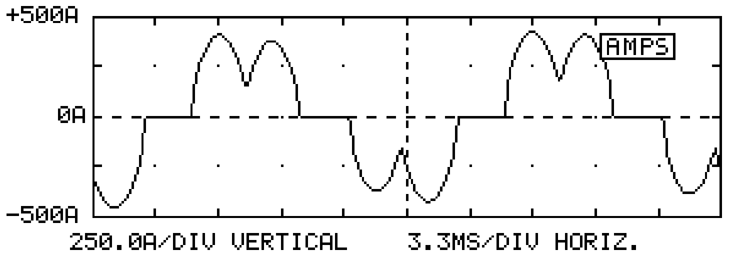
Evaluating Wind and Solar Power Plant Harmonics Against IEEE Harmonic Standards

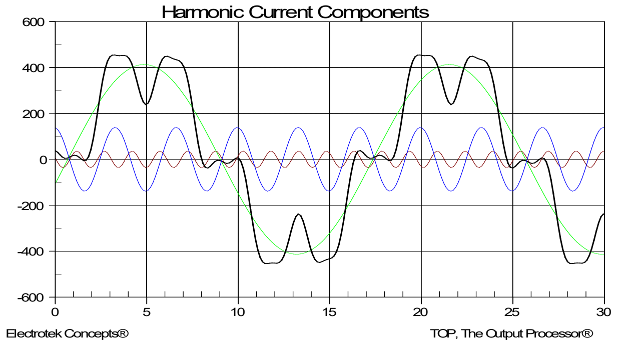
David Mueller
EnerNex

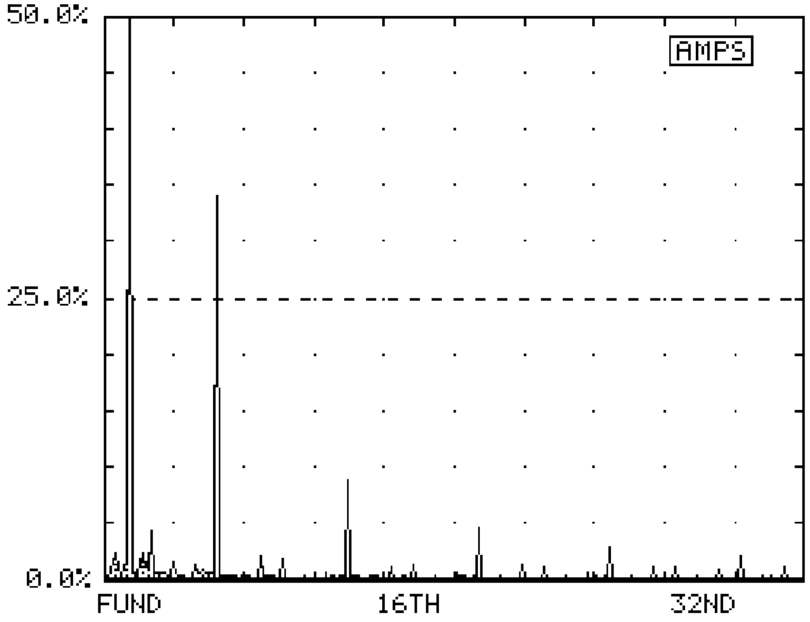
- Basic Understanding of Harmonics
- Wind and Solar Inverter Characteristics
- IEEE Standard 519
- Example 519 Compliance Evaluation
- Inverter/Grid Resonance Considerations
- IEEE 1547 and P2800
- Modeling Analysis Considerations

Harmonic Distortion - Definition

- *Harmonics are repetitive distortion in the waveform.*

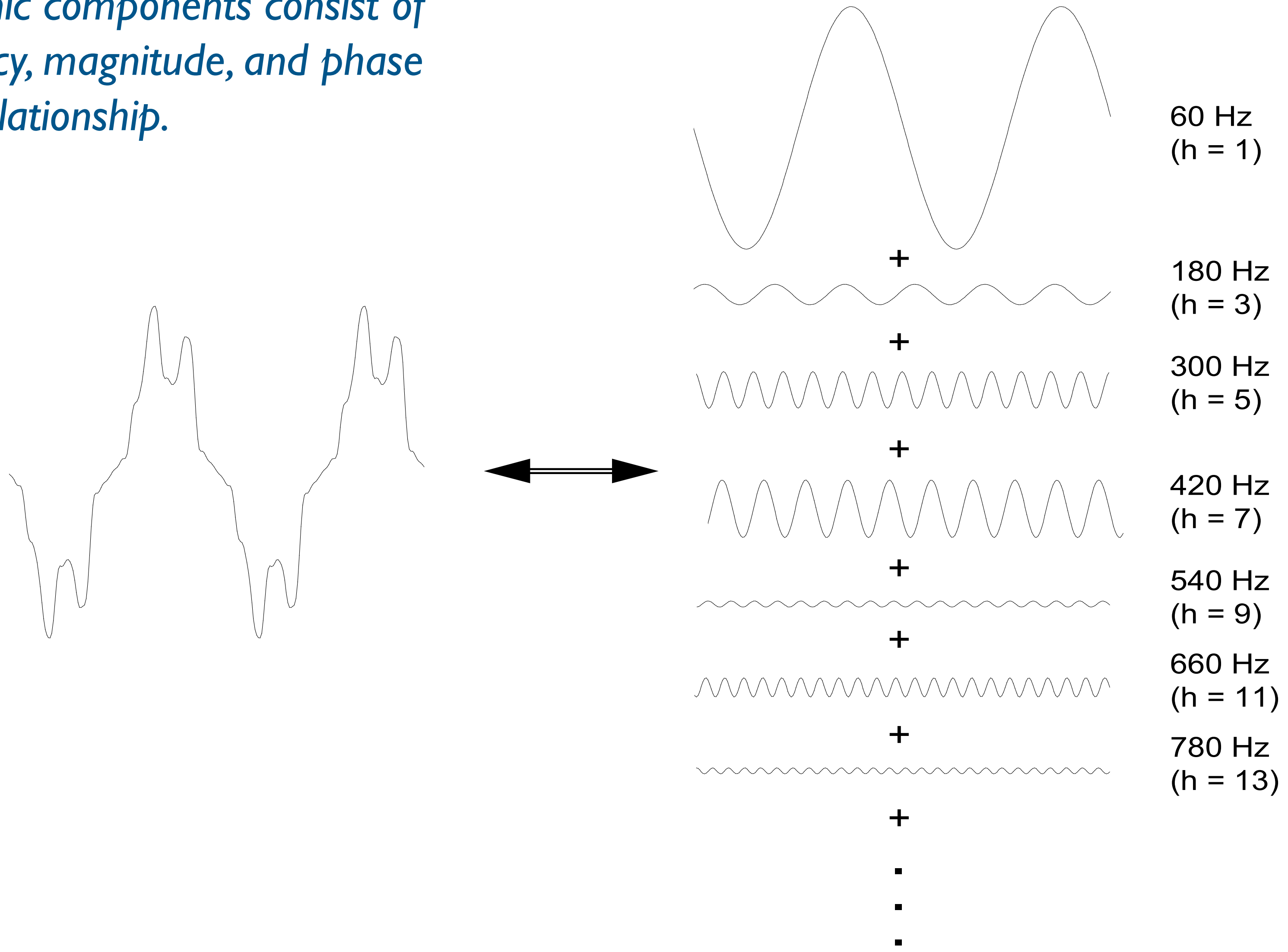






Harmonic Components

- *Harmonic components consist of frequency, magnitude, and phase angle relationship.*

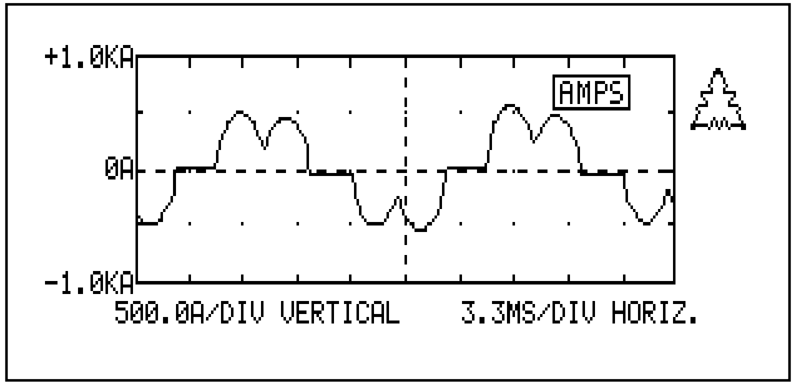


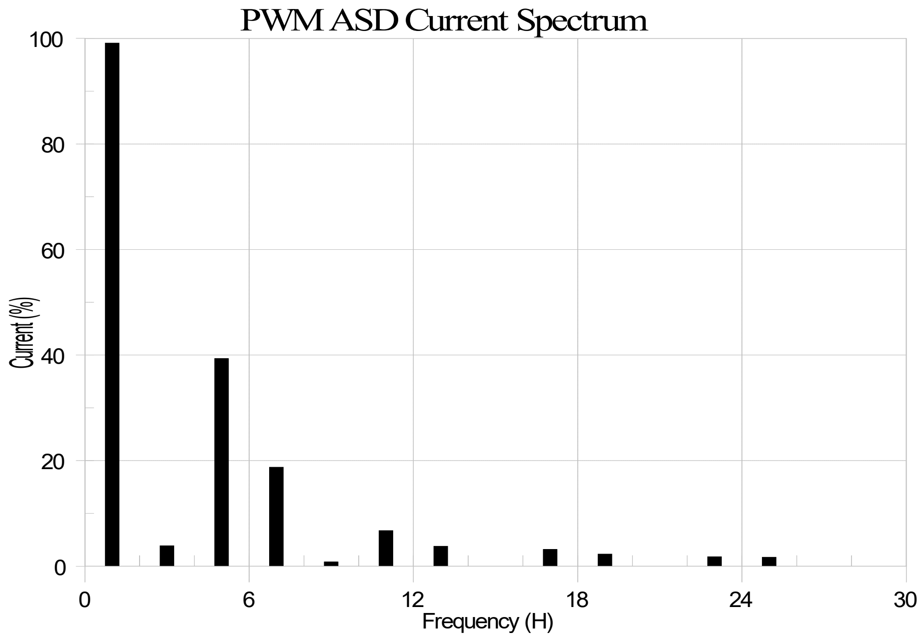
Sources of Harmonics

- *Saturable devices (e.g., transformers, and nonlinear inductors/reactors).*
- *Arcing devices (e.g., arc furnaces, welders, and fluorescent lighting – magnetic ballast).*
- *Power electronics equipment (e.g., adjustable-speed motor drives, dc motor drives, electronic power supplies (SMPS), fluorescent lighting – electronic ballast).*

Symptoms of Harmonic Problems

- *Capacitor fuse blowing*
- *Motor overheating*
- *Equipment misoperating*
- *Circuit breakers tripping mysteriously*
- *Transformer overheating at less than full load*
- *Customer capacitor or transformer failure*
- *Clocks running fast*
- *High neutral currents*
- *Telephone interference*

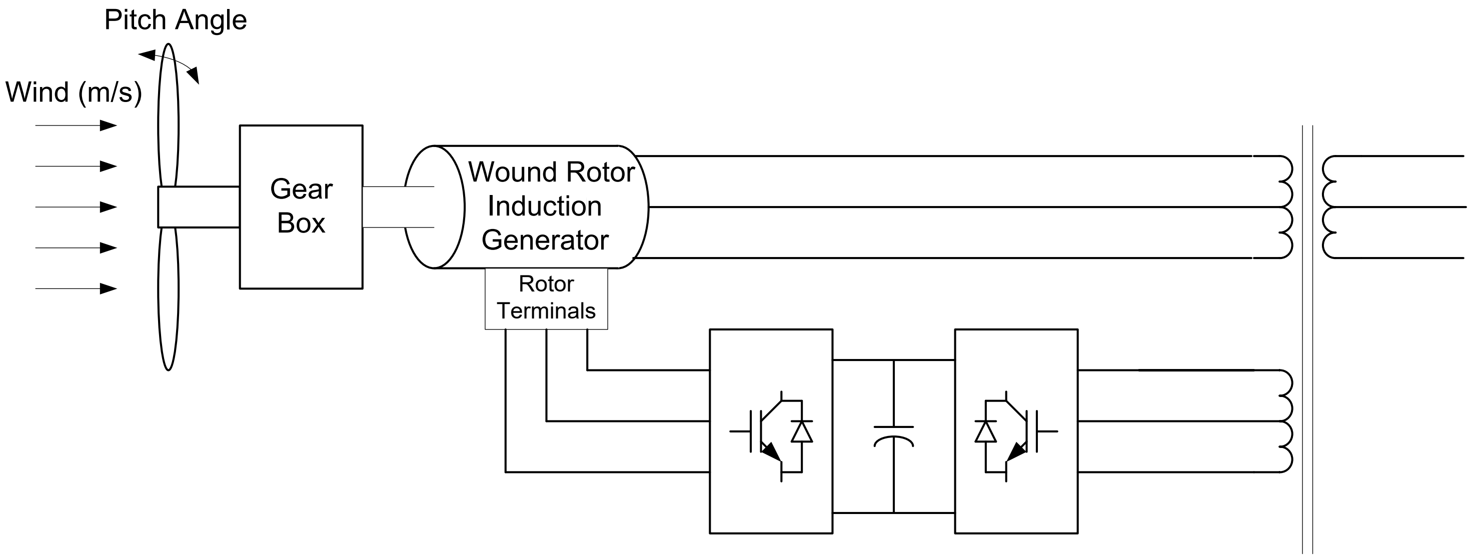




Wind Turbine Harmonics Characteristics

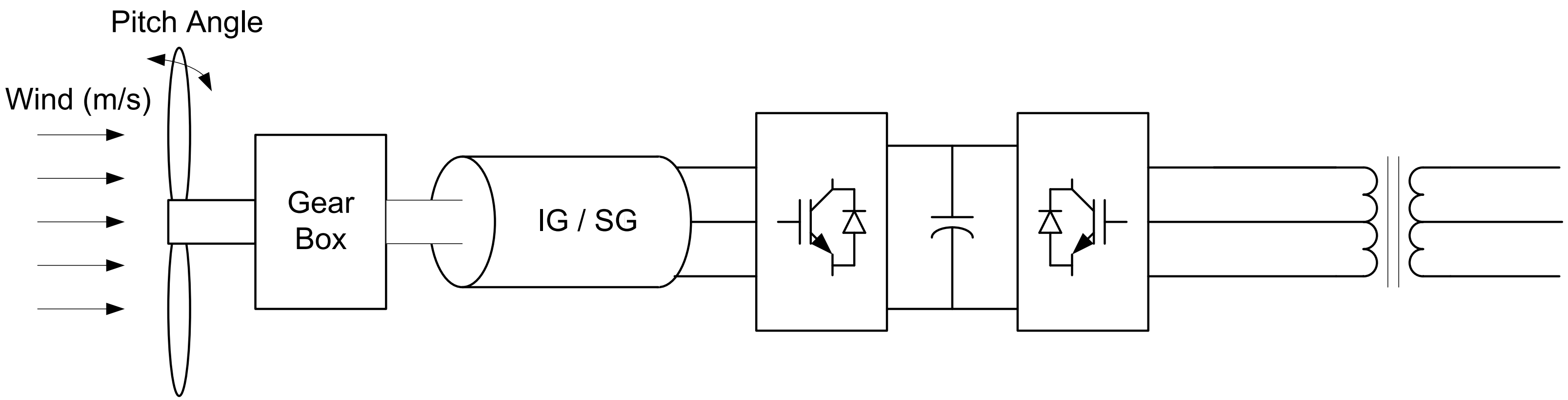
Type 3 Wind Turbine - Doubly Fed Asynchronous Induction Generator

- *Power conversion system on the excitation system allows for wide speed range, and real and reactive power control.*
- *About 1/3 of the machine rating is converted through power electronics.*



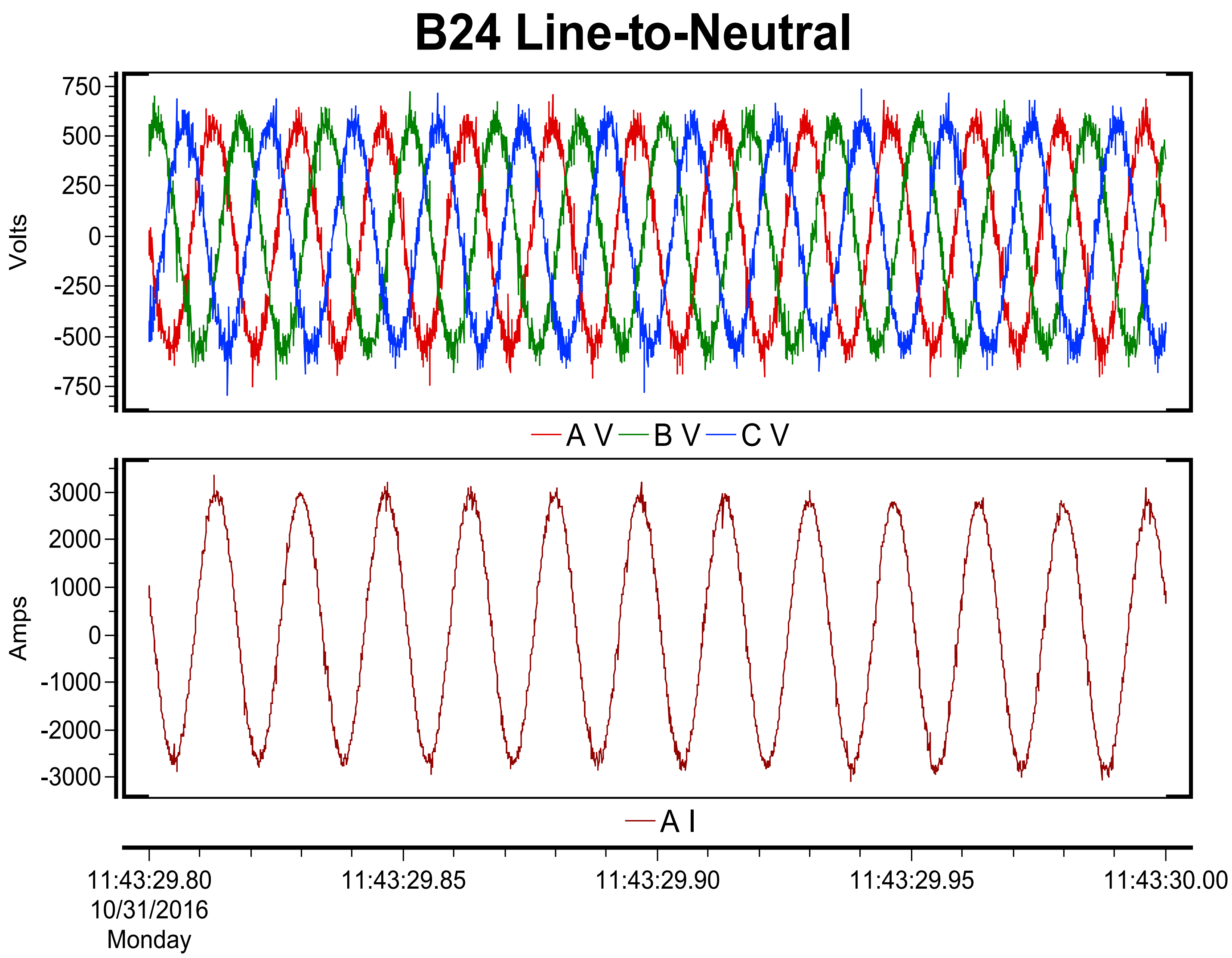
Type 4 Wind Turbine - Full Conversion Power System

- *Full (four quadrant) power conversion allows for frequency changing and power factor control.*
- *PWM technology allows for low harmonic current distortion (<5% THDi).*
- *Full power rating of the turbine. PV solar inverters have similar characteristics*



