Harmonic Mitigation for 3-Phase Electric Vehicle DC Fast Chargers

EV Battery Charger Types

Home Charging:

- Level 1
  - 120V charging through EV supplied charger
  - 200 km (124 mi) charge in ~ 20 hours
- Level 2
  - 240V charging through either EV supplied or separately purchased charger
  - Charges 5x to 7x faster than Level 1

Public Charging:

- Level 2
  - 3 to 20 kW
  - 200 km charge in ~ 5 hours
- Level 3 (DC Fast Charger)
  - ~ 50 kW
  - 80% of 200 km in ~ 30 min, 80% of 400 km in ~ 1 hr
- Higher power and multiple charging stations makes harmonic mitigation necessary

Various Topologies of Fast DC Charger Rectifiers

- 6-Pulse Diode Bridge Rectifier
  - Will almost certainly not meet the harmonic limits specified in IEEE Std 519 and IEC 61000 series standards
- Multipulse Rectifier
  - Phase shifts applied to multiple rectifiers to create 12, 18 or 24-Pulse systems
  - Power system conditions, such as voltage imbalance and background voltage distortion make them less effective
  - May not always meet harmonic requirements
- Active Rectifier
  - Frontend IGBTs used to reduce low frequency harmonics but introduce switching frequency harmonics
  - Typically meet requirements at low frequencies but can cause bigger problems due to the high frequencies they introduce
- 6-Pulse Diode Bridge Rectifier with passive Wide Spectrum Harmonic Filter
  - Series application of passive filter with simple 6-Pulse rectifier can ensure that all harmonic standard limits are met

3-Phase, 6-Pulse Rectifier Battery Charger

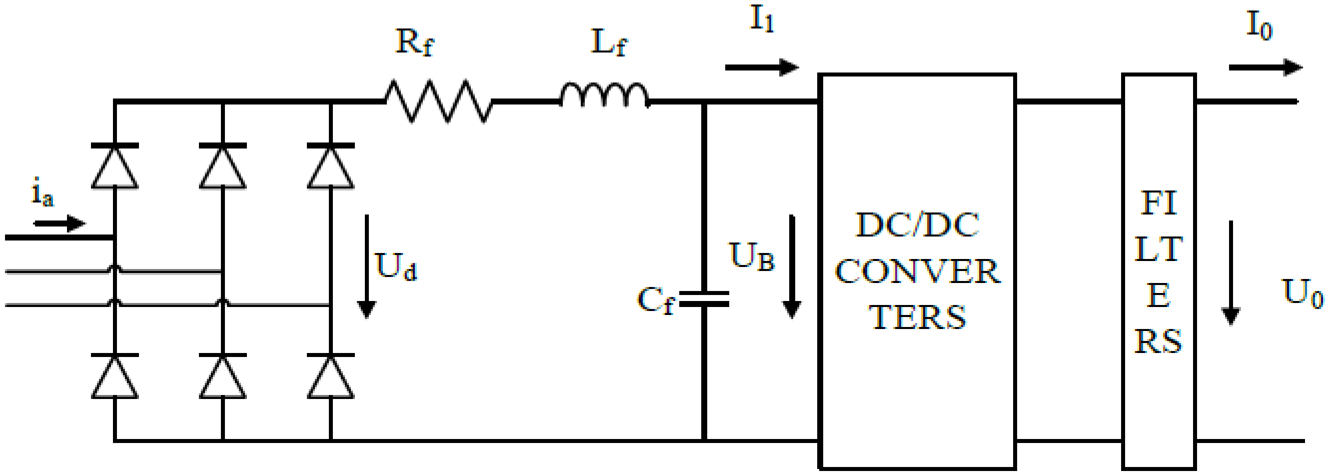
For simple diode bridge rectifiers:

