum	Maximum	Tap
:From	To	Circuit	R	X	Charging	Rating	Tap	Tap	Step Size
:Bus	Bus	Number	(pu)	(pu)	(%)	(%)	(pu)	(pu)	(pu)
:(I)	(I)	(I)	(F)	(F)	(F)	(F)	(F)	(F)	(F)
1	2		0.362154	2.730579					
1	3		0.206945	1.560331					
3	4		0.258682	1.950414					
4	5		0.103473	0.780166					
4	6		0.155209	1.170248					
5	6		0.155209	1.170248					
1	7		0.01	0.01					
:comment		miles	km	Rohms	Lmillh	jXohms	Rpu	jXpu	
:1	2	7	11.263	0.56315	11.263	4.246051	0.362154	2.730579	
:1	3	4	6.436	0.3218	6.436	2.426315	0.206945	1.560331	
:3	4	5	8.045	0.40225	8.045	3.032894	0.258682	1.950414	
:4	5	2	3.218	0.1609	3.218	1.213157	0.103473	0.780166	
:4	6	3	4.827	0.24135	4.827	1.819736	0.155209	1.170248	
:5	6	3	4.827	0.24135	4.827	1.819736	0.155209	1.170248	

PCFLO Spectral Data

:GMD Substation Transformer Current Spectrum				
:Harmonic Current Spectral Data				
:				Current
:Type of			Current	Harmonic
:Series	Nonlinear	Harmonic	Harmonic	Phase
:(SIN or	Load	Order	Mag.	Angle
:COS)	Type	(Integer)	(pu)	(Degrees)
:(A)	(I)	(I)	(F)	(F)
COS	25	1	1	0
COS	25	2	14.5	-17.4
COS	25	4	7.1	155.4
COS	25	5	3.4	-14.1





Bus	name	v1(pu)	thdv(%)
1	Bus1	0.8984	26.09
2	Bus2	0.8539	24.01
3	Bus3	0.8362	23.97
4	Bus4	0.7896	24.21
5	Bus5	0.7847	24.36
6	Bus6	0.7841	24.71
7	SWING	0.9	26.04
the highest VTHD	26.09 percent	occurs at b	"Bus1 "

Harmonic Power Analyzer (PCFLO Postprocessor). April 10, 2011. MG

Read_VSOLN_ISOLN | .csv | Data Type: pu / V,I

BUSSES — VSOLN,ISOLN extension

```
00001,Bus1      , 0.898, 26.1%
00002,Bus2      , 0.854, 24.0%
00003,Bus3      , 0.836, 24.0%
00004,Bus4      , 0.790, 24.2%
00005,Bus5      , 0.785, 24.4%
00006,Bus6      , 0.784, 24.7%
00007,SWING     , 0.900, 26.0%
```

CONNECTED BRANCHES (Select. Those with * are summed and reported below)

```
*    4,    0,  1,"Bus4        ","shunt q     "
     4,    3,  1,"Bus4        ","Bus3        "
     4,    5,  1,"Bus4        ","Bus5        "
     4,    6,  1,"Bus4        ","Bus6        "
 Residual (linear load plus its harmonic model),
```

See Norton

BUS VOLTAGE MAG, SINE SERIES

```
00001,     0.78960200,-015.000
00002,     0.16007200, 099.900
00004,     0.09622810,-002.700
00005,     0.04060490,-118.200
```

NET CURRENT MAG, SINE SERIES FOR SELECTED BRANCHES

```
00001,     0.00710642, 075.000
00002,     0.00288130,-170.100
00004,     0.00346421, 087.300
00005,     0.00182722,-028.200
```

Auto_Analyze

Max abs (current) - pu on system base: 0.0185

Voltage, Current

V1ANG = 0

THDV = 24.2%

THDI = 68.4%

NET ACTIVE POWER P (pu on system base, and pu of fundamental)

```
00001,  6.83E-11,  NA
00002, -4.55E-12,  NA
00004,  3.78E-12,  NA
00005,  4.85E-12,  NA
PHTOT,  4.08E-12,  NA
```

NET REACTIVE POWER Q (pu on system base, and pu of fundamental)

```
00001, -5.61E-03,  1.00E+00
00002, -4.61E-04,  8.22E-02
00004, -3.33E-04,  5.94E-02
00005, -7.42E-05,  1.32E-02
QHTOT, -8.69E-04,  1.55E-01
```