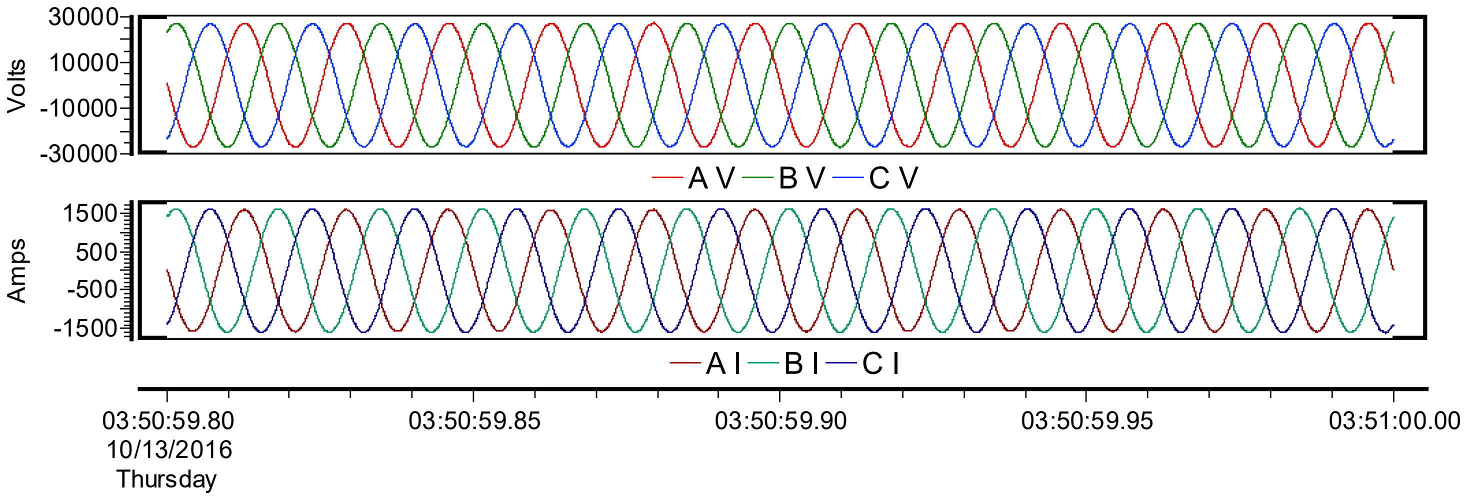
Site Measurements – At the Wind Turbine Padmount

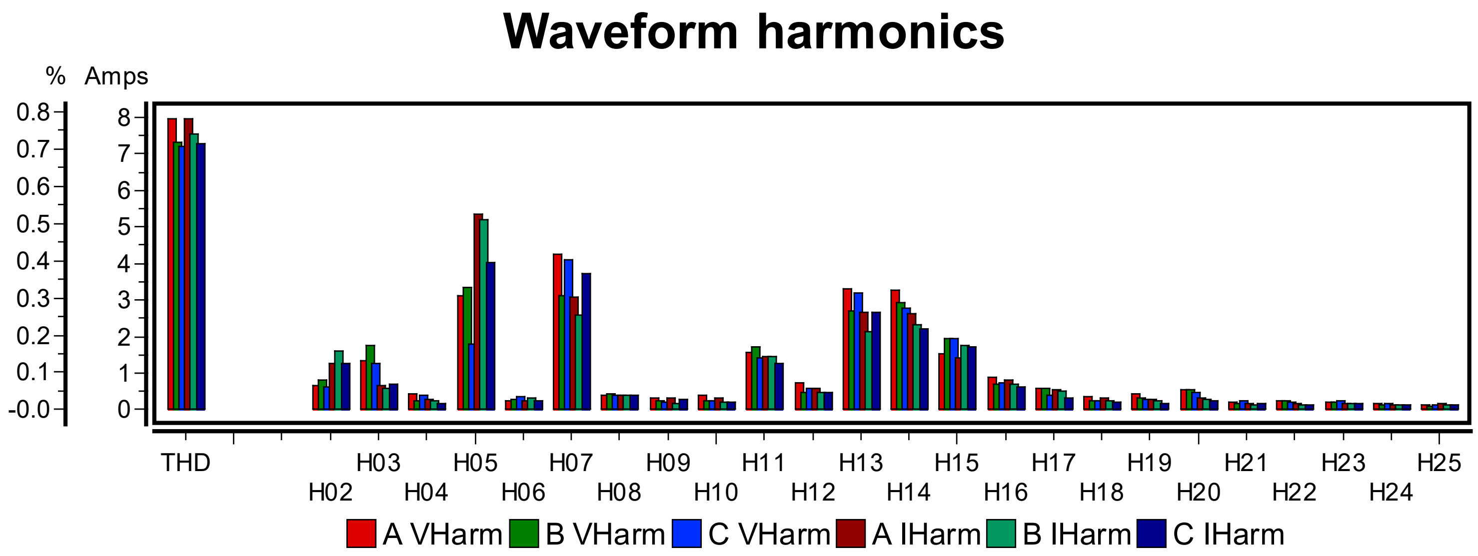
Measurements at the Padmount Transformer (690V)



Waveforms at the 34.5 kV Substation

- *High frequency components cancel at the substation*



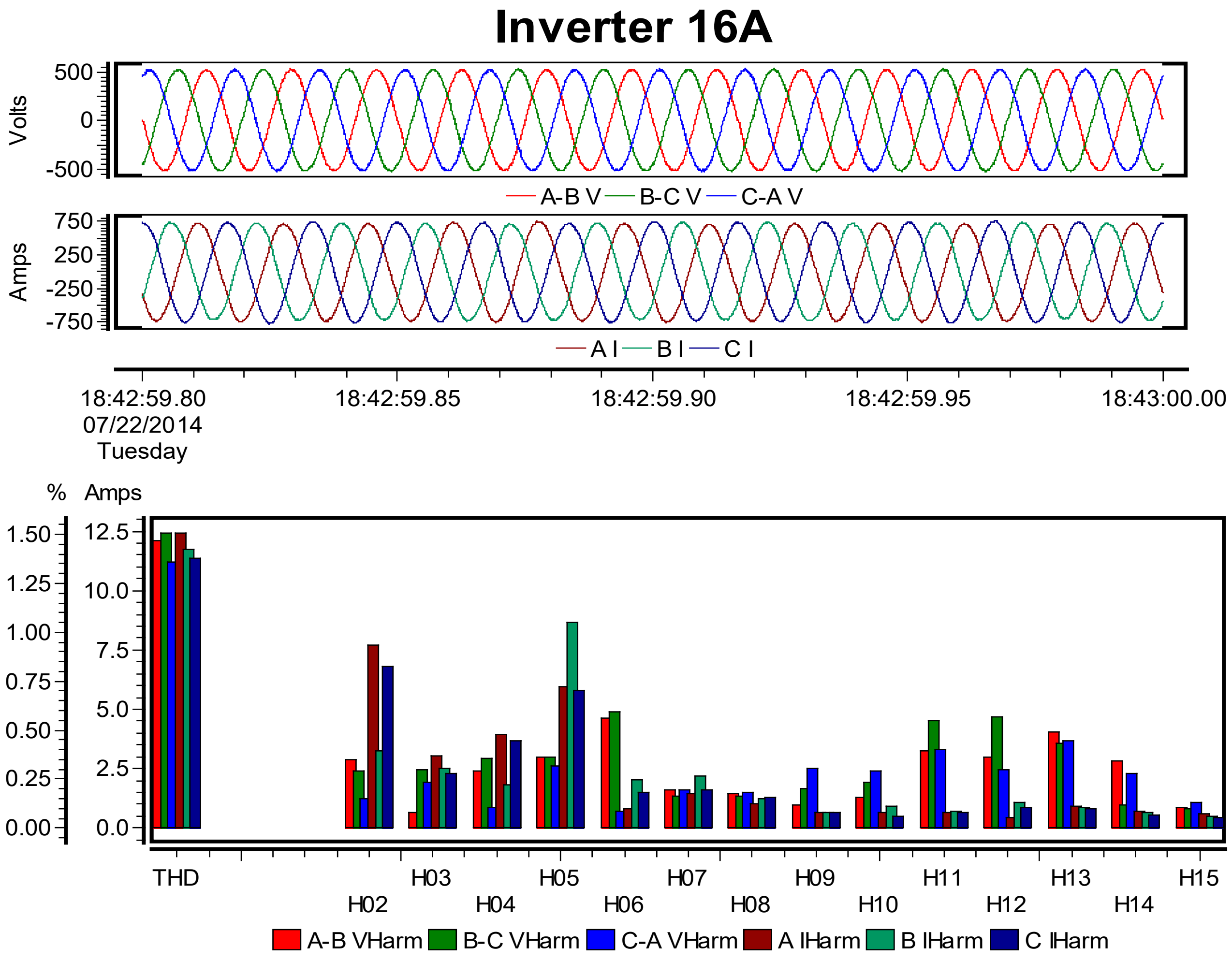


EnerNex
A CESI Company

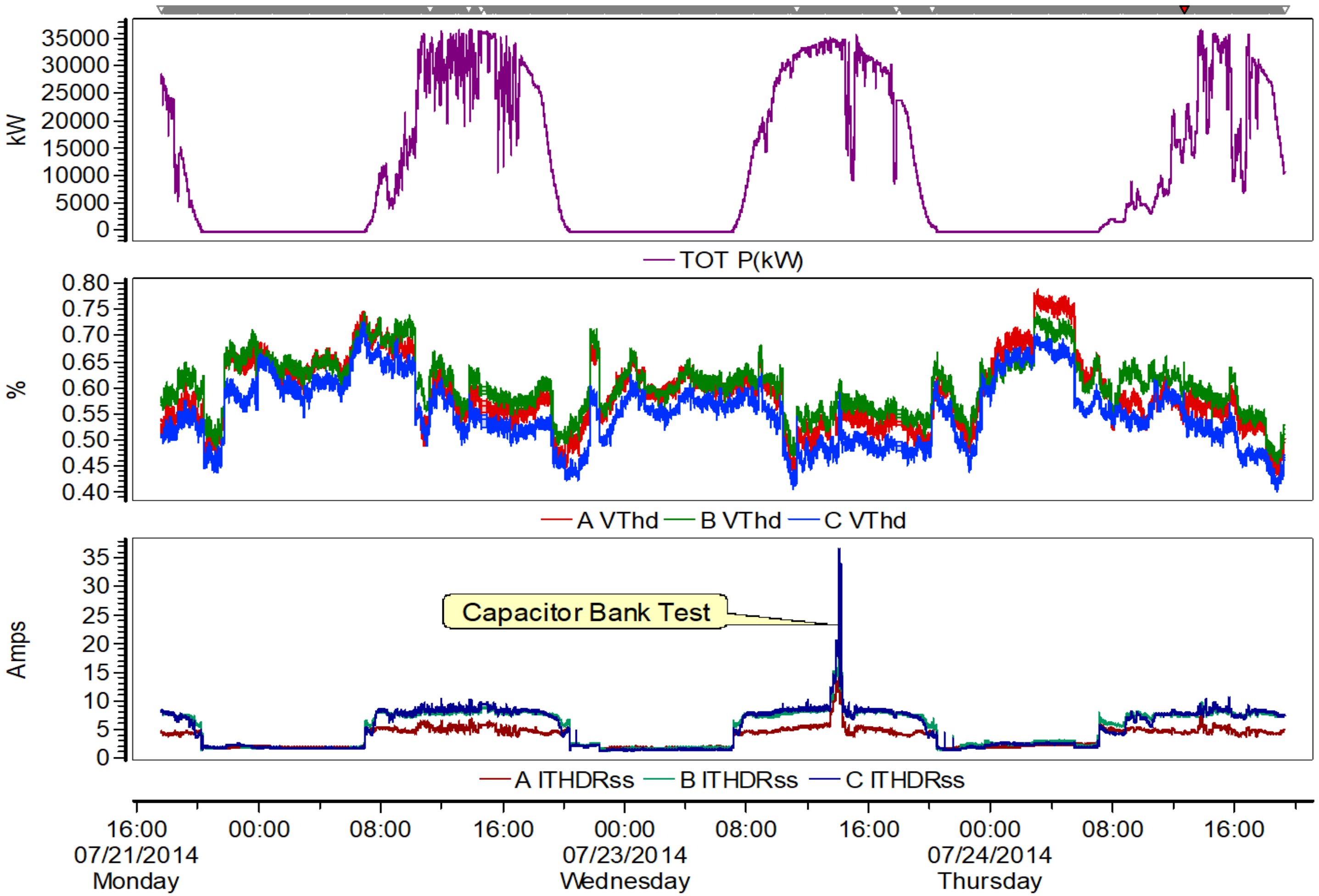
Solar Inverter Harmonics Characteristics

Inverter Characteristics

- *IGBT switching schemes provide low harmonic current total demand distortion (<5% TDD).*



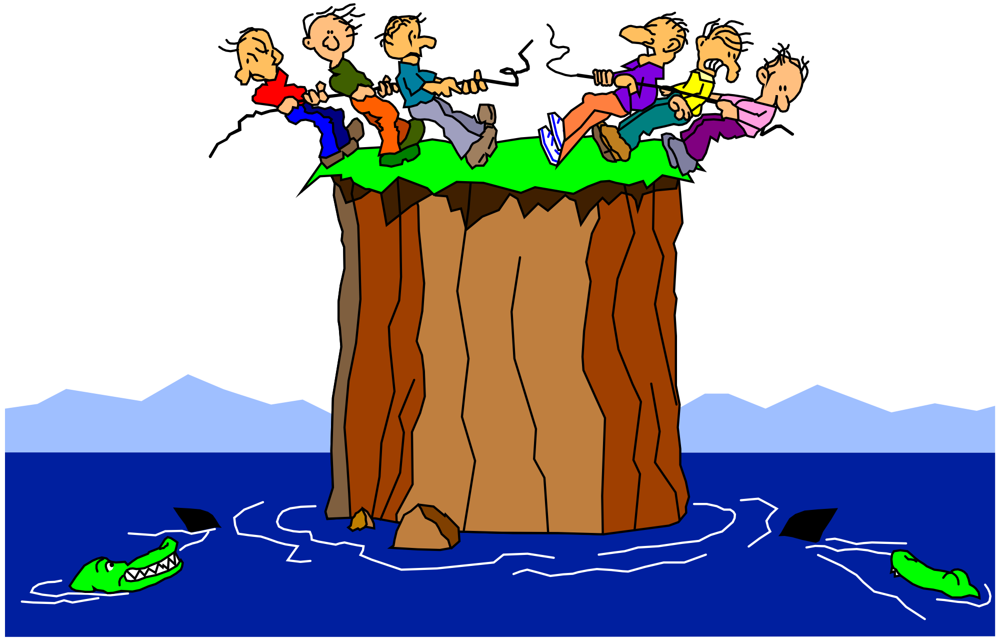
Harmonics Commissioning Test Results at a Solar Plant



IEEE 519 “Recommended Practices and Requirements for Harmonic Control in Electric Power Systems”

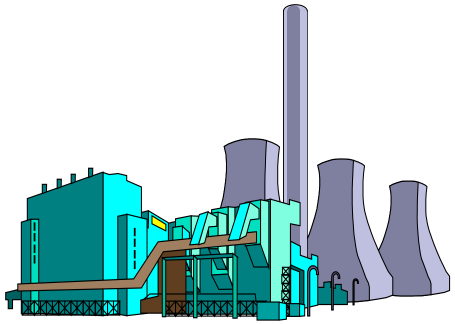
Scope of IEEE 519-2014

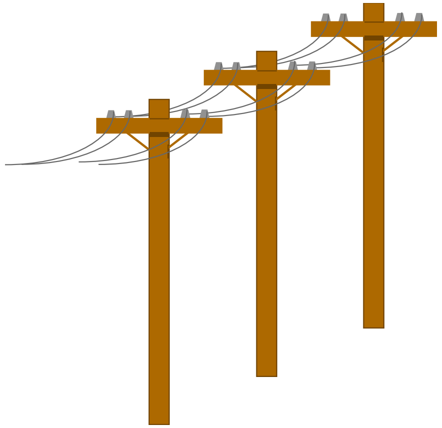
- *Provide methodology for preventing harmonic voltage and current distortion problems on the power system through utility and customer cooperation.*



EnerNex
A CESI Company

Basic Philosophy of IEEE 519





- *The customer is responsible for limiting harmonic currents injected onto the power system.*
- *The utility is responsible for maintaining quality of voltage waveform.*

IEEE 519 Voltage Distortion Recommended Limits

- *The limits are applicable for normal conditions.*
- *For shorter periods (e.g. startup) limits may be exceeded by 50%.*

Table 1—Voltage distortion limits

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \leq 1.0$ kV	5.0	8.0
1 kV $< V \leq$ 69 kV	3.0	5.0
69 kV $< V \leq$ 161 kV	1.5	2.5
161 kV $< V$	1.0	1.5[a]

[a]High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected.

EnerNex
A CESI Company

Applying the IEEE 519 Voltage Distortion Limits

- *Reference measurements according to IEC 61000-4-7*
  - 10 minute values (short)
  - 3 sec values (very short)
- *Evaluation of limits*
  - 95% of 10 minute values
  - 99% of 3 sec values should be less than 1.5 times limits
- *Duration*
  - One week or perhaps one or two wind or solar cycles

MV Harmonic Current Limits

Harmonic Current Limits - Customer Responsibility

SCR $=I_{sc}/I_L$	<11	11<h<17	17<h<23	23<h<35	35<h	TDD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20 - 50	7.0	3.5	2.5	1.0	0.5	8.0
50 - 100	10.0	4.5	4.0	1.5	0.7	12.0
100 - 1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Values shown are in percent of "*average maximum demand load current*"

SCR = short circuit ratio (utility short circuit current at point of common coupling divided by customer average maximum demand load current)

TDD = Total Demand Distortion (uses maximum demand load current as the base, rather than the fundamental current)

IEEE Standard 519-1992 Summary of Recommended Harmonic Current Limits

- *Summary of current harmonic distortion limits (%IL) for individual customers*

Base voltage Limit (kV)	I_{SC}/I_L	h<11	11≤h<17	17≤h<23	23≤h<35	35≤ h
0.12 – 69	<20	4.0	2.0	1.5	0.6	0.3
	20-50	7.0	3.5	2.5	1.0	0.5
	50-100	10.0	4.5	4.0	1.5	0.7
	100-1000	12.0	5.5	5.0	2.0	1.0
	>1000	15.0	7.0	6.0	2.5	1.4
69.001 – 161	<20	2.0	1.0	0.75	0.3	0.15
	20-50	3.5	1.75	1.25	0.5	0.25
	50-100	5.0	2.25	2.0	0.75	0.35
	100-1000	6.0	2.75	2.5	1.0	0.5
	>1000	7.5	3.5	3.0	1.25	0.7
> 161	<25	2.0	0.5	0.38	0.15	0.15
	≥50	3.0	1.5	1.15	0.45	0.22

Important Concepts

- *Point of Common Coupling:*
  - Interface between the utility and the customer
  - This is where limits are applied (NOT AT INDIVIDUAL PIECES OF EQUIPMENT)
- *Average Maximum Demand Load Current:*
  - Maximum monthly demand load current averaged over 12 months
  - All percentages in the table are based on this current (NOT THE FUNDAMENTAL)
- *SCR - Short Circuit Ratio:*
  - Ratio of the short circuit current at the point of common coupling to the "average maximum demand load current"
  - All generation plants must meet the most stringent limits, so SCR for harmonics evaluations is irrelevant to wind and solar plants

Total Demand Distortion

Total Demand Distortion (*TDD*) is defined as:

$$TDD = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_L} \times 100\%$$

where:

I_h = magnitude of individual harmonic components (rms amps)

h = harmonic order

I_L = maximum demand load current (rms amps) defined above

IEEE Standard 519 Current Distortion Limits

- *Even harmonics are limited to 25% of the odd harmonic limits*
- *The limits applicable for normal conditions*
- *For shorter periods (e.g. startup) limits may be exceeded by 50%*
- *Tables applicable for 6-pulse convertors*
- *For higher pulse number (q), limits may be increased by a factor of sqrt(q/6) provided non-characteristic harmonics are less than 25% of the specified limit.*

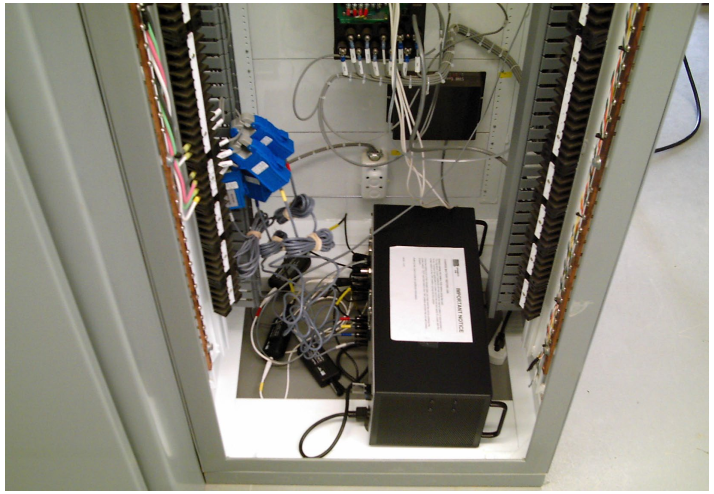
Evaluating IEEE 519 Compliance at a Wind Plant

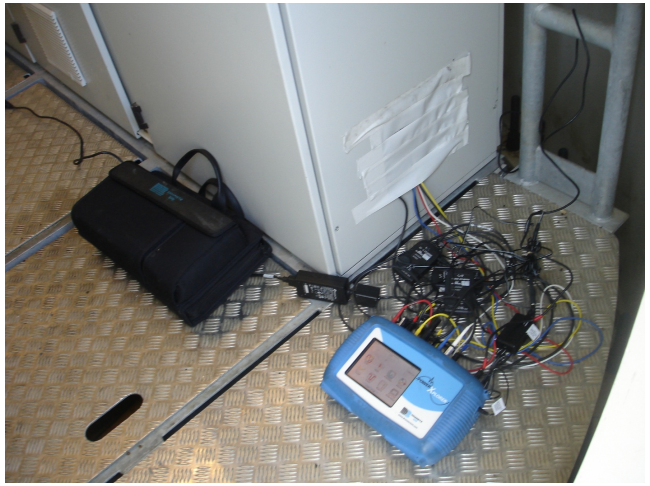
Meeting Harmonics Limits at Wind Plants

- *Most interconnection agreements will reference one of the following standards:*
  - IEEE Std 519, “Recommended Practices and Requirements for Harmonic Control in Electric Power Systems”.
  - IEEE Std 1547 “Standard for Interconnecting Distributed Resources with Electric Power Systems”.
  - IEEE P2800 is proposed for bulk electric system connected inverter based resources performance requirements
- *IEEE 519 includes*
  - Voltage Limits
  - Current Limits

EnerNex
A CESI Company

Field Measurements Compliment Simulations





EnerNex
A CESI Company

IEEE 519 Voltage Distortion Limits

- *Table 1*
- *The limits are applied on a statistical basis ("must be met 95% of the time")*

Table 1—Voltage distortion limits

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \leq 1.0$ kV	5.0	8.0
1 kV $< V \leq$ 69 kV	3.0	5.0
69 kV $< V \leq$ 161 kV	1.5	2.5
161 kV $< V$	1.0	1.5[a]

[a]High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected.