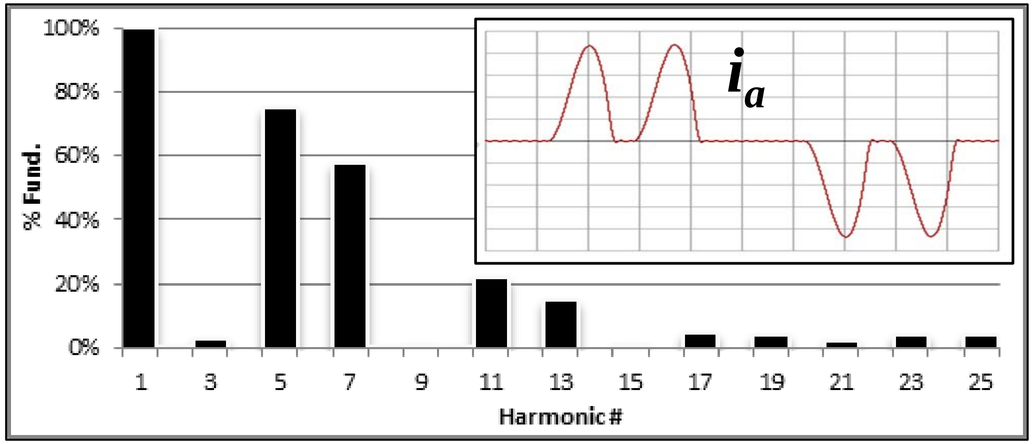
$$h = np \pm 1$$

$$I_h \sim \frac{I}{h}$$

h = harmonic number
p = # of pulses in rectification scheme
n = any integer (1, 2, 3, etc.)
I_h = magnitude of harmonic current
(addition of DC bus cap increases I_h)

When,
p = 6
h = -- 5,7,--,11,13,--,17,19...





Current Waveform and Spectrum

Harmonic Standard: IEEE Std 519 – 2022

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IEEE Std 519, Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems

- Defines voltage and current distortion limits at PCC
- Intended to be used as a system standard
- Recognizes responsibility of both User and Utility
- Considers both linear and non-linear loading
- Definitions for Total Demand Distortion (current) and Total Harmonic Distortion (voltage) apply to harmonics up to 50th but allow for inclusion of > 50 when necessary

total demand distortion (TDD): The ratio of the root mean square of the harmonic content, considering harmonic components up to the 50th order and specifically excluding interharmonics, expressed as a percent of the maximum demand current. Harmonic components of order greater than 50 may be included when necessary.

IEEE Std 519 – 2022 Definitions

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Point of Common Coupling (PCC)

Point on a public power supply system, electrically nearest to a particular load, at which other loads are, or could be, connected. The PCC is a point located upstream of the considered installation.

Total Harmonic Distortion (THD)

The ratio of the root mean square of the harmonic current, considering harmonic components up to the 50th order and specifically excluding interharmonics, expressed as a percentage of the fundamental. Harmonic components of order greater than 50 may be included when necessary.

Total Demand Distortion (TDD)

The ratio of the root mean square of the harmonic current, considering harmonic components up to the 50th order and specifically excluding interharmonics, expressed as a percentage of the maximum demand current. Harmonic components of order greater than 50 may be included when necessary.

Maximum Demand Current (I_L)

The current value at the PCC taken as the sum of the currents corresponding to the maximum demand during each of the 12 previous months divided by 12.

$$iTDD = iTHD \times \frac{I_{(meas)}}{I_L}$$

IEEE Std 519 – 2022 Voltage Distortion Limits (Table 1)

Bus voltage V at PCC	Individual harmonic (%) $h \leq 50$	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 are allowed to have up to 2.0% THD where the cause is an HVDC terminal whose effects are found to be attenuated at points in the network where future users may be connected.

- For systems < 1.0 kV, vTHD is allowed to be as high as 8%
- Therefore, connected equipment should be able to operate at these vTHD levels

IEEE Std 519 – 2022 Current Distortion Limits for Systems Rated 120V through 69kV (Table 2)

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Maximum harmonic current distortion in percent of I_L						
Individual harmonic order[b]						
I_{SC}/I_L	$2 \leq h < 11$[a]	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h \leq 50$	TDD
< 20[c]	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

[a] For $h \leq 6$, even harmonics are limited to 50% of the harmonic limits shown in the table.