S1 5.61E-03

P1 5.51E-09

PH -1.34E-07

PH / P1 0.0%

PH / S1 0.0%

Abs(PH) / P1 0.0%

Abs(PH) / S1 10.8%

Distortion Friendly Factor (DFF) 0.00

P3 0.0% P9 0.0%

P5 0.0% P11 0.0%

P7 0.0% P13 0.0%

Harmonic Voltage and Current

v1i1 vhih

vhih (zoom-in)

Harmonic Power Analyzer (PCFLO Postprocessor). April 10, 2011. MG

Read_VSOLN_ISOLN | .csv | Data Type: pu / V,I

BUSSES — VSOLN,ISOLN extension

```
00001,Bus1      , 0.900, 44.1%
00002,Bus2      , 0.891, 43.5%
00003,Bus3      , 0.902, 43.8%
00004,Bus4      , 0.907, 45.6%
00005,Bus5      , 0.908, 45.9%
00006,Bus6      , 0.909, 46.4%
00007,SWING     , 0.900, 44.1%
```

CONNECTED BRANCHES (Select. Those with * are summed and reported below)

```
*    4,    0,  1,"Bus4        ","shunt q     "
     4,    3,  1,"Bus4        ","Bus3        "
     4,    5,  1,"Bus4        ","Bus5        "
     4,    6,  1,"Bus4        ","Bus6        "
 Residual (linear load plus its harmonic model),
```

See Norton

BUS VOLTAGE MAG, SINE SERIES

```
00001,     0.90726500,-006.900
00002,     0.39152000, 059.400
00004,     0.12137300,-025.000
00005,     0.05806890,-151.100
```

NET CURRENT MAG, SINE SERIES FOR SELECTED BRANCHES

```
00001,     0.00816539, 083.100
00002,     0.00704736, 149.400
00004,     0.00436943, 065.000
00005,     0.00261310,-061.100
```

Auto_Analyze

Voltage, Current

Max abs (current) - pu on system base

V1ANG = 0 | 0.0243

THDV = 45.6%

THDI = 106.5%

NET ACTIVE POWER P (pu on system base, and pu of fundamental)

```
00001,  7.78E-11,  NA
00002,  1.07E-10,  NA
00004,  6.45E-12,  NA
00005, -1.43E-11,  NA
PHTOT,  9.92E-11,  NA
```

NET REACTIVE POWER Q (pu on system base, and pu of fundamental)

```
00001, -7.41E-03,  1.00E+00
00002, -2.76E-03,  3.72E-01
00004, -5.30E-04,  7.16E-02
00005, -1.52E-04,  2.05E-02
QHTOT, -3.44E-03,  4.65E-01
```

S1 7.41E-03

P1 7.28E-09

PH -9.52E-07

PH / P1 0.0% | PH / S1 0.0%

Abs(PH) / P1 0.0% | Abs(PH) / S1 31.5%

Distortion Friendly Factor (DFF) 0.00

P3 0.0% | P9 0.0%

P5 0.0% | P11 0.0%

P7 0.0% | P13 0.0%

Harmonic Voltage and Current

v1i1 vhih

vhih (zoom-in)

Conclusions

Loads provide damping to limit overvoltages. If no loads trip off, *maybe* not much load damage (like 2012 E3 Tests)

Bus	name	v1(pu)	thdv(%)
1	Bus1	0.8984	26.09
2	Bus2	0.8539	24.01
3	Bus3	0.8362	23.97
4	Bus4	0.7896	24.21
5	Bus5	0.7847	24.36
6	Bus6	0.7841	24.71
7	SWING	0.9	26.04
the highest VTHD	26.09 percent	occurs at b	"Bus1 "

If one-half the loads trip off during the event, or the event occurs when load is light (e.g., nighttime, weekends) the connected power electronic loads will mostly likely fail due to sustained overvoltage

Bus	Name	v1(pu)	thdv(%)
1	Bus1	0.8995	44.09
2	Bus2	0.8912	43.52
3	Bus3	0.9023	43.77
4	Bus4	0.9073	45.63
5	Bus5	0.9077	45.92
6	Bus6	0.9092	46.36
7	SWING	0.9	44.07
the highest VTHD	46.36 percent	occurs at b	"Bus6 "