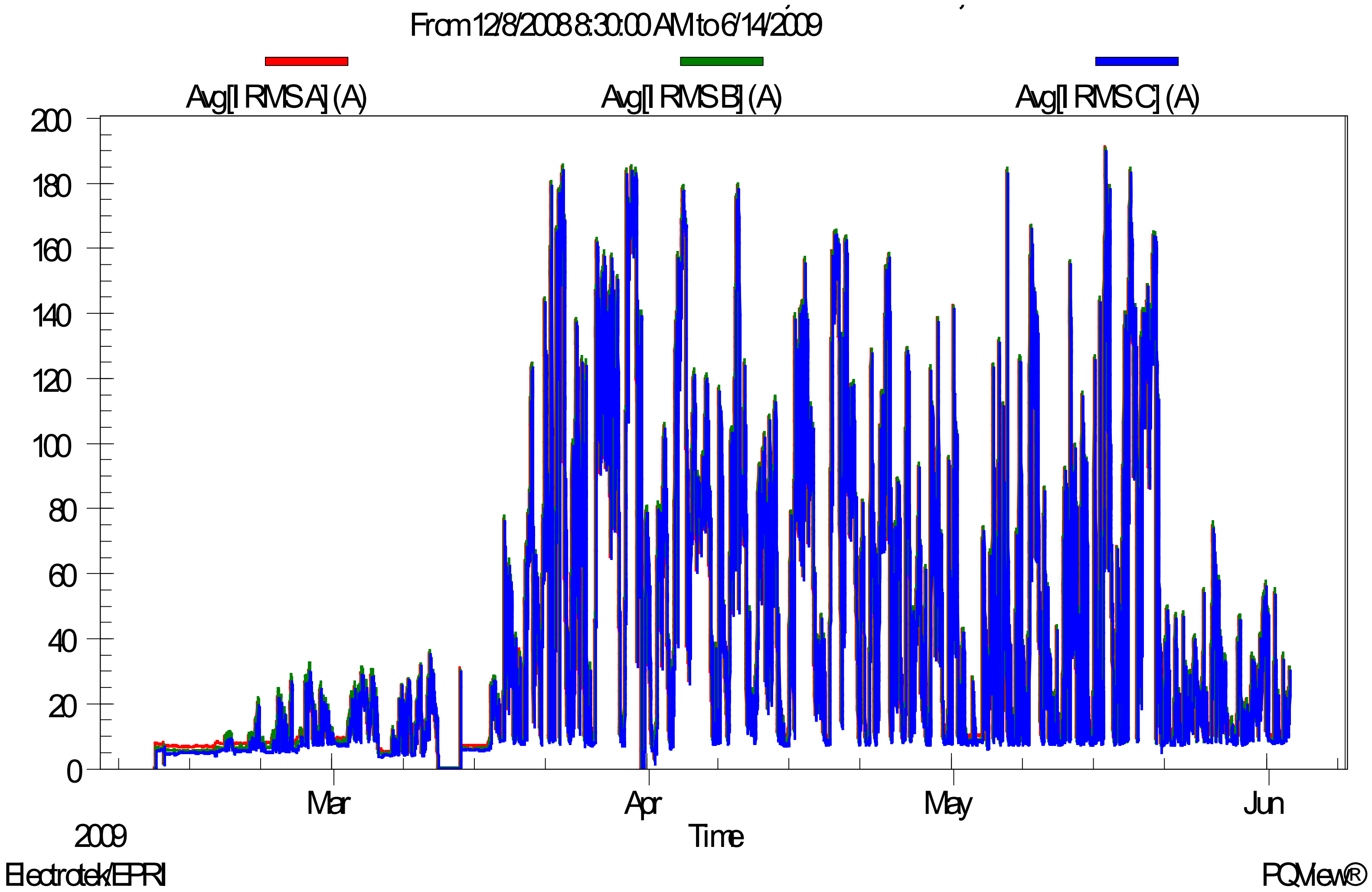
IEEE 519 Harmonic Current Limits

- *The limits are applied on a statistical basis ("must be met 95% of the time")*

Maximum Harmonic Current Distortion in Percent of I_L						
Short Circuit Ratio	Individual Harmonic Limits (Odd Harmonics)					Total
I_{SC}/I_L	**< 11**	**11 ≤ h < 17**	**17 ≤ h < 23**	**23 ≤ h < 35**	**35 ≤ h**	**TDD**
<20*	2.0	1.0	0.75	0.3	0.15	2.5
Even harmonics are limited to 25% of the odd harmonic limits above.						
* All power generation equipment is limited to these values of current distortion, regardless of actual short circuit ratio.						
Where I_L = Maximum demand load current at PCC						

EnerNex
A CESI Company

345 kV Current Trend



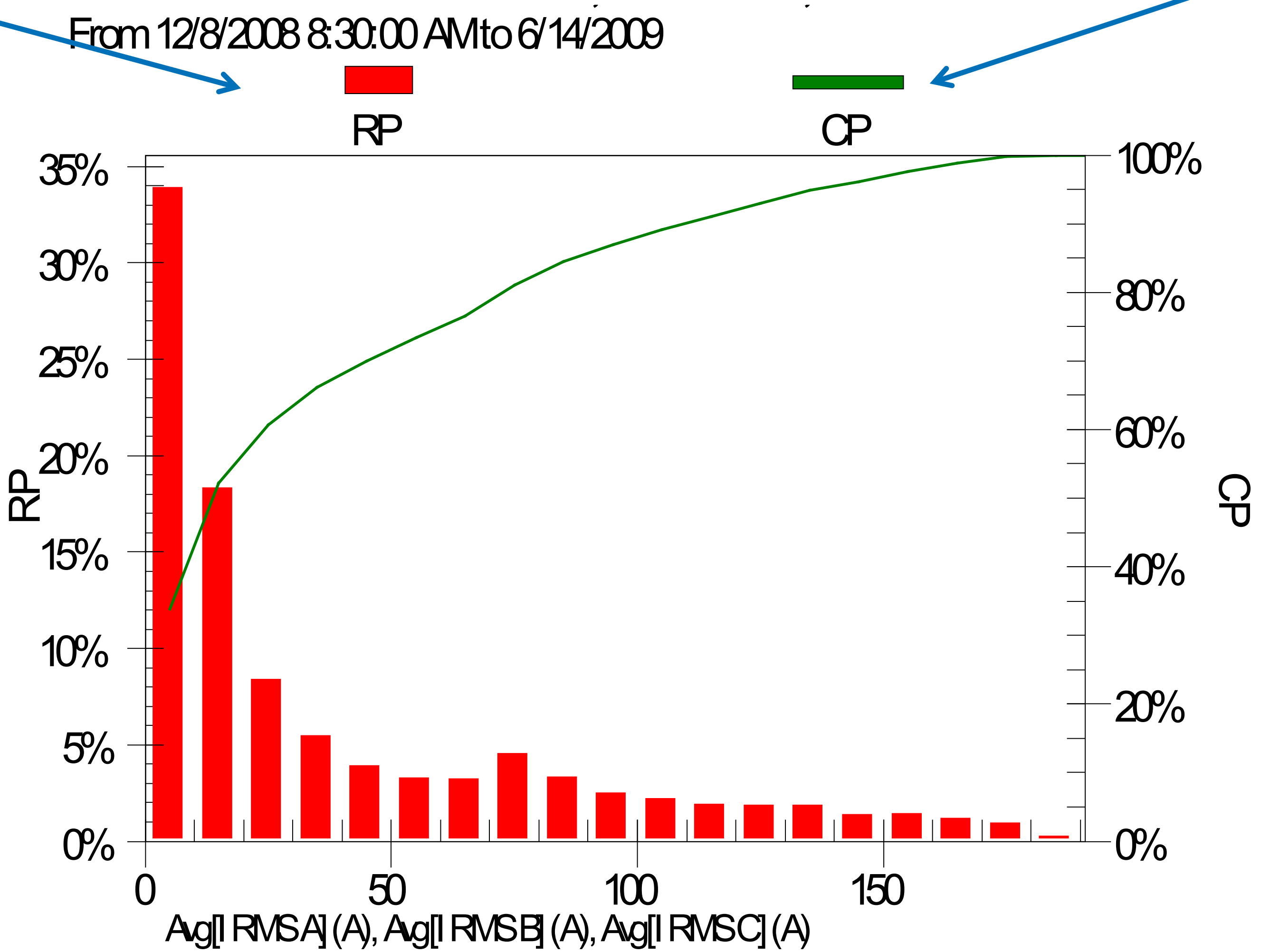
EnerNex
A CESI Company

Statistical Distribution of 345 kV Current

"Relative Probability"

"Cumulative Probability"

Count	96408
Min	0.1644
Avg	40.79
Max	191.30
Range	191.14
St Dev	44.82
Avg +3 St Dev	175.26
Avg -3 St Dev	-93.67
CP01	0.2044
CP05	5.075
CP25	8.598
CP50	18.13
CP75	65.22
CP95	140.94
CP99	171.94
SI Range	28.31



EnerNex
A CESI Company

Harmonic Current Limits (Primary Amperes)

Primary Current IL

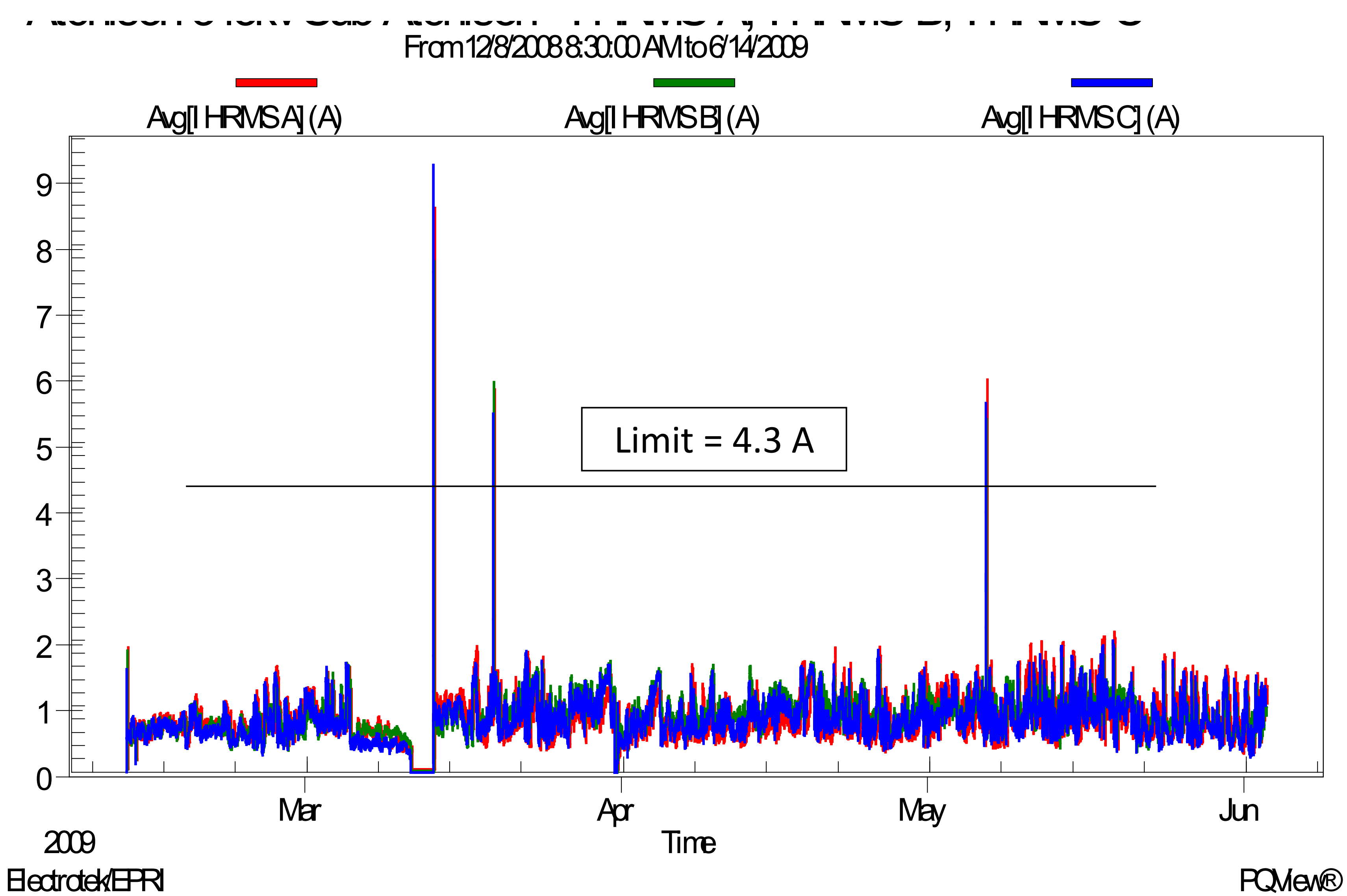
102.8	MVA
345	kV
172.0	Amps

IEEE 519 (1992) Table 10-5 -- Current Distortion Limits for General Transmission Systems >161kV

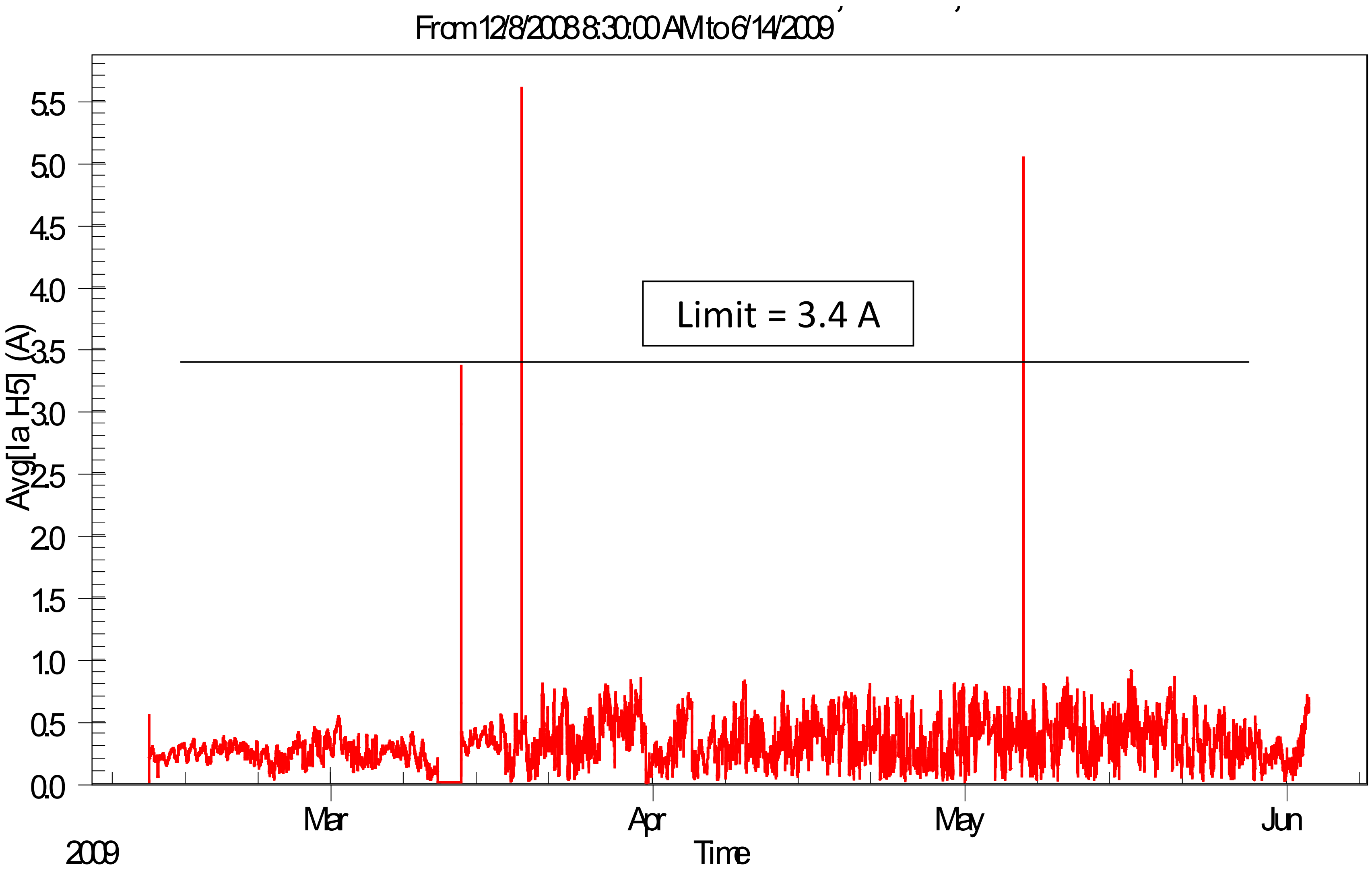
	<11	**11=<h<17**	**17=<h<23**	**23=<h<35**	**35=<h**	**TDD**
Limits (Percent)	2.0%	1.0%	0.75%	0.3%	0.15%	2.5%
Limits (Primary Current Amps)	**3.4**	**1.7**	**1.3**	**0.5**	**0.3**	**4.3**