[b] Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

[c] Power generation facilities are limited to these values of current distortion, regardless of actual I_{sc}/I_L unless covered by other standards with applicable scope.

where:

I_{sc} = maximum short-circuit current at PCC

I_L = maximum demand load current at PCC under normal load operating conditions

IEC Harmonic Standards – Low Frequency

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- IEC 61000-3-2, Limits for harmonic current emissions (equipment input current < 16A/ph single & 3 phase)
- IEC 61000-3-12, Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current > 16A and < 75A
- IEC 61000-3-6, Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems
- Only applied to harmonics up to the 40th

THD

ratio of the r.m.s. value of the harmonics (in this context harmonic currents I_n of the order n) to the r.m.s. value of the fundamental, viz.

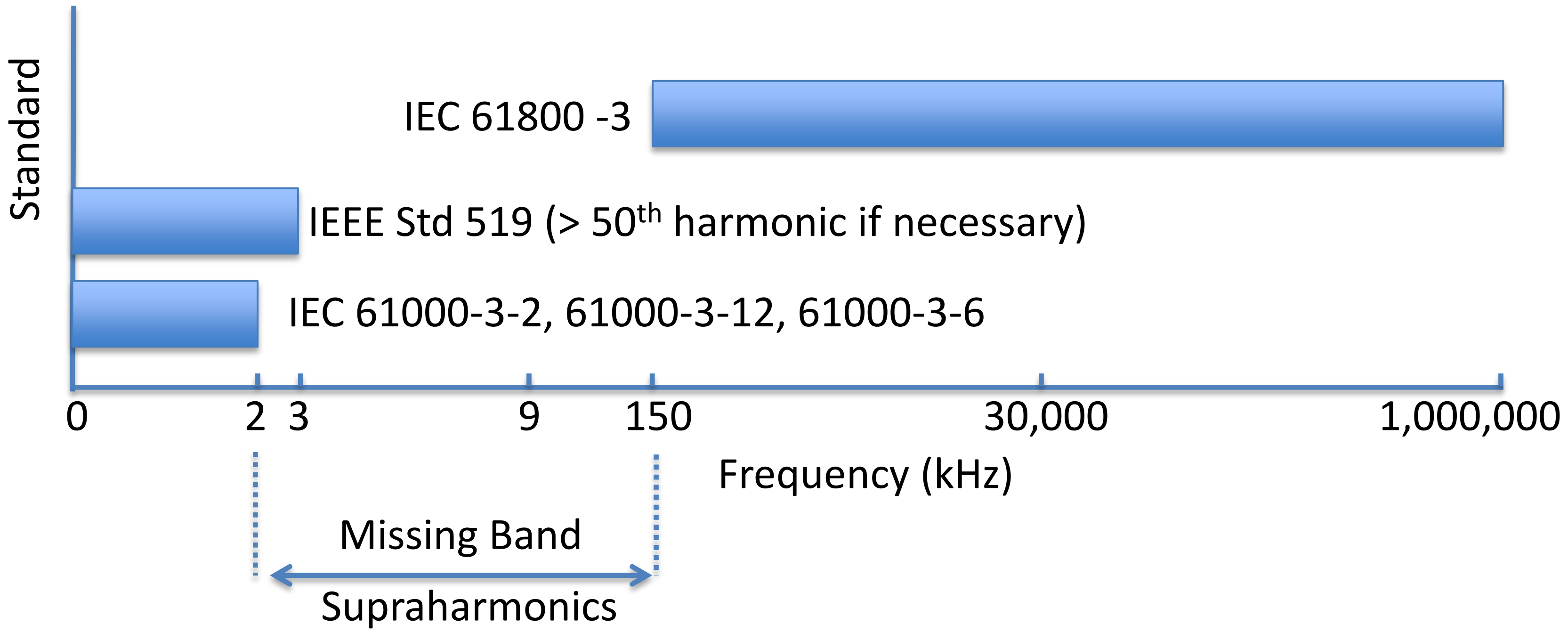
$$THD = \sqrt{\sum_{n=2}^{40} \left(\frac{I_n}{I_1} \right)^2}$$

High Frequency Standards

- IEC 61800-3, EMC Product Standard for Power Drive Systems
  - The source of high frequency emission from frequency converters is the fast switching of power components such as IGBTs
  - Covers frequency range from 150 kHz to 30 MHz conducted and 30 MHz to 1000 MHz radiated