EnerNex
A CESI Company

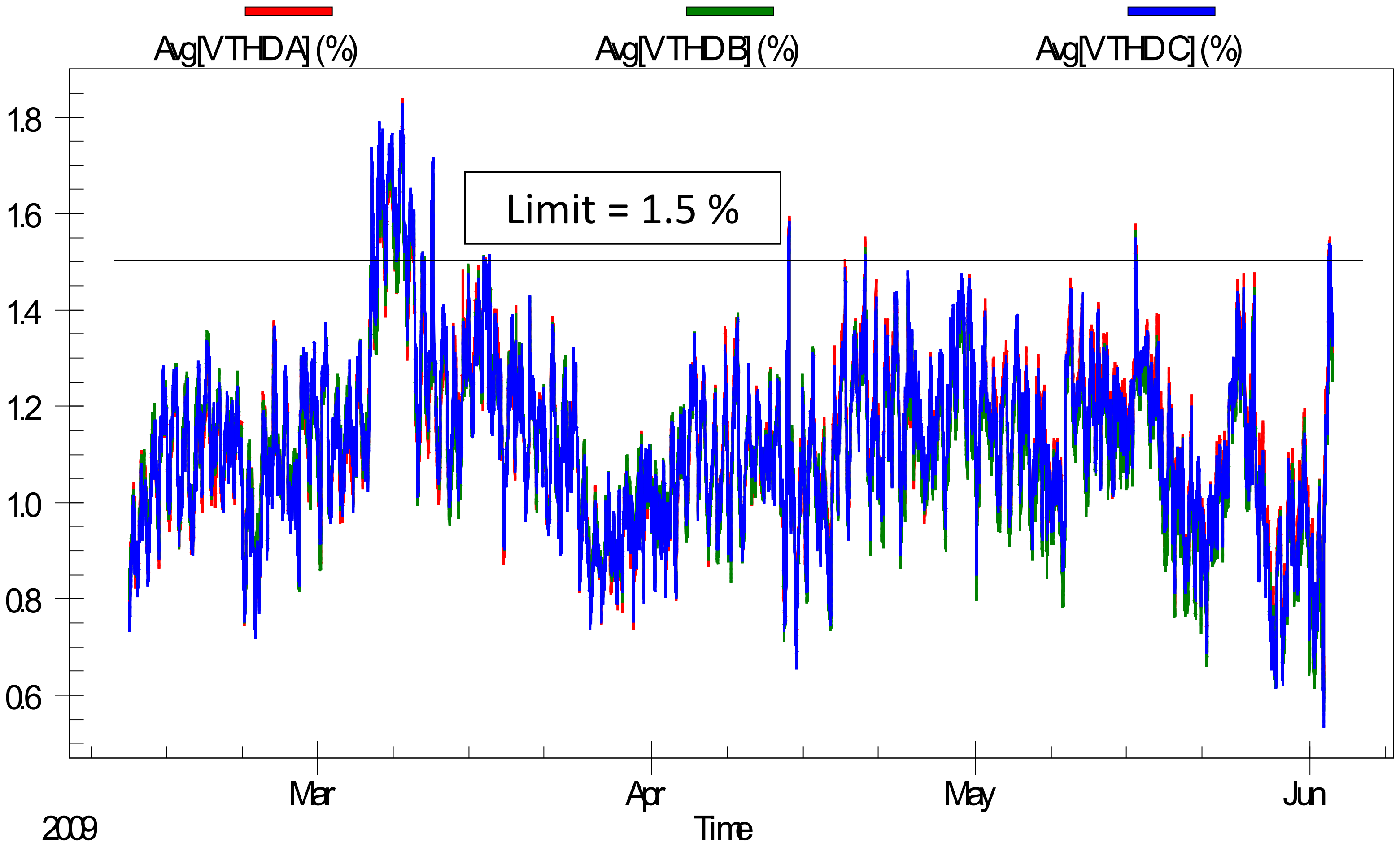
Total Harmonic Current Trend



5th Harmonic Current Trend



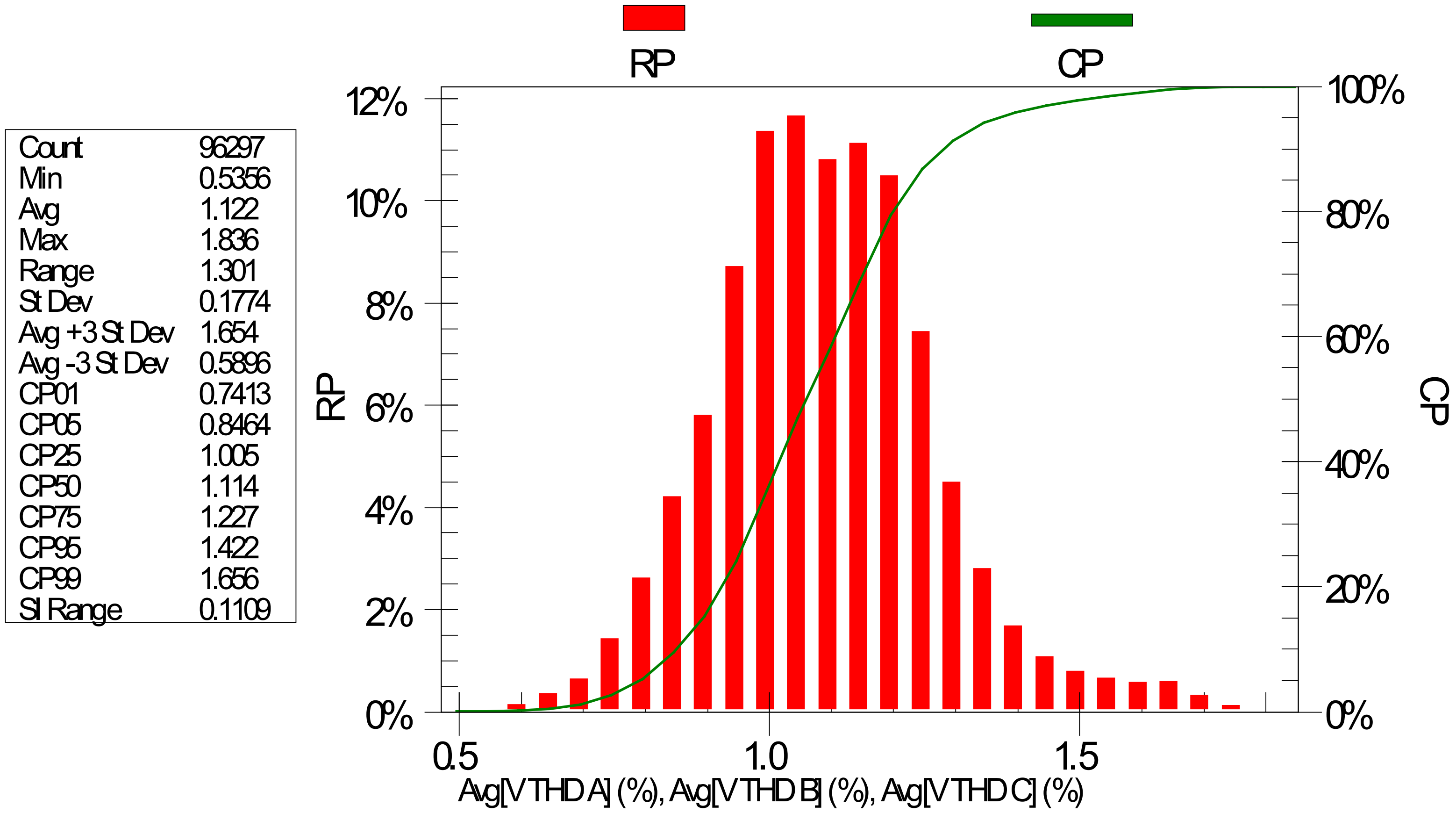
Total Harmonic Voltage Distortion (THDv)



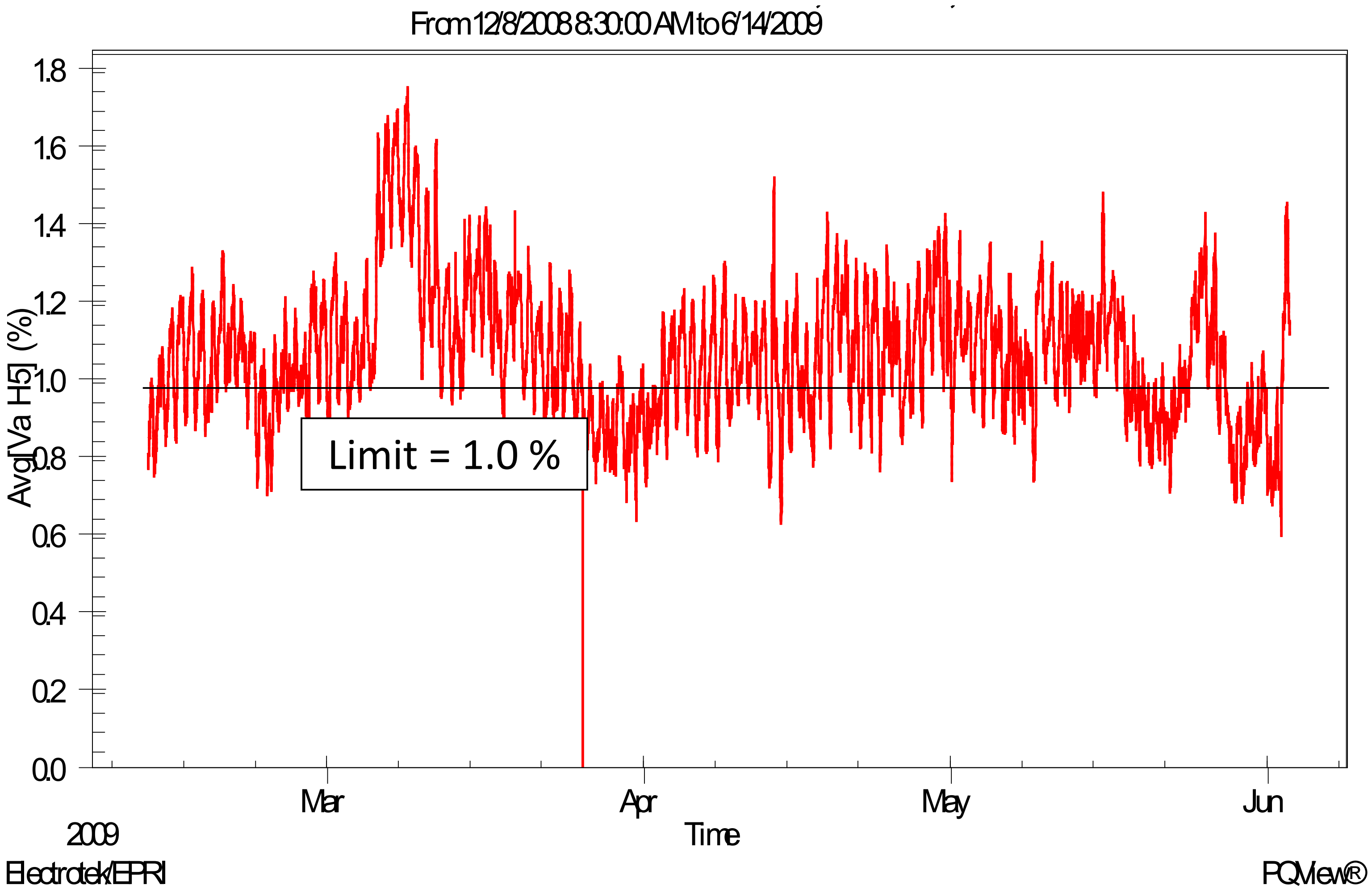
EnerNex
A CESI Company

Histogram of THDv

- *The CP 95% (cumulative probability) value meets the limits!*



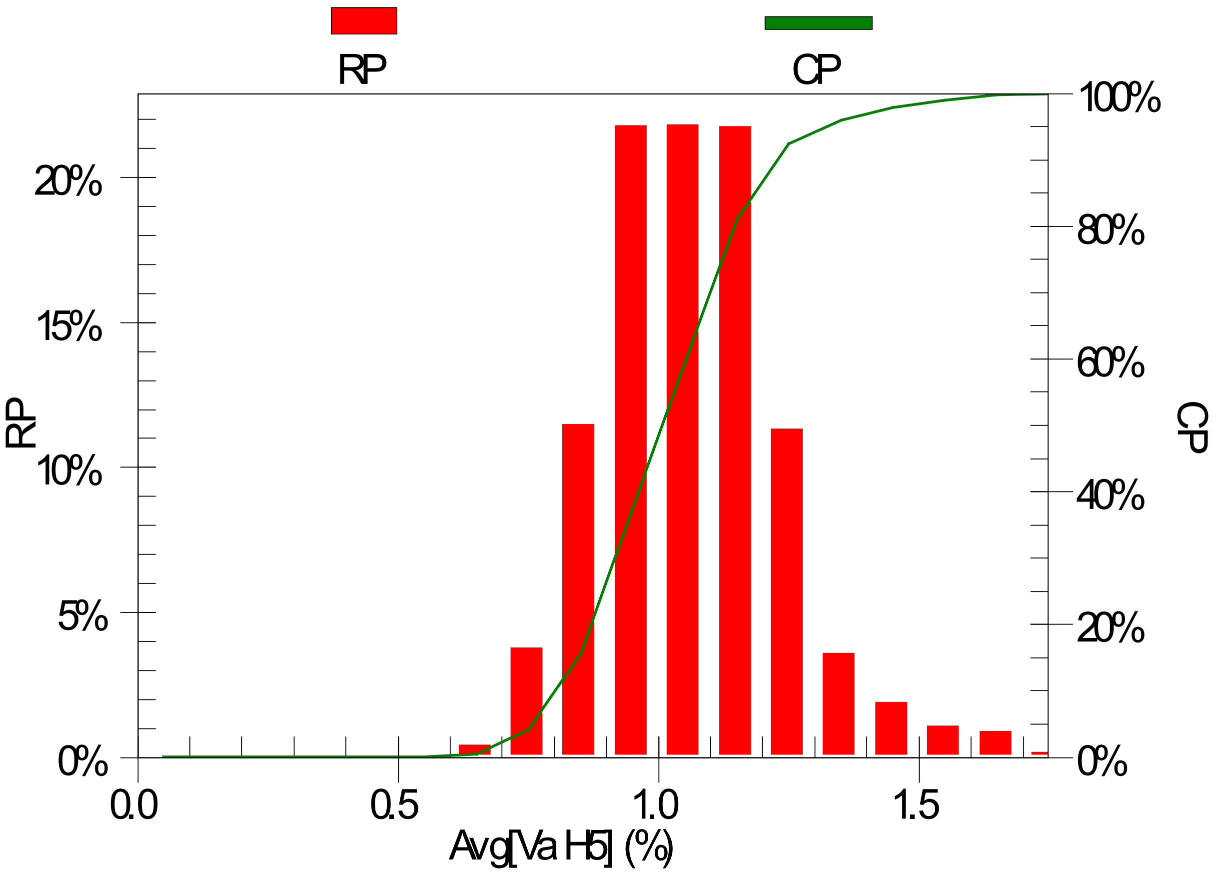
5th Harmonic Voltage Distortion



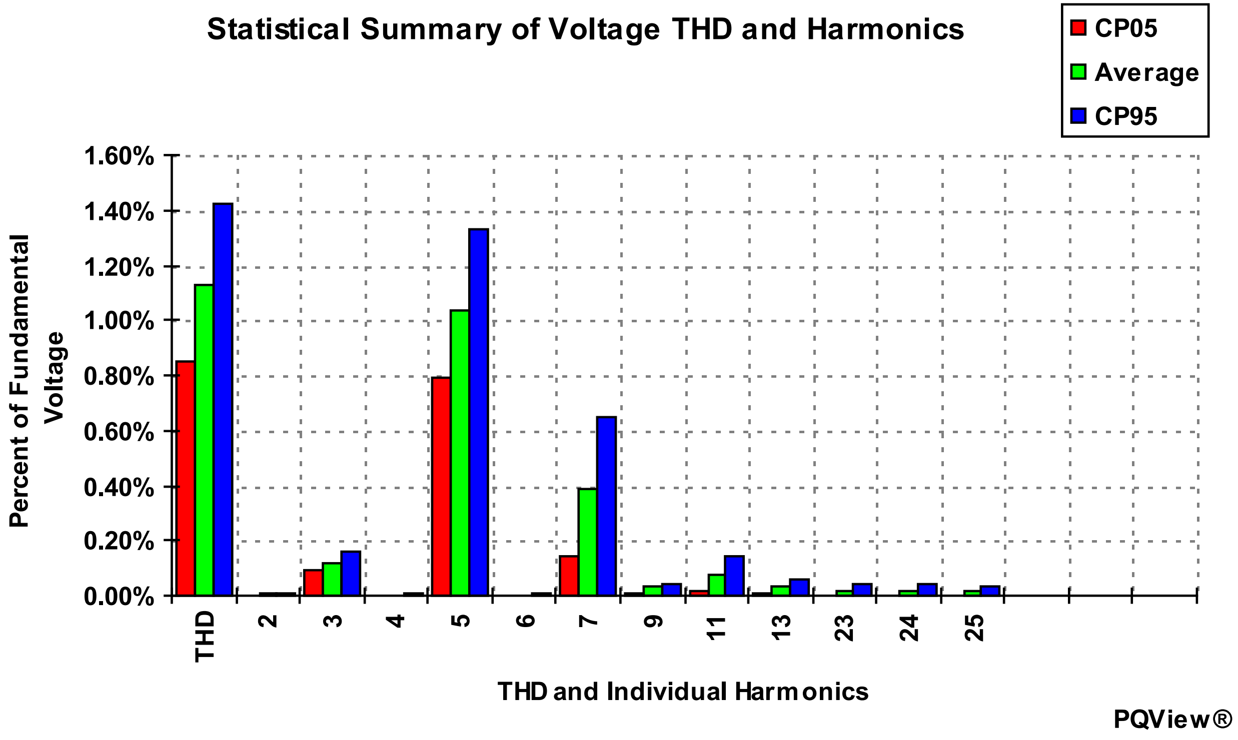
Histogram of 5th Harmonic Voltage (%)

- *The 5th harmonic voltage does not meet the individual harmonic limit.*
- *This will be common for utility 230 kV and above transmission limits, with or without wind turbines.*

Count	32099
Min	0
Avg	1.067
Max	1.759
Range	1.759
St Dev	0.1721
Avg +3 St Dev	1.584
Avg -3 St Dev	0.5512
CP01	0.7298
CP05	0.8096
CP25	0.9465
CP50	1.060
CP75	1.169
CP95	1.359
CP99	1.605
SI Range	0.1114



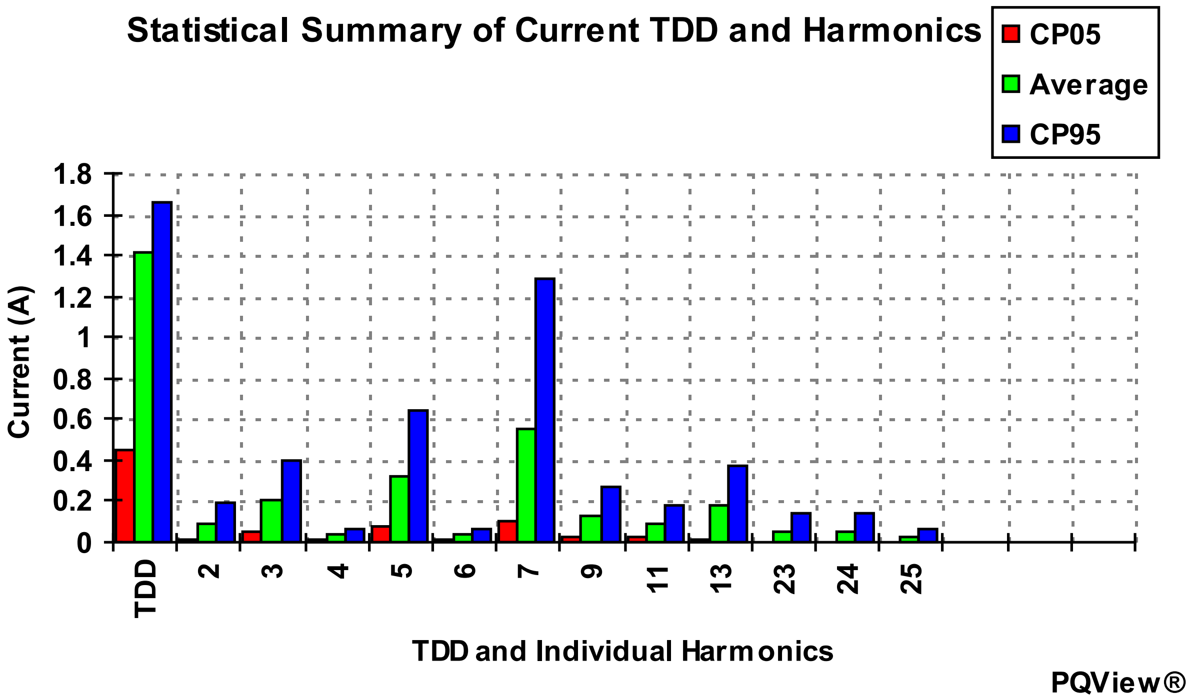
Voltage Harmonic Summary



Harmonic	Limit %	Measured CP95% %	Pass/Fail
THD	1.5	1.42	Pass
2	1.0	0.01	Pass
3	1.0	0.16	Pass
4	1.0	0.01	Pass
5	1.0	1.33	Fail
6	1.0	0.01	Pass
7	1.0	0.65	Pass
11	1.0	0.14	Pass
13	1.0	0.06	Pass
23	1.0	0.04	Pass
24	1.0	0.04	Pass
25	1.0	0.03	Pass

EnerNex
A CESI Company

Harmonic Current Summary



Harmonic	Limit (A)	Measured CP95% (A)	Pass/Fail
TDD	4.3	1.4	Pass
2	0.85	0.19	Pass
3	3.40	0.4	Pass
4	0.85	0.06	Pass
5	3.40	0.64	Pass
6	0.85	0.07	Pass
7	3.40	1.28	Pass
11	1.70	0.19	Pass
13	1.70	0.37	Pass
23	0.50	0.14	Pass
24	0.13	0.14	Fail
25	0.50	0.07	Pass

IEEE 519 Evaluation Conclusions

- *The Wind Plant meets the harmonic current limits of IEEE 519, with the exception of the 24th harmonic current that slightly exceeds the limits. The small amount of 24th harmonic current should not present any practical concern.*