- FCC 47 CFR Part 15
  - Regulates emissions in the radio frequency spectrum from 9 kHz and higher
  - Rarely applied to EV Charging Infrastructure

Harmonic Standards and the Missing Band - Supraharmonics



- Low frequency regulations end at 40th or 50th harmonic unless IEEE 519 allowance of including harmonics above 50 is applied
- High frequency standards begin at 150 kHz
- Range from 2 kHz to 150 kHz is now referred to as Supraharmonics

Missing Frequency Band in Standards

Is this a concern?

Absolutely, since typical IGBT switching frequencies are between 2 kHz and 16 kHz which falls precisely within this band

Active Rectifier solutions may comply with standards but they often introduce bigger problems than they resolve

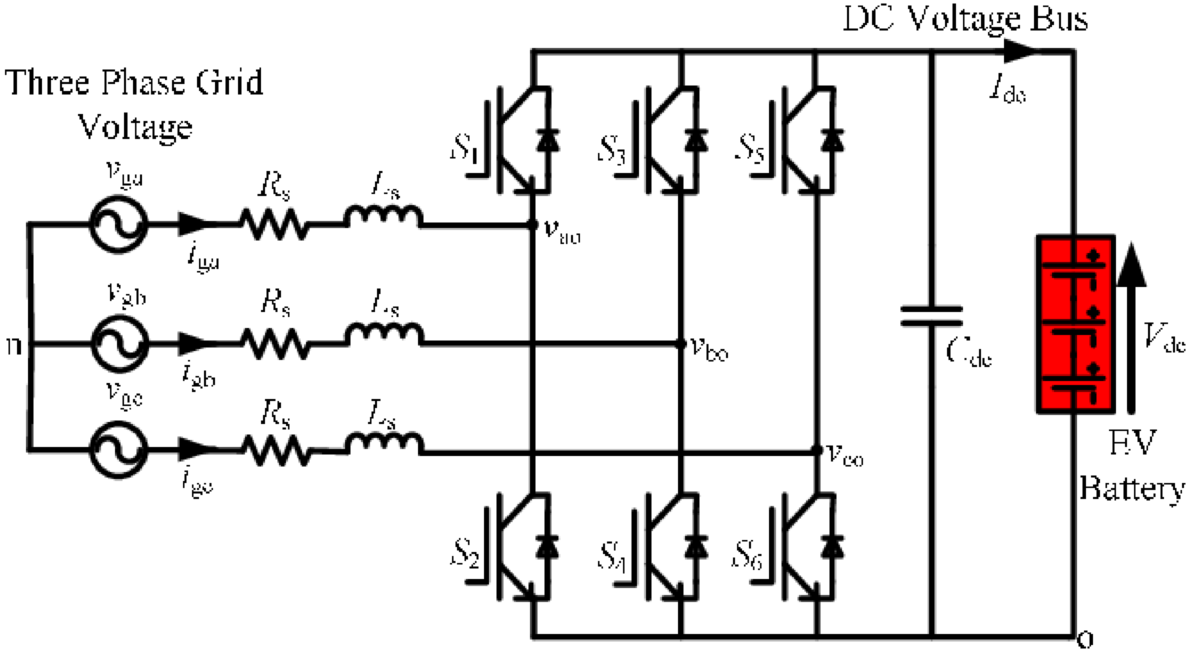
Active Rectifier Battery Charger

Operation:

- 6-pulse diode bridge rectifier is replaced by a fully controlled IGBT bridge

Pros:

- Can achieve lowest ITHD but only when measured at harmonics lower than 50th
- Allows for bi-directional power flow



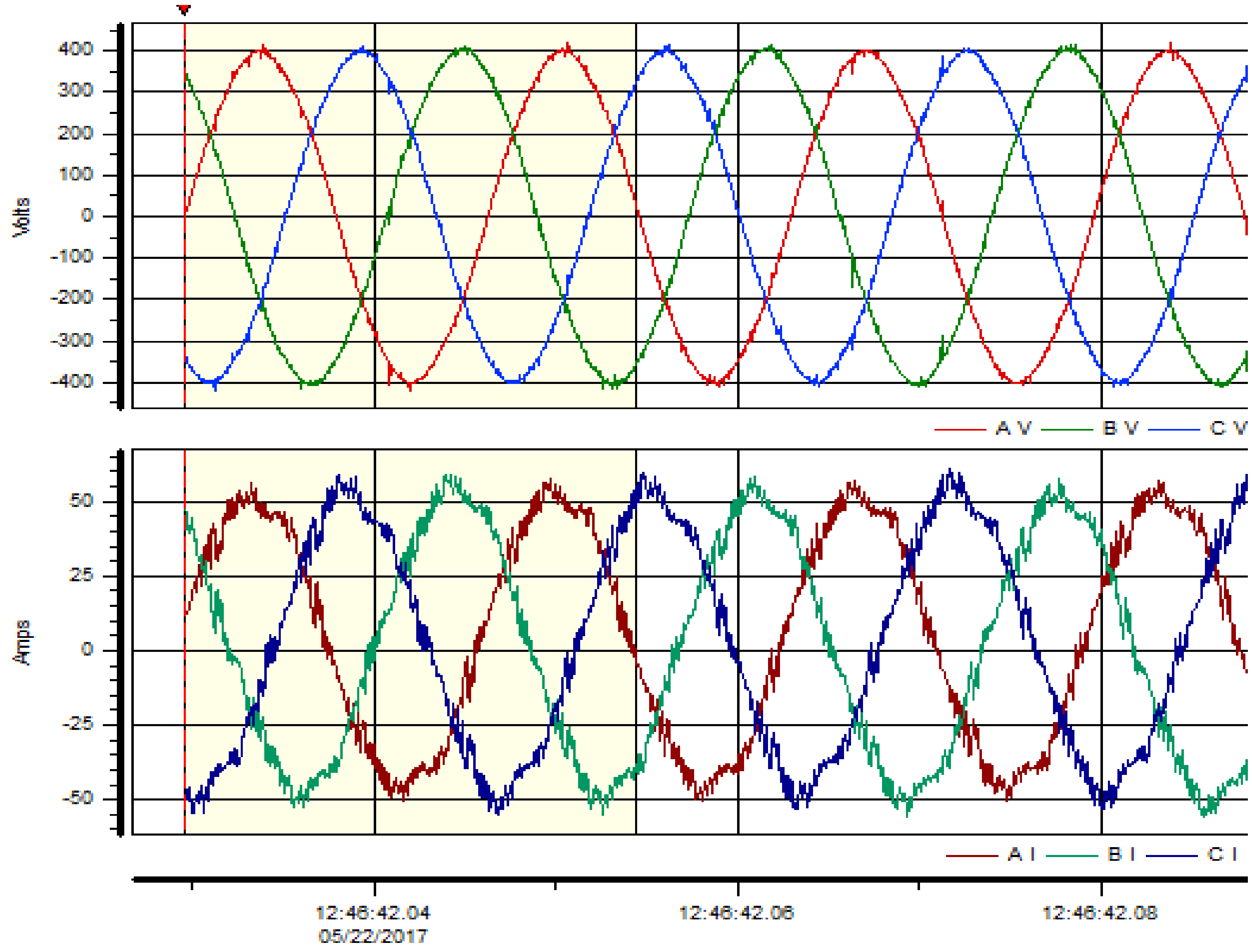
Cons:

- More expensive
- Introduces higher order harmonics
- Higher EMI radiation
- Higher losses
- More complex