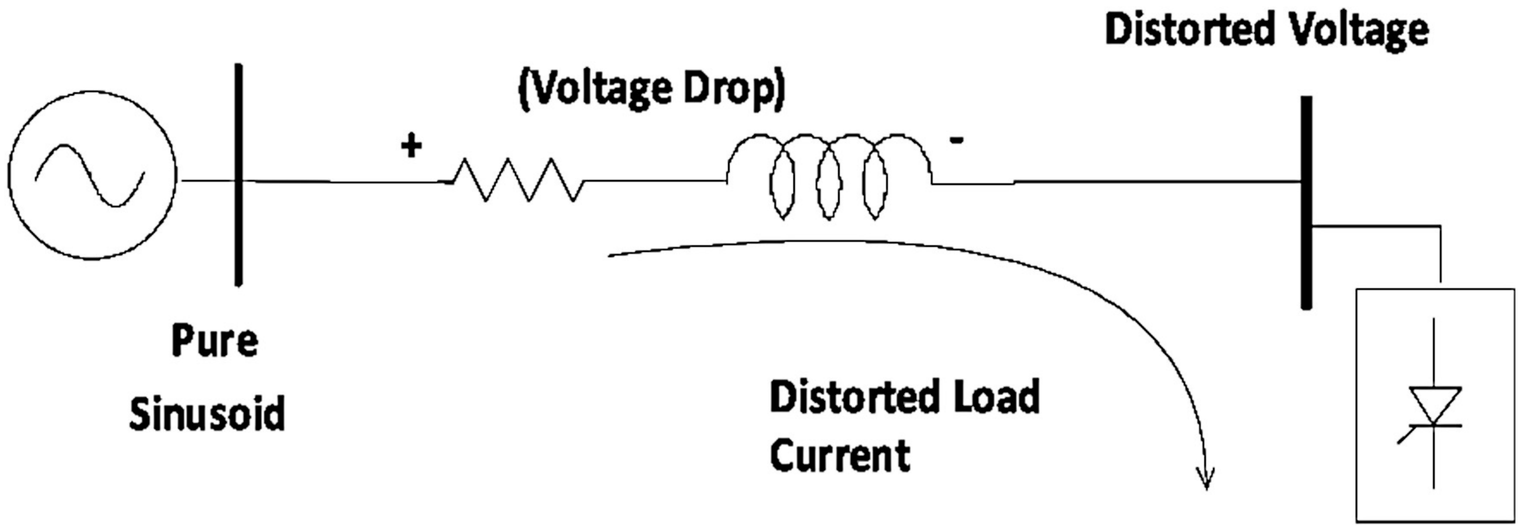
- *The total harmonic voltage distortion meets the IEEE 519 limits. However, the 5th harmonic voltage distortion exceeds the IEEE-519 single frequency limit of 1.0%, with the CP95% value of 1.33%.*

- *The harmonic voltage limits of IEEE 519 are extremely conservative, and it is not unusual for transmission systems to exceed those limits, particularly at the 5th harmonic voltage. The voltage distortion should not be expected to cause any practical problems, but the conditions deserve some further monitoring.*

Plant Collection System Resonance

Voltage Distortion vs. Current Distortion

- *When nonlinear loads inject harmonic current components into a linear power system, the relationships are fairly simple.*
- *The system impedance vs. frequency characteristics determine the harmonic voltage distortion levels.*

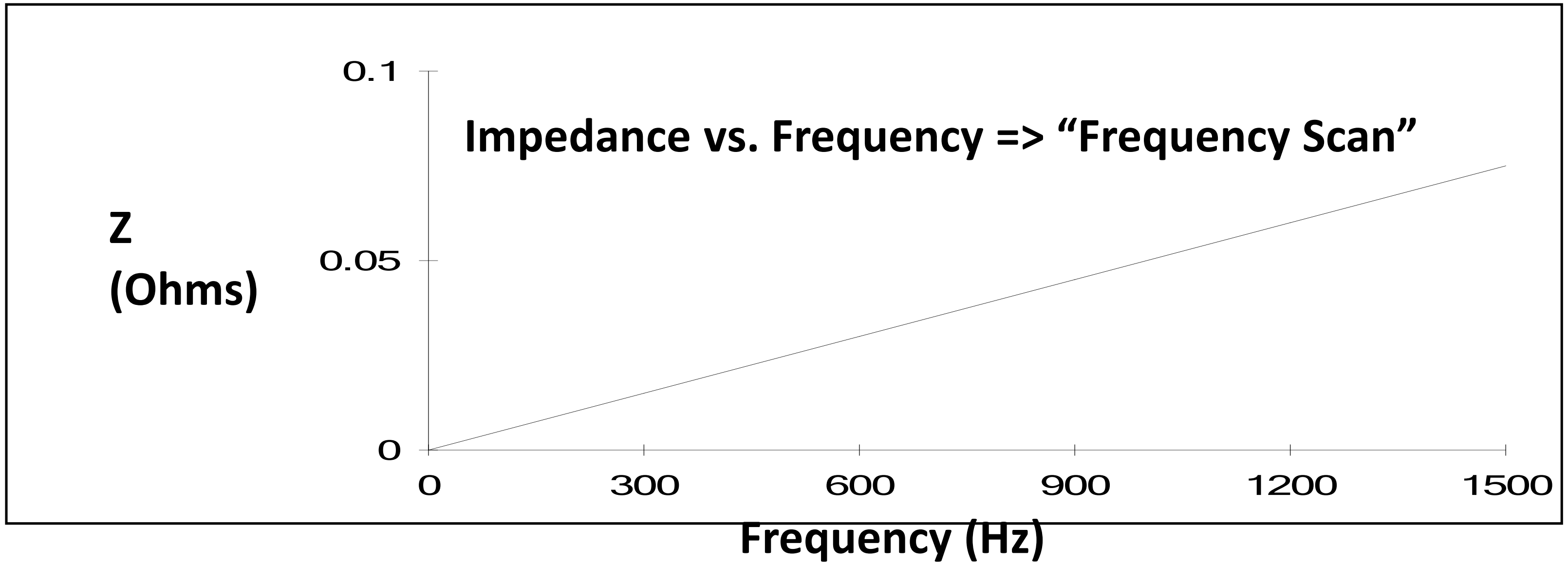


Frequency Scan - Impedance vs. Frequency

- *At harmonic frequencies, the impedance of the equivalent inductance is:*

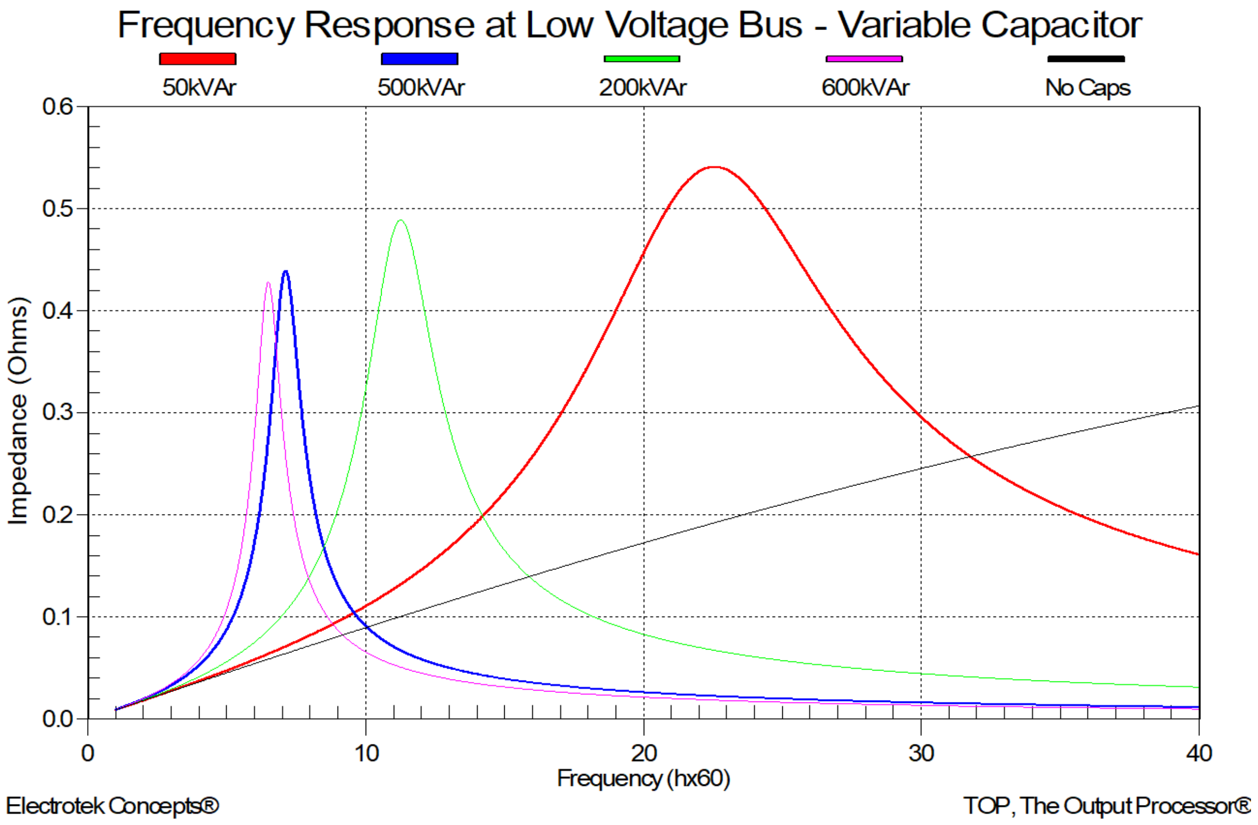
$$X_h = 2 \cdot \pi \cdot f_h \cdot L_{eq} = 2 \cdot \pi \cdot 60 \cdot h \cdot L_{eq}$$

h = harmonic number
f_h = harmonic frequency



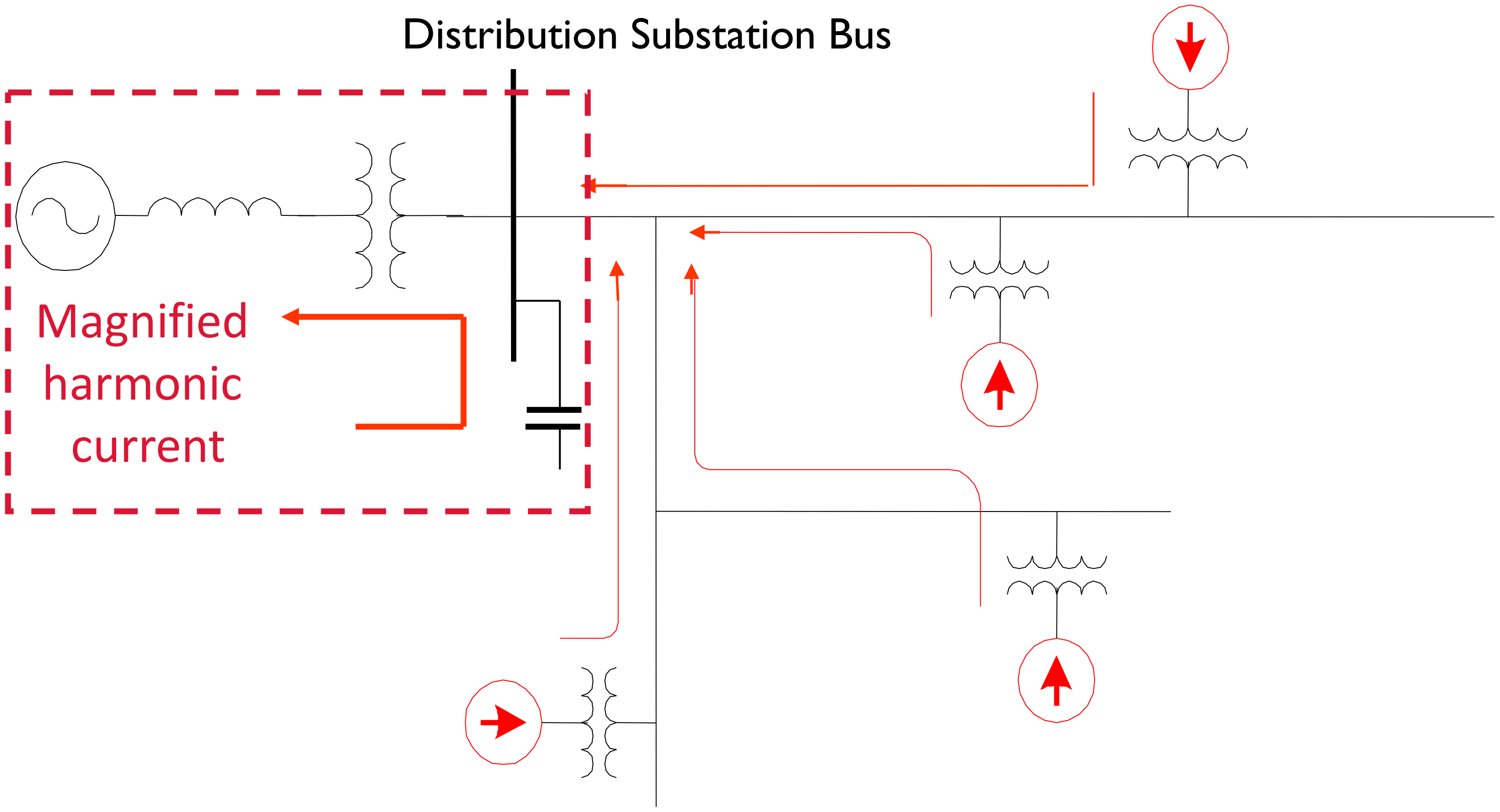
Effect of Capacitors

- *However, it is not as simple and wind and solar plants. Capacitor banks, underground cables, and inverter filters all alter the system frequency response. They create a parallel resonance that can magnify harmonic currents and increase voltage distortion levels.*

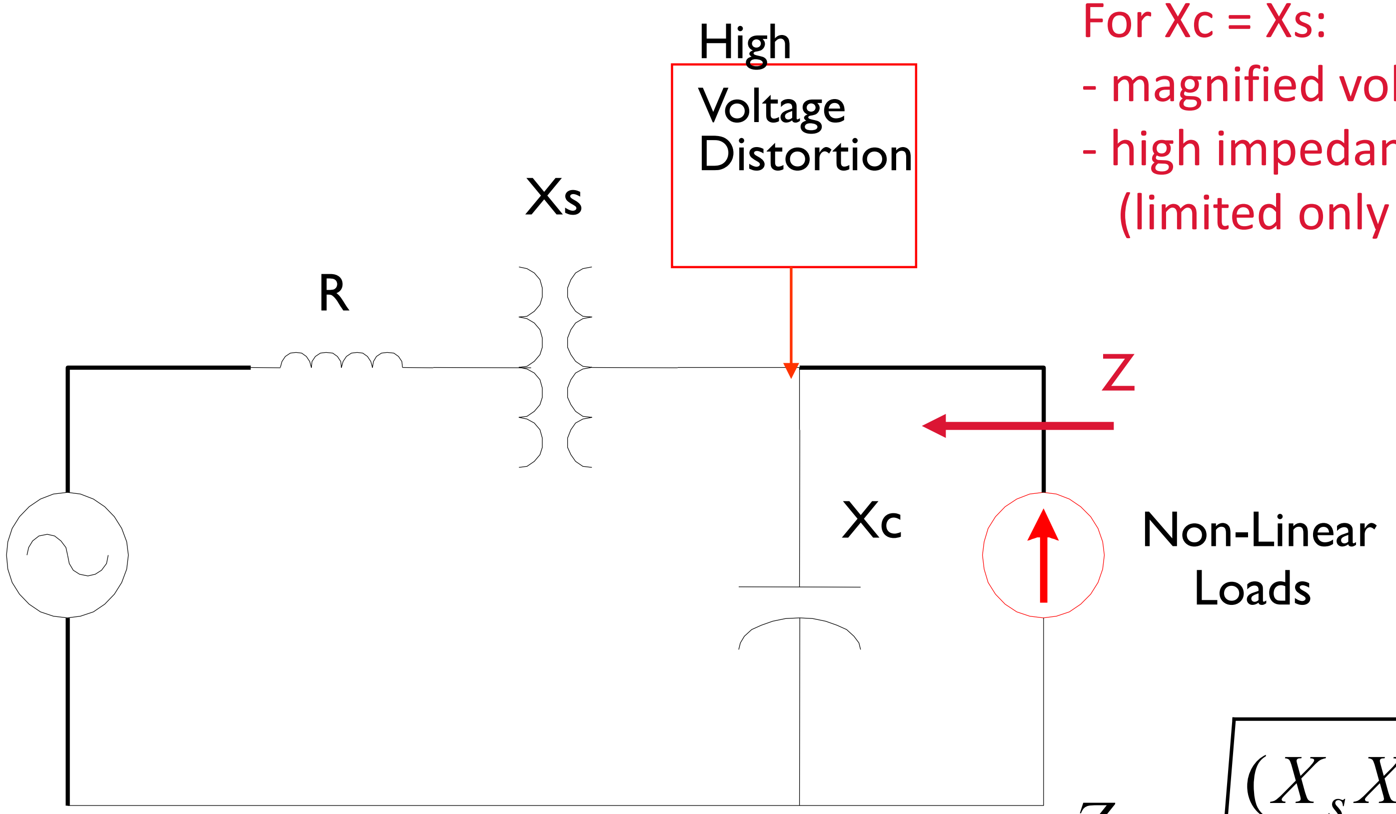


EnerNex
A CESI Company

- *Parallel resonance is often set up by capacitor banks at a substation.*



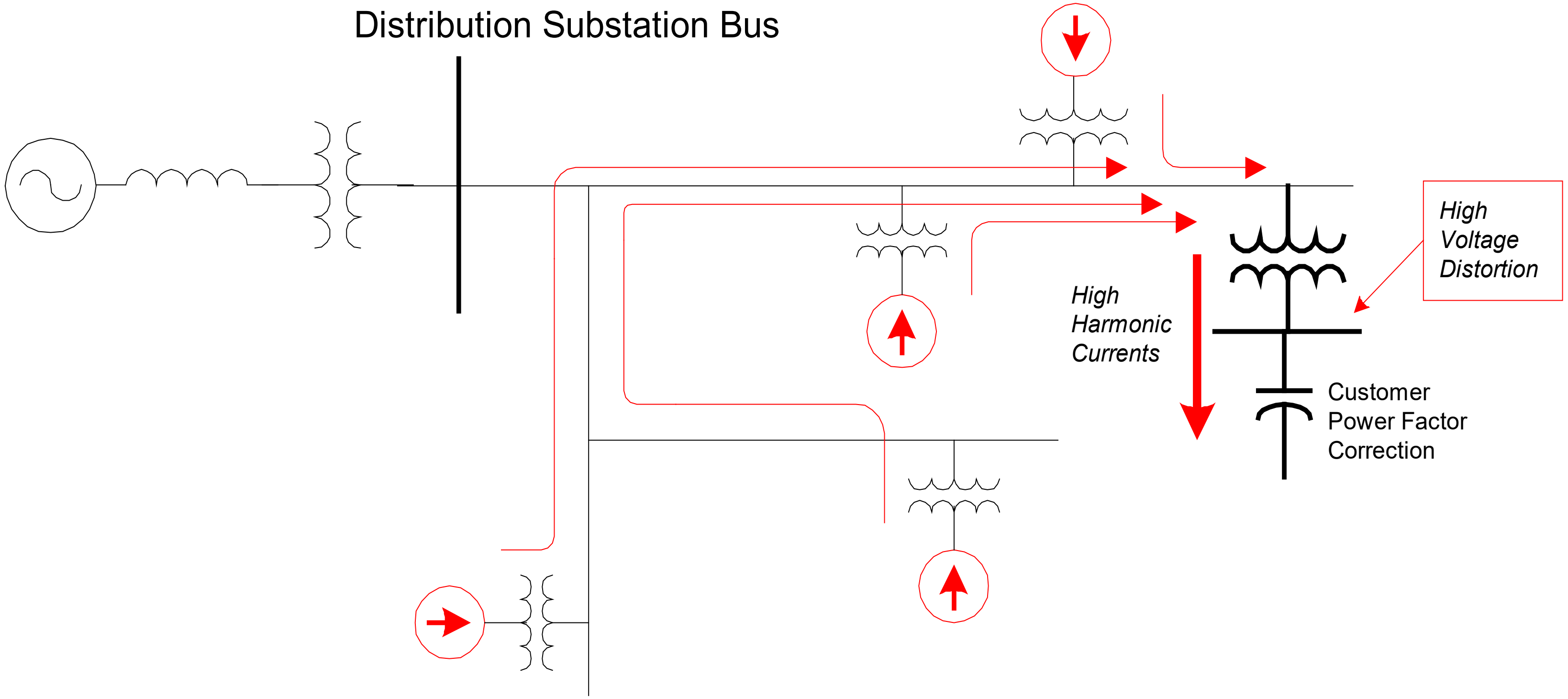
Parallel Resonance – Simplified Network



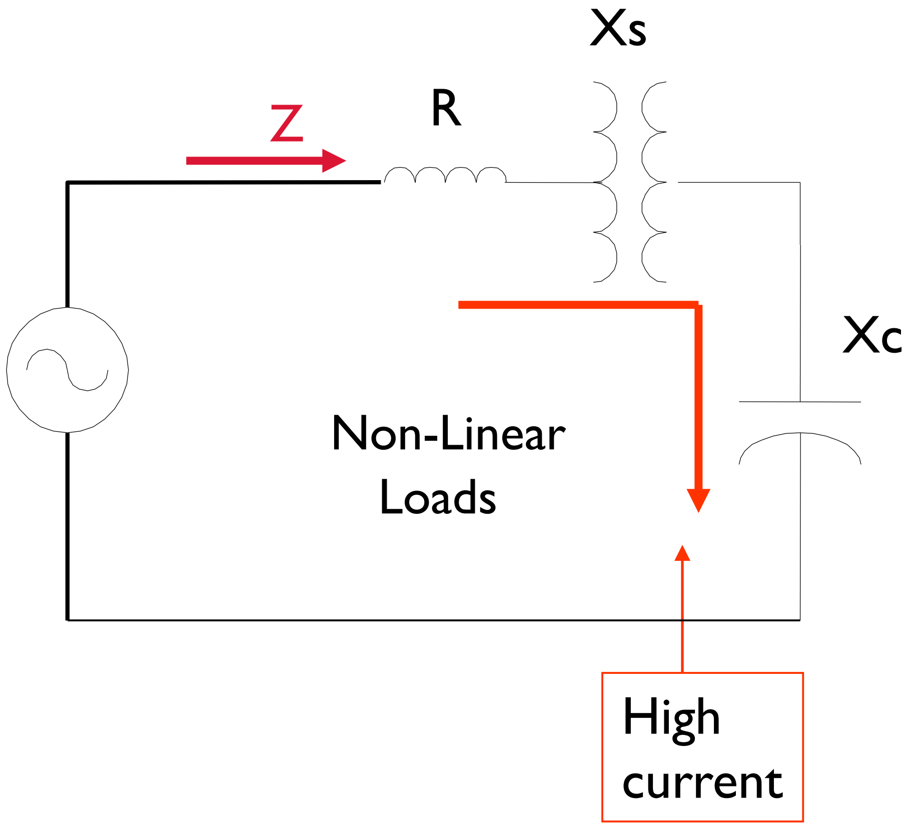
For Xc = Xs:
- magnified voltage
- high impedance
  (limited only by R)

$$Z = \sqrt{\frac{(X_s X_c)^2 + (RX_c)^2}{R^2 + (X_s - X_c)^2}}$$

- *But series resonance is more significant at wind and solar plant. The utility grid background) sources of harmonics cause harmonic current flows.*