Example of an Active Rectifier Load

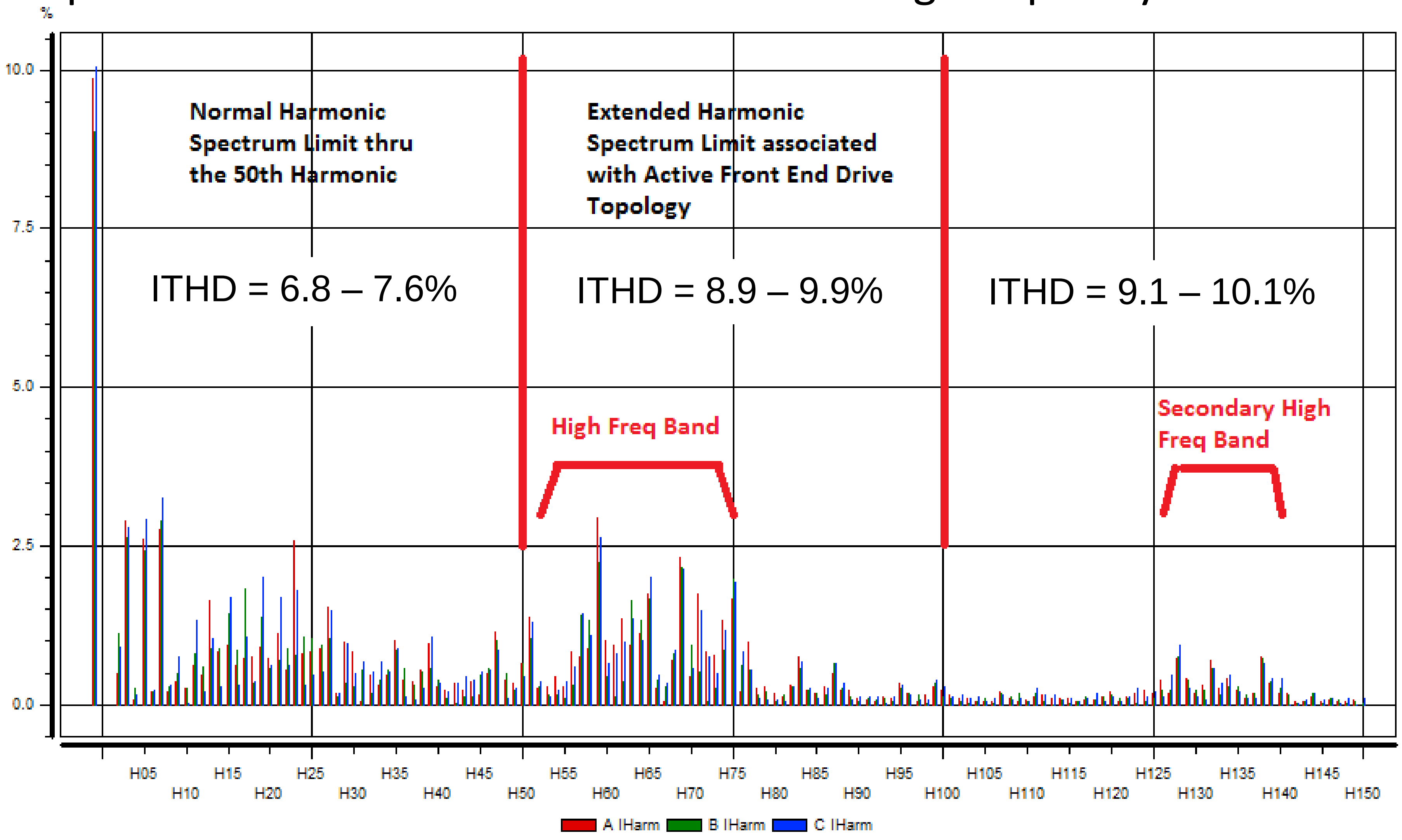
Voltage Waveform

Current Waveform



Example of an Active Rectifier Load

Input Current Harmonics with IGBT Switching Frequency Contribution



Evaluating Supraharmonics in Electric Vehicle Charging: University of Applied Sciences - Bingen, Germany