Series Resonance – Simplified Network



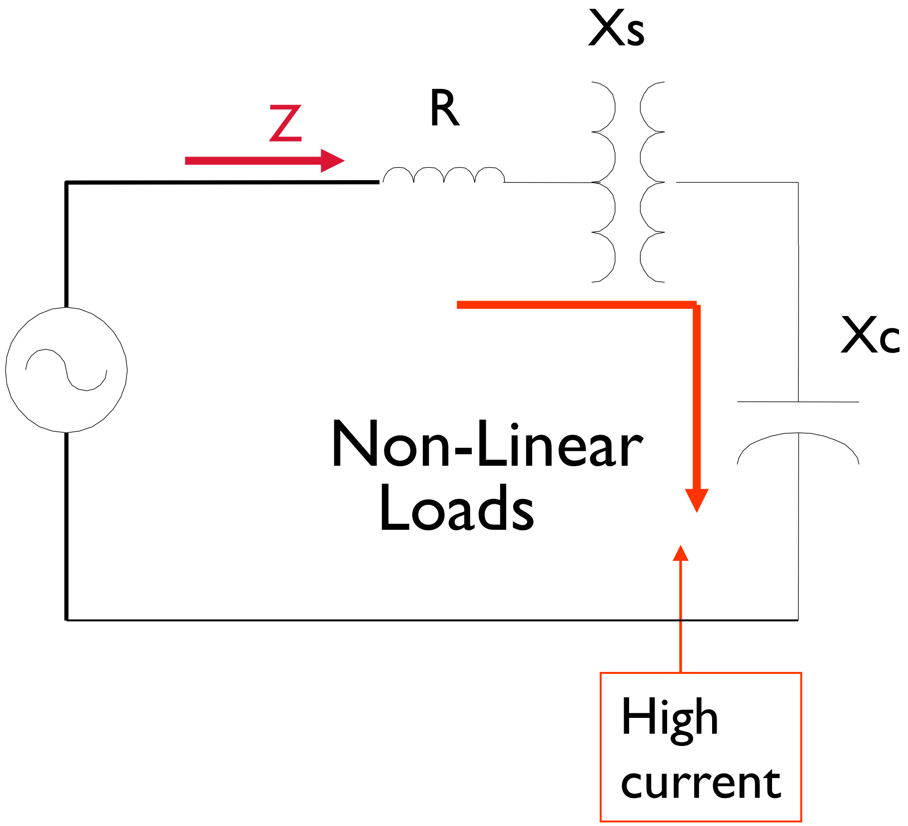
For Xc = Xs:

- magnified current
- low impedance
  (limited only by R)
- fuses blown
- overheating

$$\underline{I} = \frac{\underline{V}}{\underline{Z} \rightarrow 0} \rightarrow \infty$$

$$Z = \sqrt{R_2 + (X_s - X_c)^2}$$

Series Resonance – Simplified Network



For Xc = Xs:
- magnified current
- low impedance (limited only by R)
- fuses blown
- overheating

$$\underline{I} = \frac{\underline{V}}{\underline{Z} \to 0} \to \infty$$

$$Z = \sqrt{R_2 + (X_s - X_c)^2}$$

IEEE 1547 Harmonic Current Limits

- *IEEE 1547 (2018) "IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces"*

Table 26 —Maximum odd harmonic current distortion in percent of rated current (I_{rated})[a]

Individual odd harmonic order h	$h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h < 50$[109]	Total rated current distortion (TRD)
Percent (%)	4.0	2.0	1.5	0.6	0.3	5.0

[a] I_{rated} = the DER unit rated current capacity (transformed to the RPA when a transformer exists between the DER unit and the RPA).

Table 27 —Maximum even harmonic current distortion in percent of rated current (I_{rated})[a]

Individual even harmonic order h	$h = 2$	$h = 4$	$h = 6$	$8 \le h < 50$
Percent (%)	1.0	2.0	3.0	Associated range specified in Table 26

[a] I_{rated} = the DER unit rated current capacity (transformed to the RPA when a transformer exists between the DER unit and the RPA).

The total rated current distortion (TRD) in Table 26 , which includes the harmonic distortion and inter-harmonic distortion, can be calculated using Equation (2):

$$\%TRD = \frac{\sqrt{I_{rms}^2 - I_1^2}}{I_{rated}} \times 100\%$$

where

I_1 is the fundamental current as measured at the RPA

I_{rated} is the DER rated current capacity (transformed to the RPA when a transformer exists between the DER unit and the RPA)

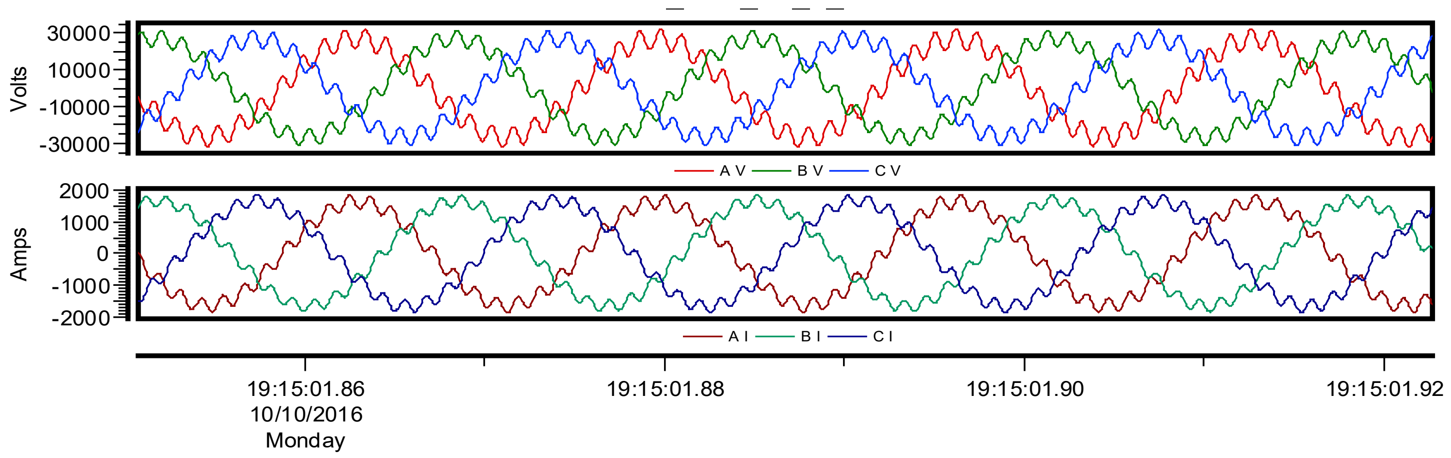
I_{rms} is the root-mean-square of the DER current, inclusive of all frequency components, as measured at the RPA

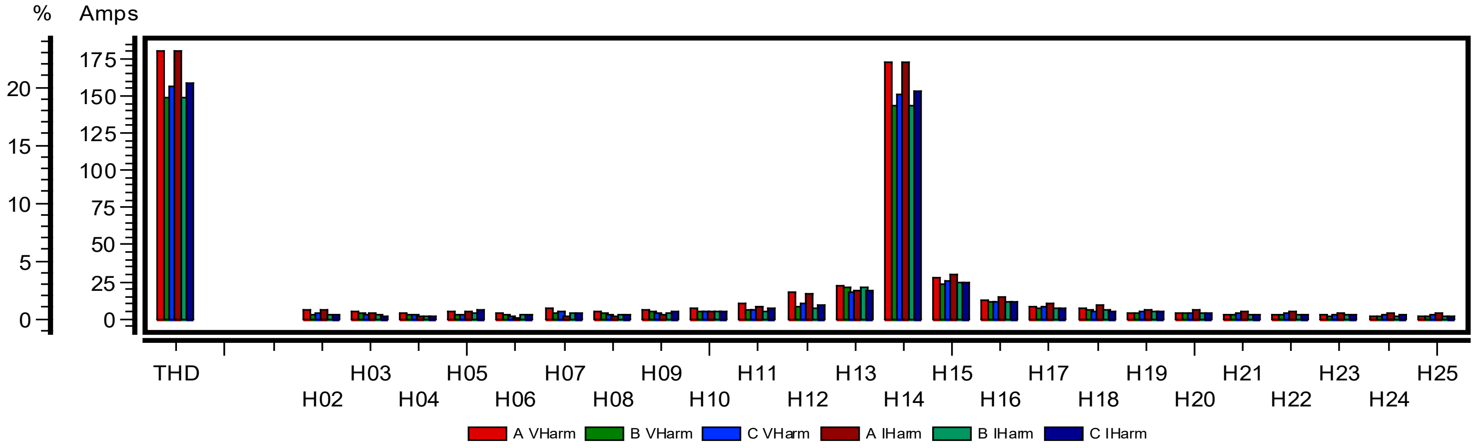
EnerNex
A CESI Company

Inverter/Grid Resonance Controls Interactions

Harmonics Problems

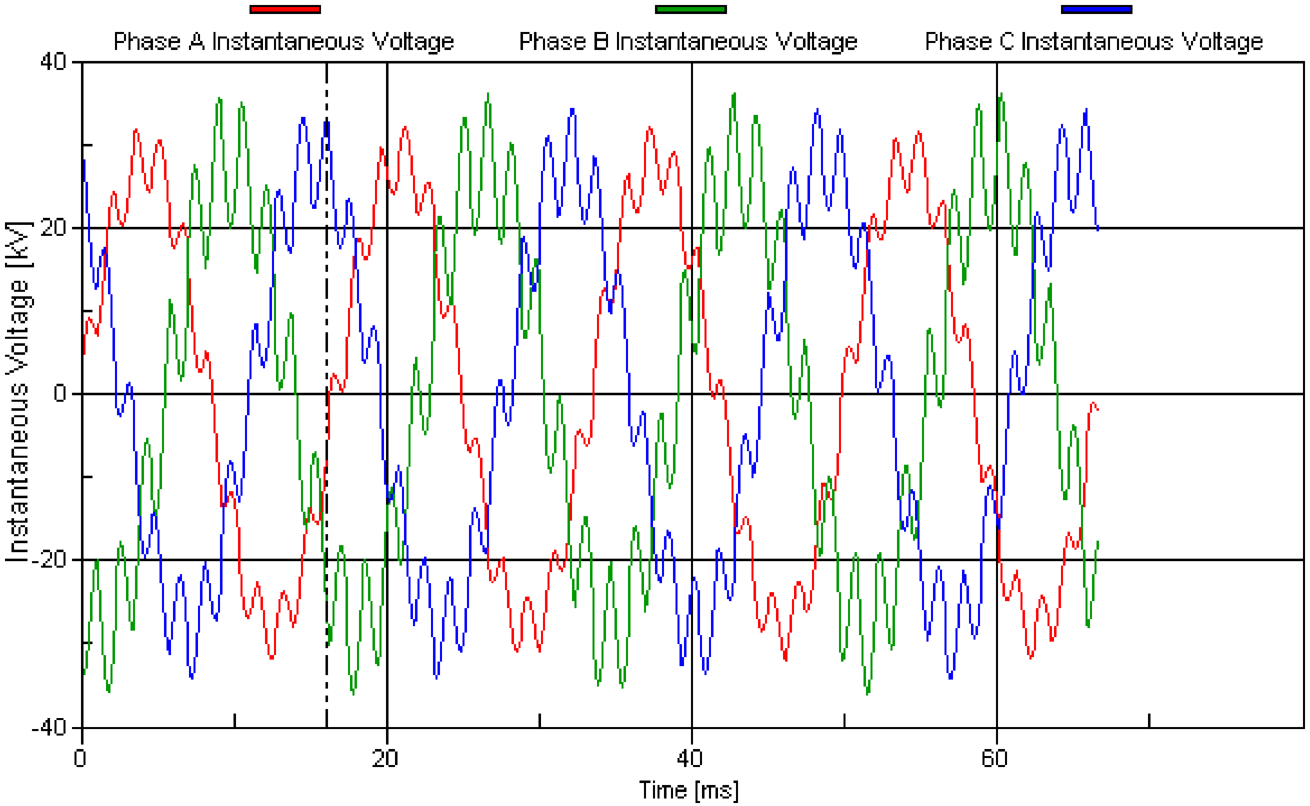
- *Not a normal condition, but in about a dozen projects there have been serious problems!*





Case History #2 (Type 4)

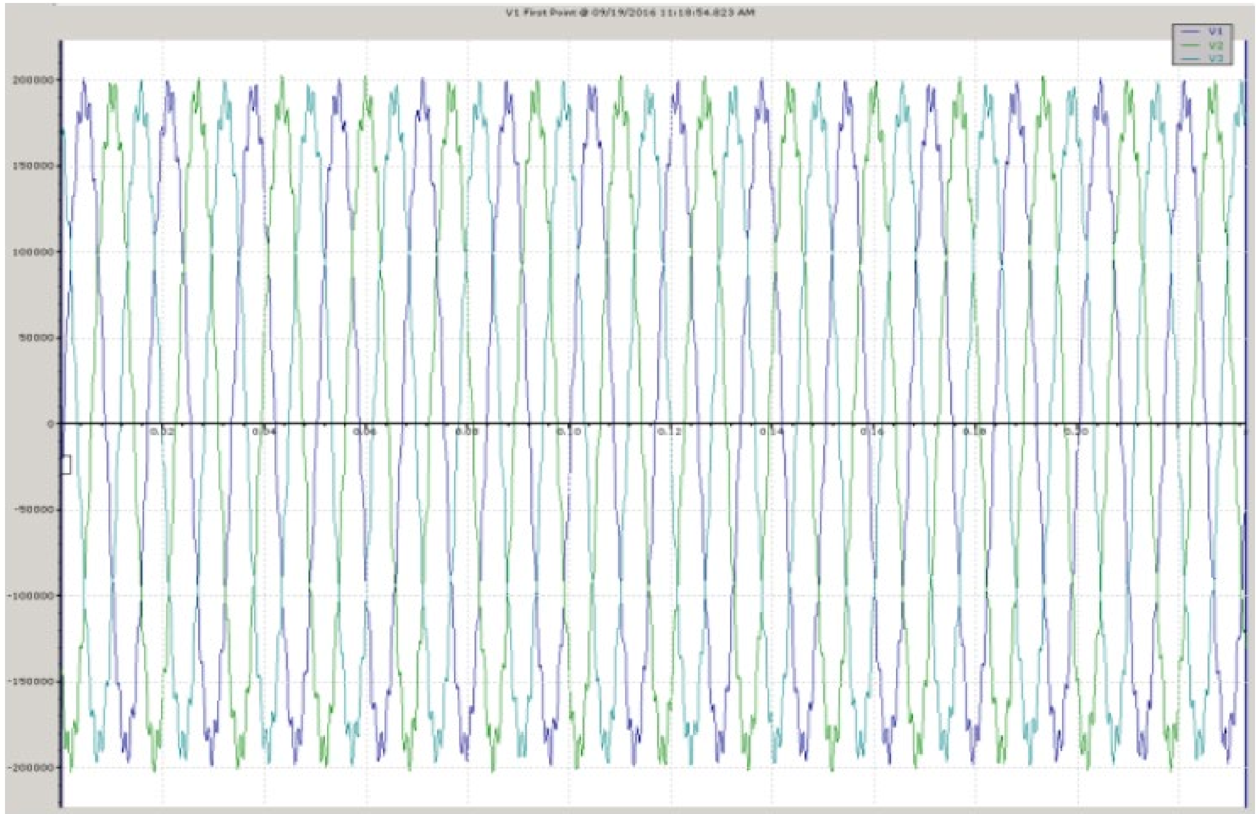
- 2009-2010
- Failed Lightning Surge Arresters
- Affected industrial plant equipment 20 miles away

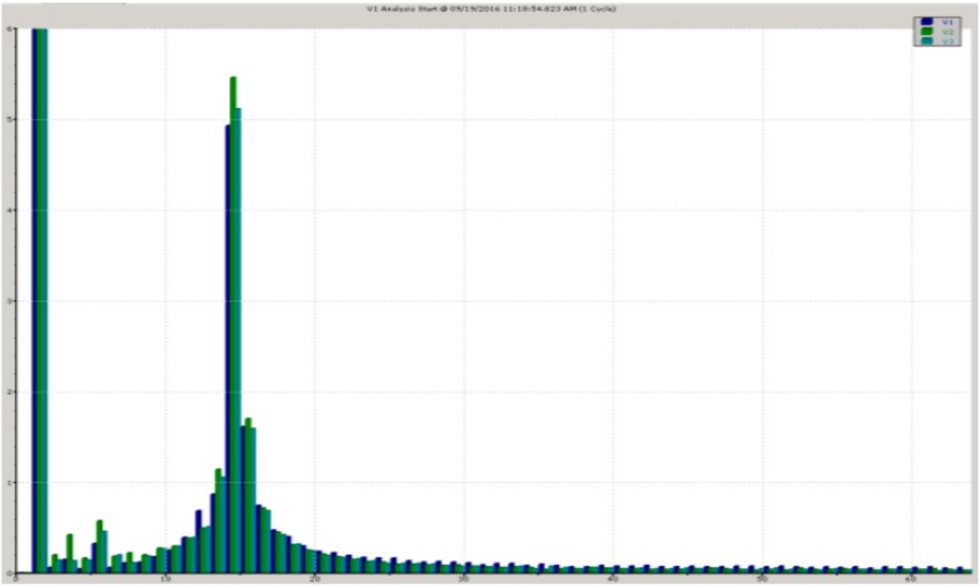


EnerNex
A CESI Company

Case History #5 (Type 3)

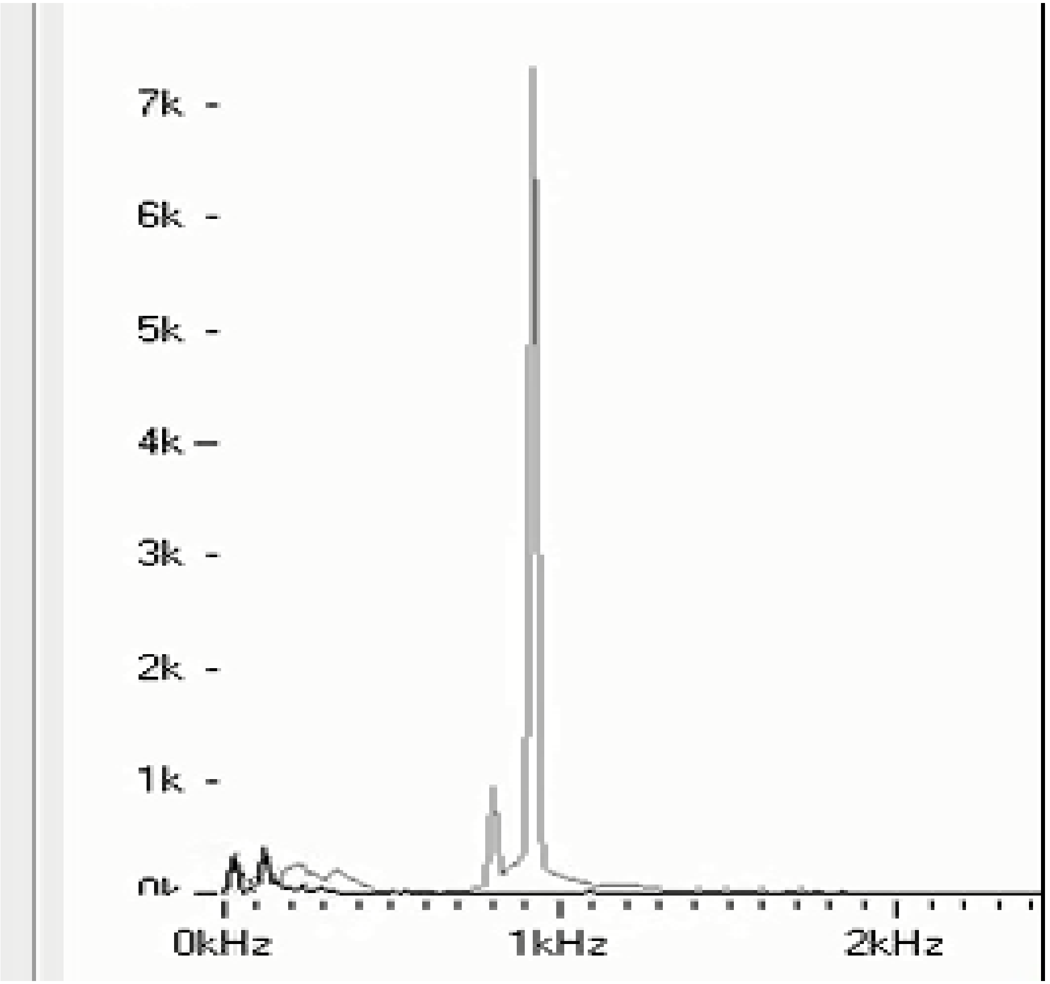
- *High reactive power swings*
- *Main GSU transformer made a strange noise*
- *Presence of harmonics*





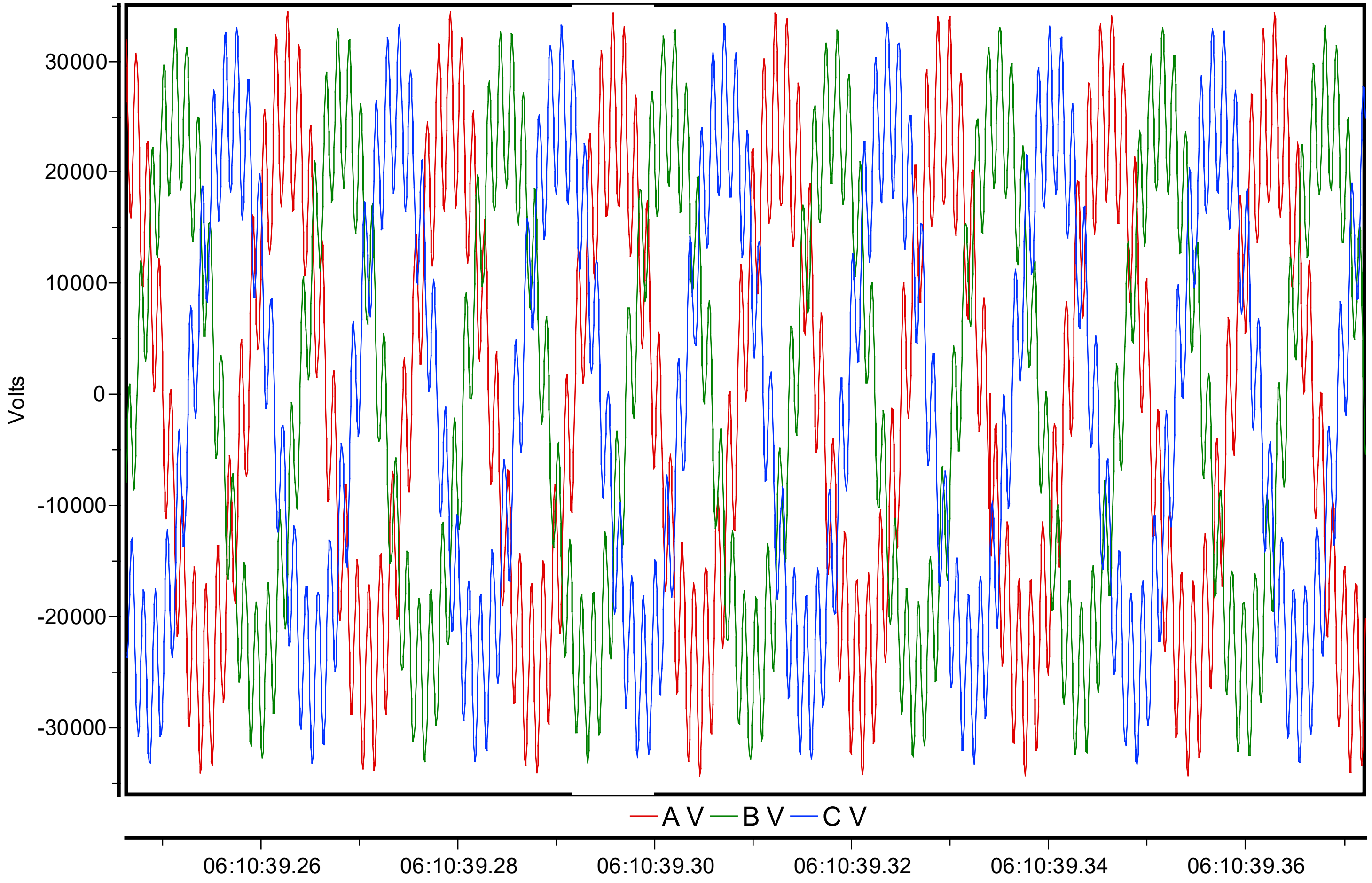
Audible Noise from Main GSU

- *Sound spectrum matched harmonics*
- *Recorded using an IPhone*



Voltage Waveform During Disturbances

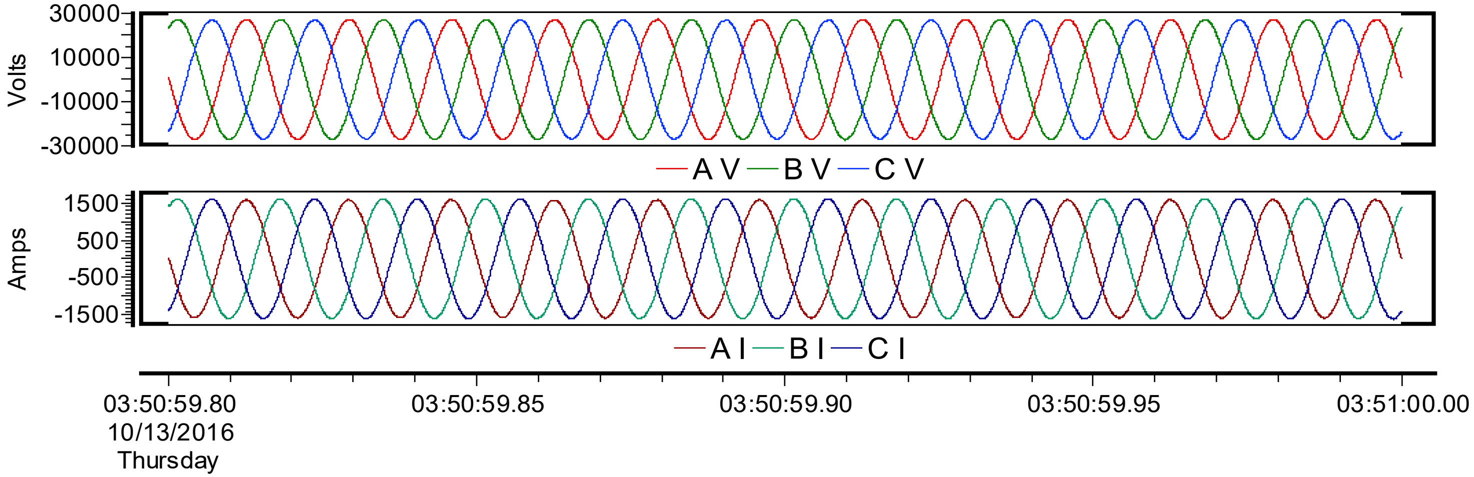
- *Once again, the peaks reveal the interharmonics*

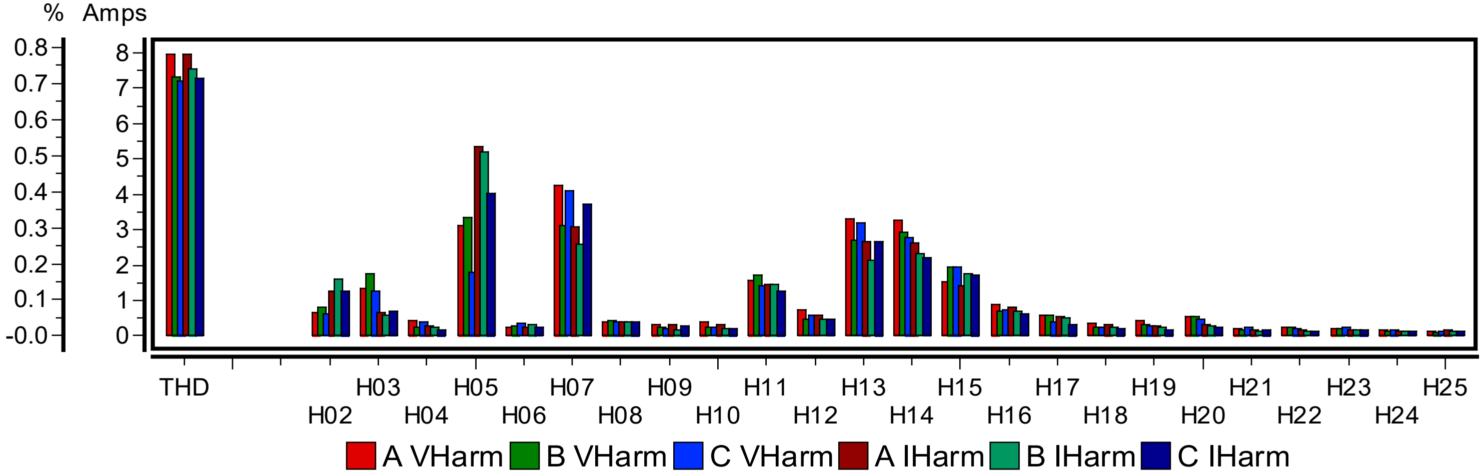


EnerNex
A CESI Company

Voltage Waveform Most of the Time

- *"Ordinary" grid conditions*

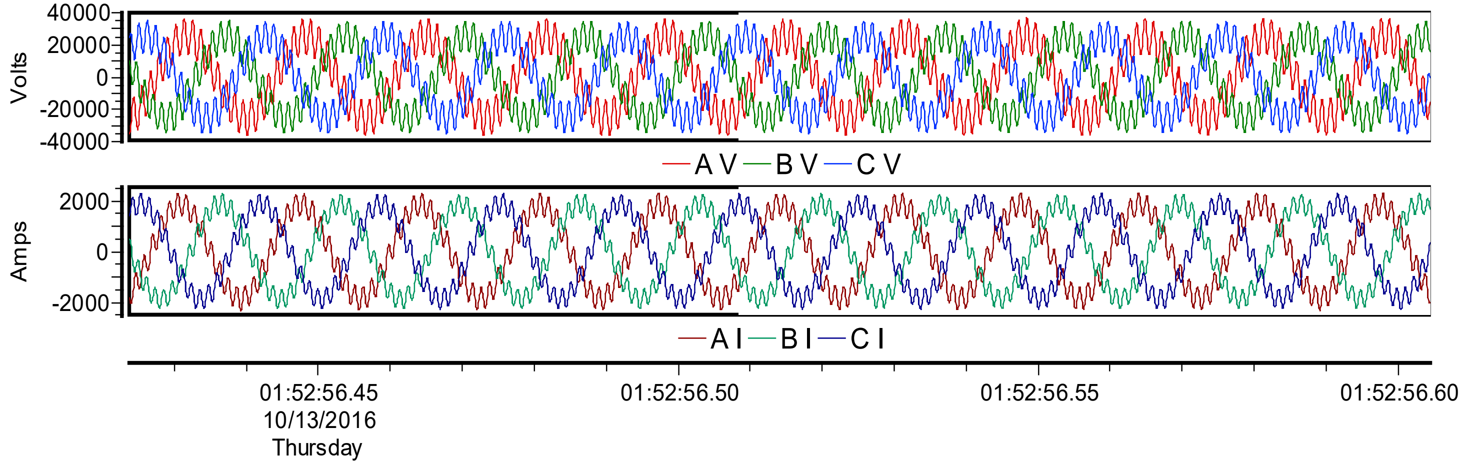


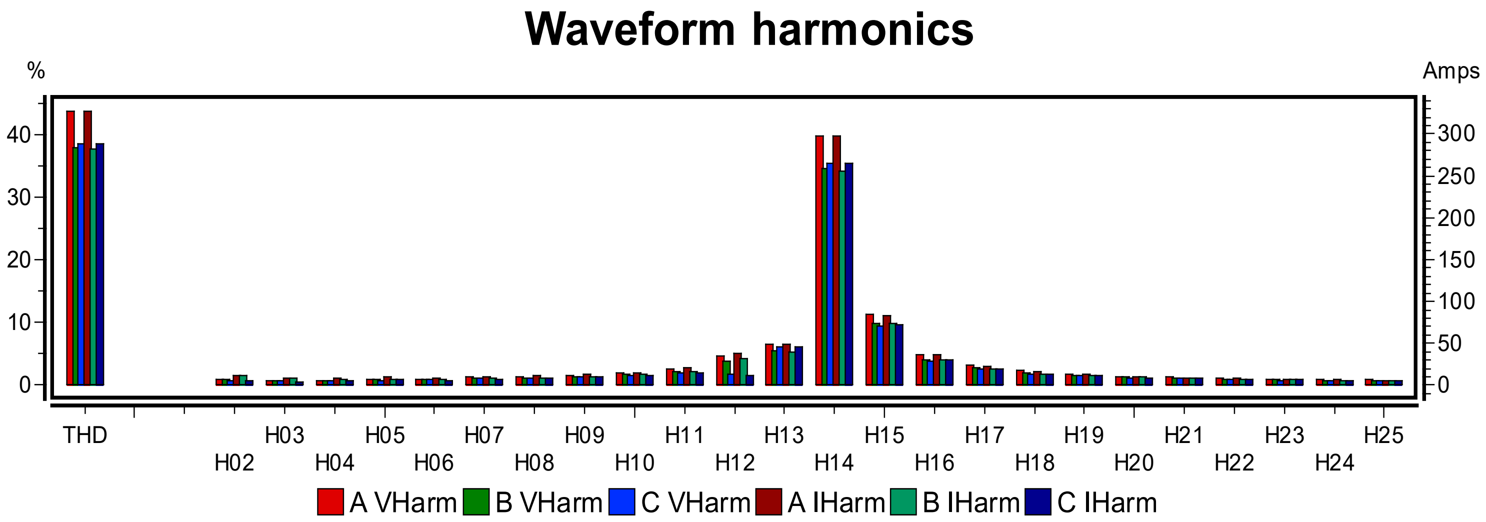


EnerNex
A CESI Company

System Resonance Conditions

- *The resonance would swing between harmonic subgroups and interharmonic subgroups*

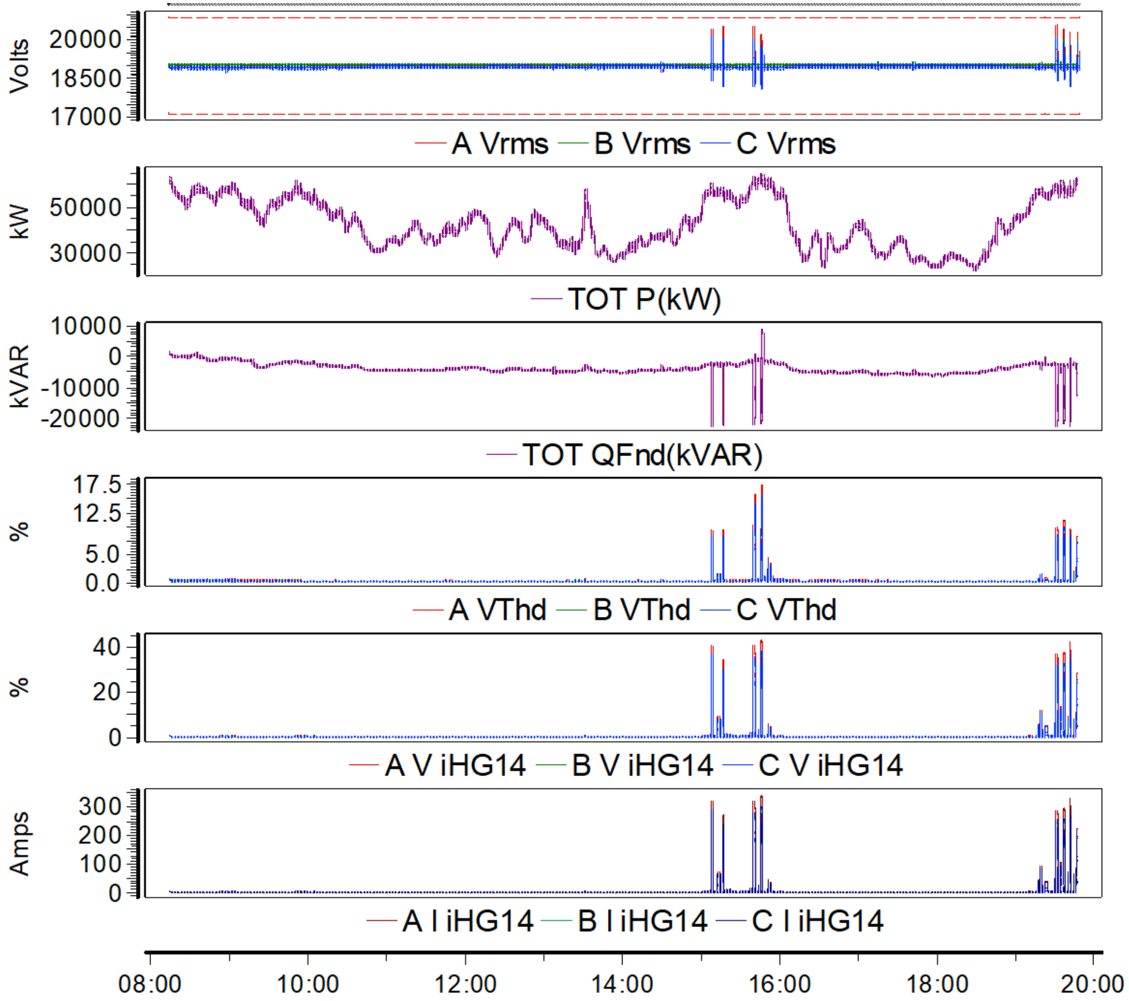




EnerNex
A CESI Company

Time Variation (Interharmonic Groups)

- *At times the interharmonic group had the most voltage, other times the harmonic group had the most voltage.*



EnerNex
A CESI Company

Interharmonics

Interharmonic problems were rare in the last millennium, but there were notable exceptions…

- *"Analysis of DC Arc Furnace Operation and Flicker Caused by 187 Hz Voltage Distortion"*

  IEEE Transactions on Power Delivery, April 1994.

  Le Tang, David Mueller, David Hall, Marek Samotyj, John Randolf

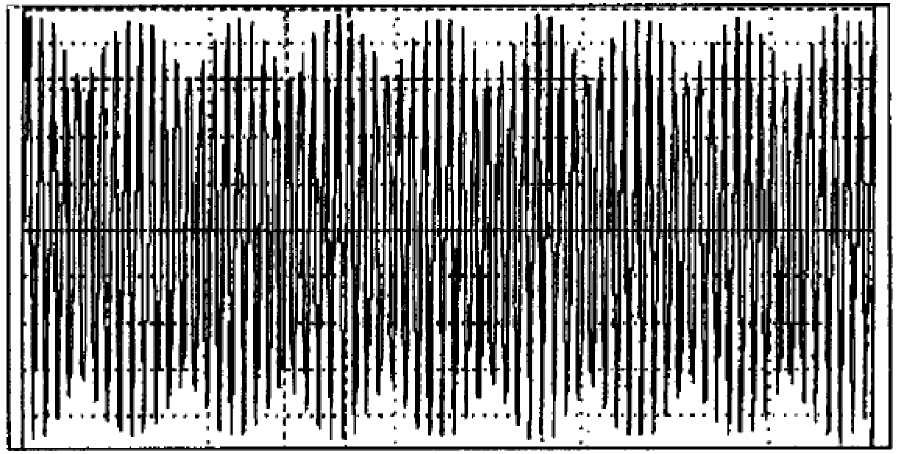


Figure 1 - Voltage Variation Recorded at the DC Arc Furnace 26.4 kV Bus

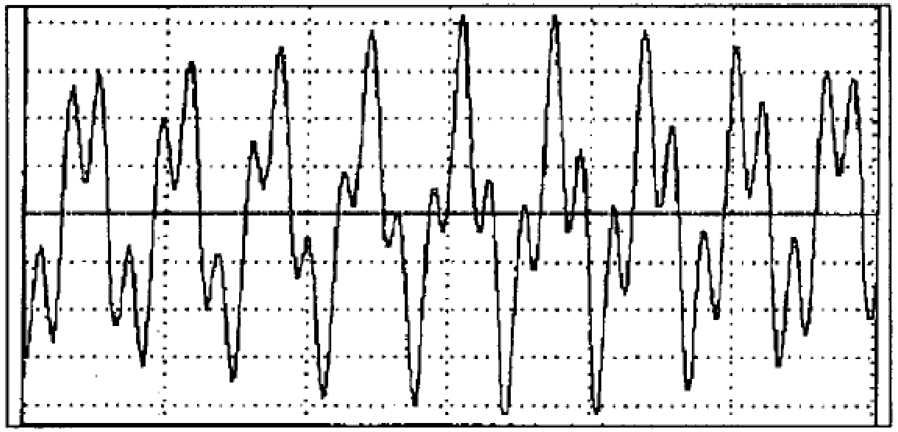


Figure 2 - Current Variation Recorded at the DC Arc Furnace 26.4 kV Bus

EnerNex
A CESI Company

Summary of Experiences

- *Problem is caused by grid resonance interaction with converter controls, very similar to SSCI (subsynchronous controls interactions)*
- *EnerNex was involved in 5 or 6 situations at wind plants, and another at a 40 MW PV Solar Power Plant*
- *Occurs in Type 3 and Type 4 wind plants (and PV solar)*
- *Occurs at medium size (50-100 MW) and large (200-1000 MW) plants*
- *Occurred in "all" major turbine suppliers*
- *Turbines where the manufacturers are no longer in business*
- *Occurs at plants with high short circuit ratios (>3)*
- *Occurs at plants with low short circuit ratios (<3)*
- ***Current control firmware creates the condition, and solves the problem in most all of the cases.***

IEEE Interharmonic Standard?

- *Not necessary for extraordinary circumstances*
  - "One of" problems should be custom engineered
- *Important for ordinary circumstances*
  - PV Inverters
- *Handle with care*
  - Standards have "inertia"
  - Our world is becoming more "legalistic"
- *Measurements/compliance considerations*
  - Low levels – high resolution necessary
  - Fringing/grouping with harmonic frequencies
- *Harmonization with other international standards*

Summary

- *Most wind and solar inverters are very slight sources of harmonic currents*
- *IEEE Standard 519 harmonics limits are overly stringent*
- *Wind and solar plants often have extensive capacitance for reactive power control, underground cables, and inverter filter units*
- *Sometimes inverters have created interharmonic currents, which is a sign of grid resonance/converter controls interactions*
- *Often firmware changes either create or solve harmonics issues*
- *Harmonic filters are rarely needed*

Harmonic Standards for Wind and Solar Plants

▶ *IEEE 519 is a standard for load generated harmonics, so…*

		Performance	Test & Verification & Model Validation
BES[1]	BPS[3]	• FERC Orders • NERC Reliability Standards & Guidelines IEEE P2800	• NERC compliance monitoring & enforcement IEEE P2800.1
	BPS[3]	• Not available **IEEE P2800**	• Not available **IEEE P2800.1**
DER[2]		• IEEE Std 1547-2018 ✓	• IEEE P1547.1 • Ul 1741 (SA) • IEEE ICAP *In ballot!*

[1] NERC definition of Bulk Electric System: ≥100 kV with gross individual / aggregate nameplate rating greater than 20 MVA / 75 MVA

[2] DER connected at typical (radial) primary and secondary voltage levels

[3] transmission and meshed sub-transmission

EnerNex
A CESI Company

Harmonic Voltage Limits

Advantages

- What we care about – voltage harmonics
- Utilized for large HVDC projects
- Are appropriate when a HV cable creates a resonance condition
- Used in Australia, Spain, Brazil, etc.

Disadvantages

- Hard to apportion limits, may require a plant shutdown to determine impacts
- What voltage limits to establish? Many existing systems >161 kV now exceed IEEE 519 recommended limits.

EnerNex
A CESI Company

Harmonic Current Limits

Advantages

- Familiar to utility PQ engineers
- Provide an easy screening methodology without requiring a plant shutdown
- Limits from IEEE 1547 and/or IEEE 519 can be adapted

Disadvantages

- Difficult to determine harmonics direction in resonance situations.

EnerNex
A CESI Company

IEEE P2800 Draft Limits

- *"Draft Standard for Interconnection and Interoperability of Inverter-Based Resources Interconnecting with Associated Transmission Electric Power Systems"*
- *For now current limits only. These numbers are still draft and are subject to change!*
- *Notes to these limits will likely include*
  - Comments about considering measurement resolution/accuracy
  - Comments about studies determining alternative limits
  - Comments to differentiate passive or beneficial harmonic currents

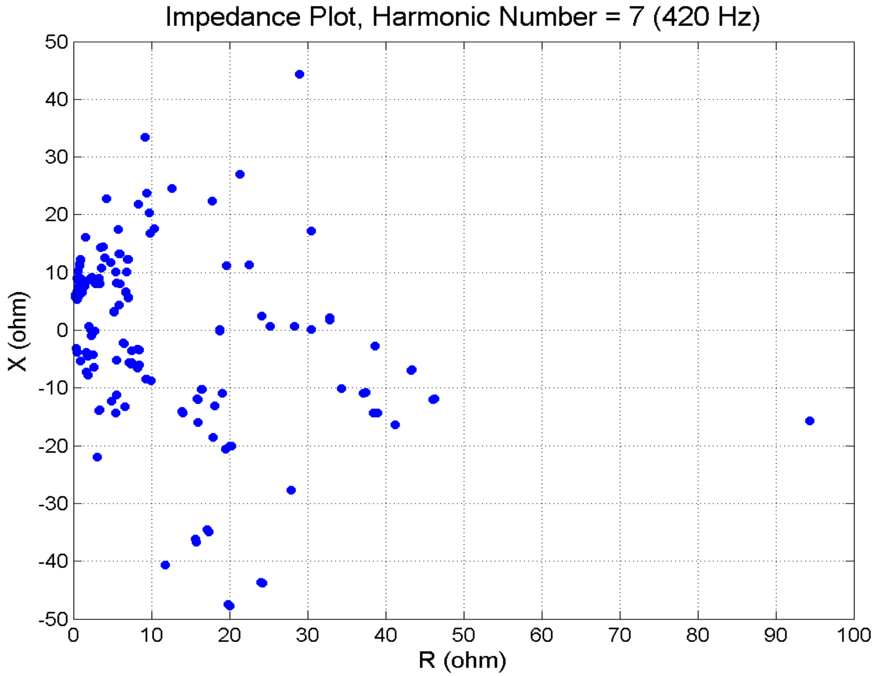
Table 14—Maximum current distortion in percent of rated current (I_{rated})

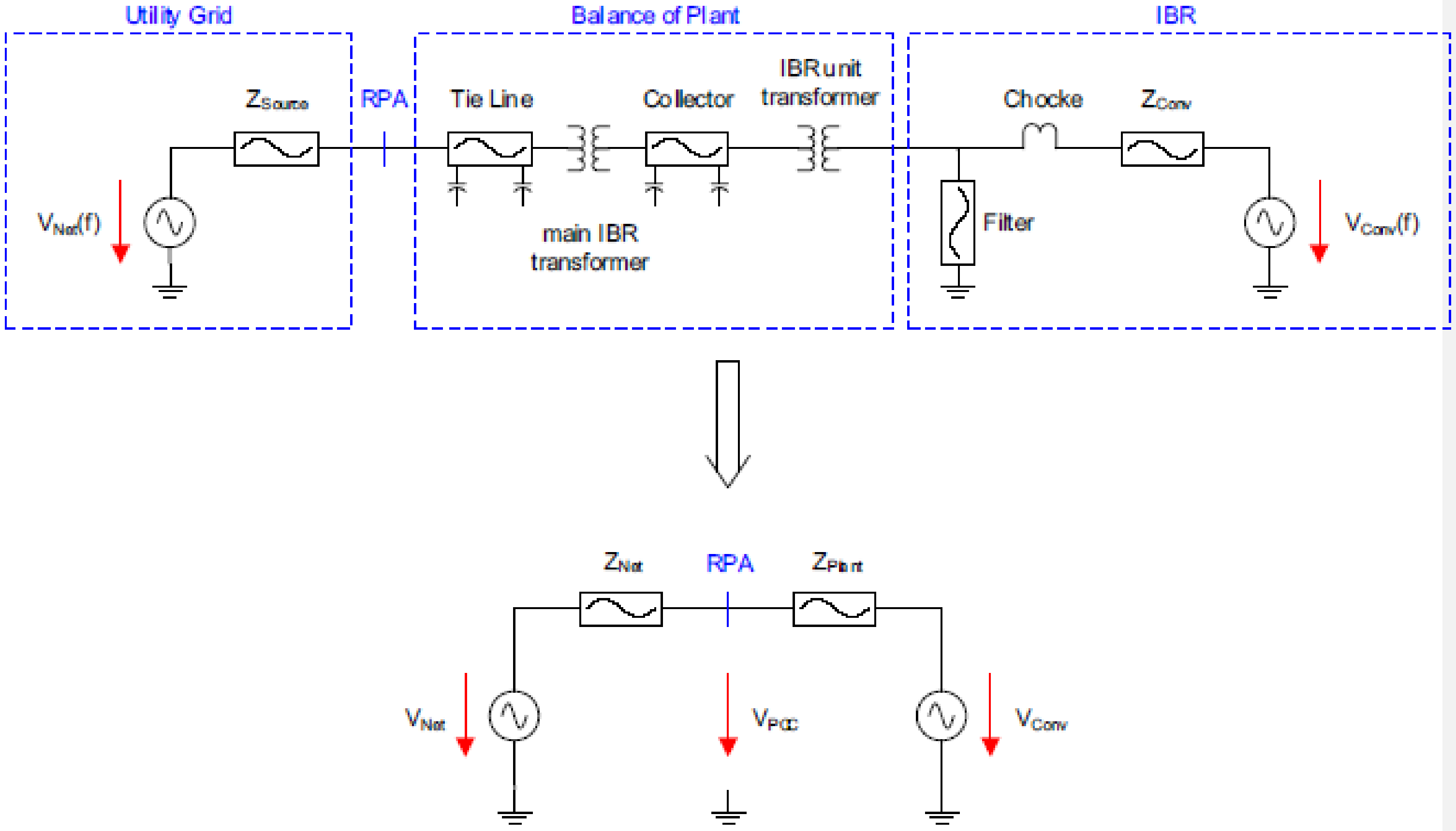
Individual odd and even harmonic or h	RPA LL Voltage (kV)	h <11	$11 \le h < 17$	$17 \le h$	Total rated current distortion (TRD)
Percent (%)	≤ 69	4.0	2.0	1.5	5.0
	69.001-161	2.0	1.0	1.0	2.50
(see notes below)	>161	1.5	1.0	1.0	2.0

EnerNex
A CESI Company

Incremental Harmonic Voltage Determination

- *P2800 Draft, Annex F Discusses Harmonics Models for Determination of Incremental Harmonic Voltage Contribution*



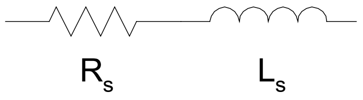


Simulation Modeling Considerations

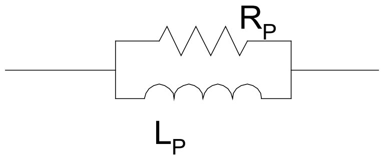
- *EnerNex uses a combination of frequency domain and time domain models*
- *Norton or Thevenin equivalent with frequency dependence of wind turbines and inverters*
- *Type 3 DFAG machine model considerations*
  - Subtransient reactance (Xd”)
  - Locked rotor current may be a better indicator
- *Turbine filters*
  - Important but often considered “proprietary” details
- *Inverter PLL synchronizing techniques may be important, also negative damping at certain frequencies*
- *Trend is toward more time domain modeling (PSCAD, EMTP-RV, DigSilent)*

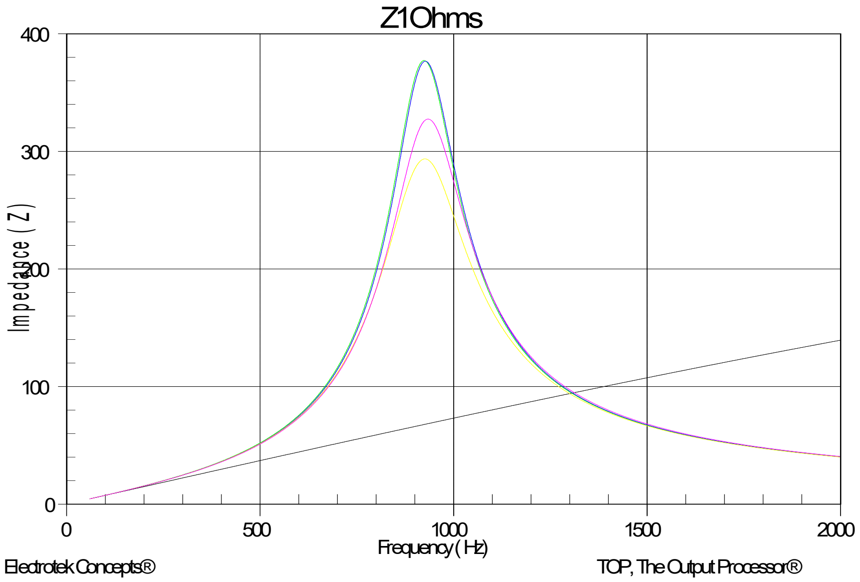
- *The impact of load is often ignored or significantly under-represented during transient and harmonic studies.*

Series R-L

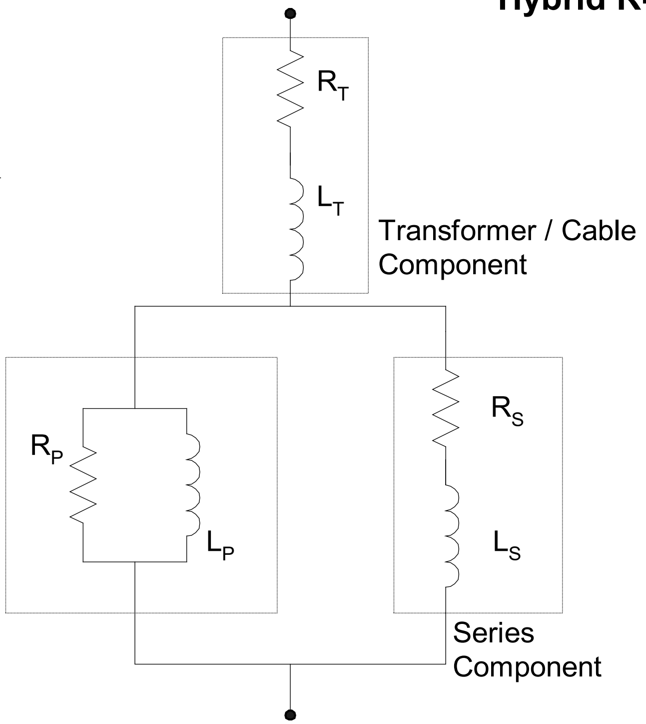


Parallel R-L





Hybrid R-L



Summary

- *Wind turbines and solar inverters are very slight sources of harmonic currents.*
- *Wind and solar plants often utilize capacitor banks for reactive power control. The step size of these units should be designed to avoid resonance at grid characteristic harmonic frequencies.*
- *Sometimes inverters generate interharmonic currents, which is a sign of grid resonance/converter controls interactions. Almost always firmware changes either create, or solve these most serious harmonics issues.*
- *The converters have individual (high pass) filters, large plant harmonic filters are rarely needed.*

Questions / Comments

David Mueller, PE
Director, Energy System Studies

EnerNex
620 Mabry Hood Road, Suite 300
Knoxville, TN 37932

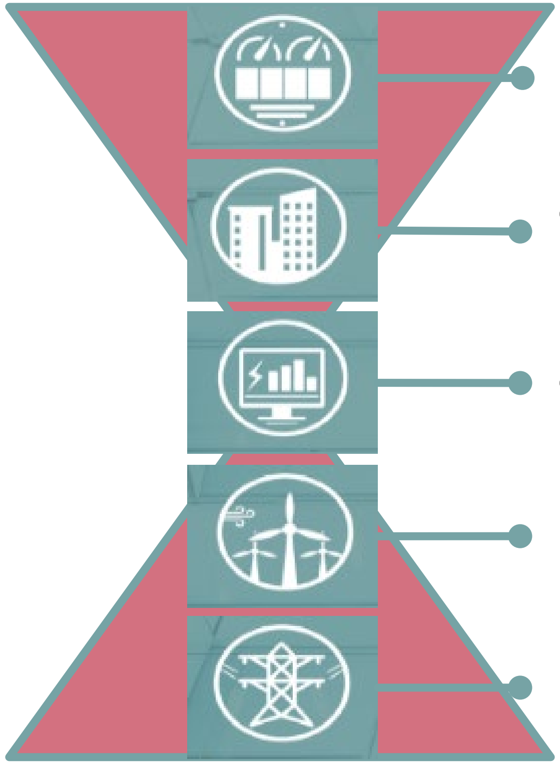
dmueller@enernex.com
www.enernex.com

EnerNex
A CESI Company

EnerNex skills

EnerNex Service Lines

Strategic Perspective



Electric Industry Evolution

Grid Modernization

Grid Technology Consulting

Renewable & Distributed Resource Integration & Interconnection

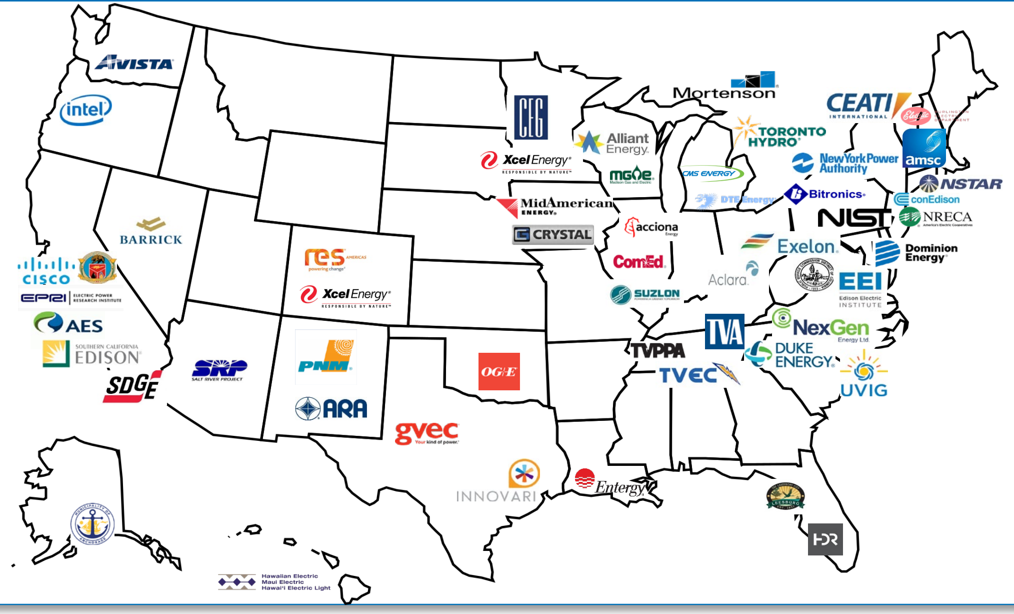
Electric Energy System Engineering & Analysis

Tactical Perspective

Sample of EnerNex's Capabilities

- **Strategic Planning**, road maps, program development, use-case and specifications, business case support
- **DER & Intermittent Resource** integration, grid modernization, technology plans & support
- **Demand Response** business planning, technical requirements
- **Storage & Microgrid** technical guidance covering initial feasibility through commissioning
- **Solar & Wind** modeling, integration & interconnection studies & recommendations
- **Cybersecurity** evaluation of strategies, risks, requirements, & mitigation measures

Key EnerNex US clients



EnerNex
A CESI Company

EnerNex, A CESI Company

- *CESI acquired majority share of EnerNex in June 2018*
  - Headquartered in Milan, Italy
  - 800 employees
  - Actively working in over 40 companies world-wide
  - 60% consulting and 40% testing