5 kW, 1-Ph Inverter for EV Charging

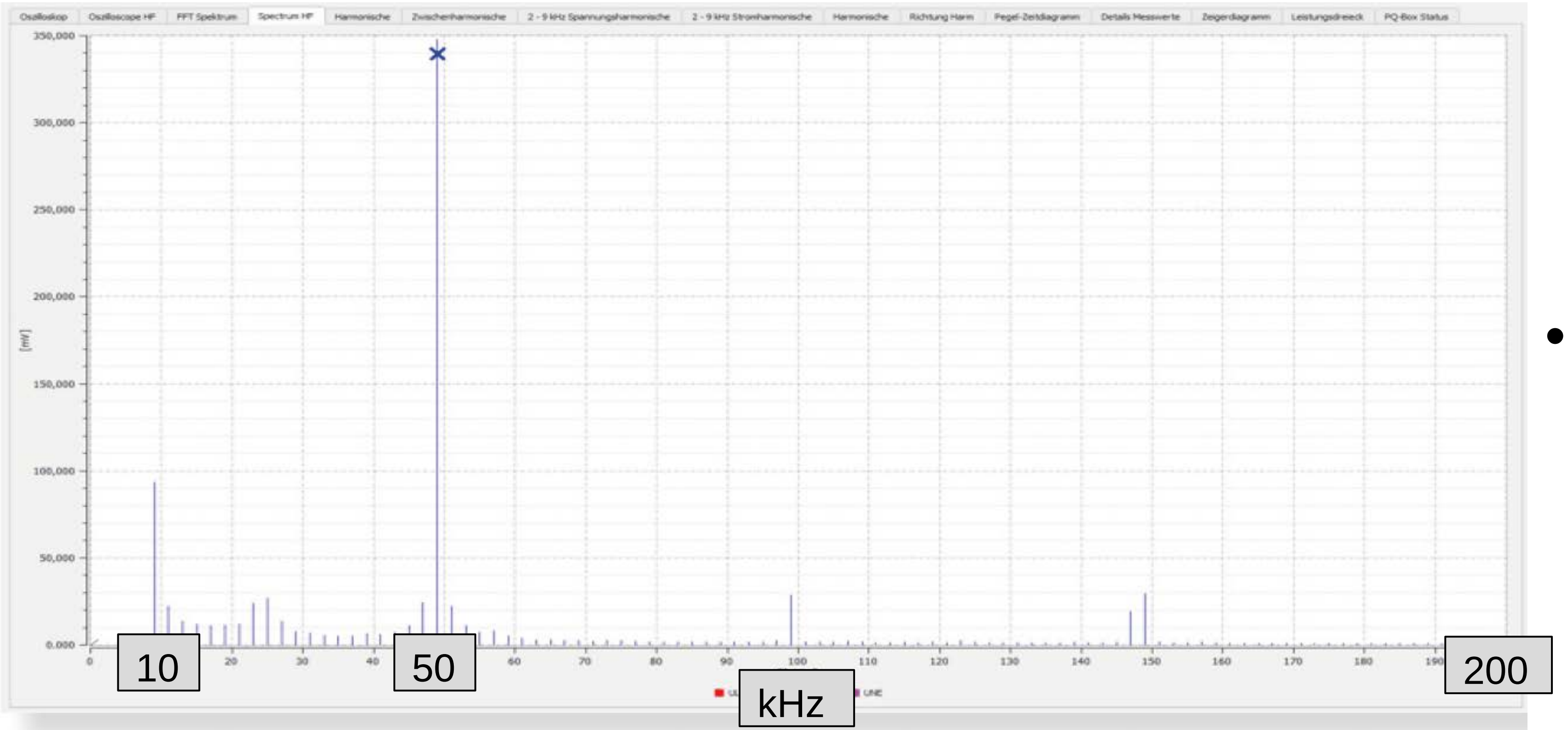


Fig. 1: Electric vehicle with a 50 kHz chopper frequency; shown with 2 kHz frequency bands

Current Spectrum of EV Charger with 50 kHz Chopper Frequency

- Various Electric Vehicles were studied
  - Chopper frequencies varied between 8 kHz and 50 kHz
  - Chart shows EV charger with 50 kHz chopper frequency
  - Clear evidence of current harmonics at 50 kHz and smaller bands at 2x and 3x

Reference:

1. Evaluating Supraharmonics up to 150 kHz in Electric Vehicles at the University of Applied Sciences Bingen, A-Eberle Power Quality document, 2016

Evaluating Supraharmonics in Electric Vehicle Charging: University of Applied Sciences - Bingen, Germany

5 kW Inverter with 50 kHz Chopper Freq

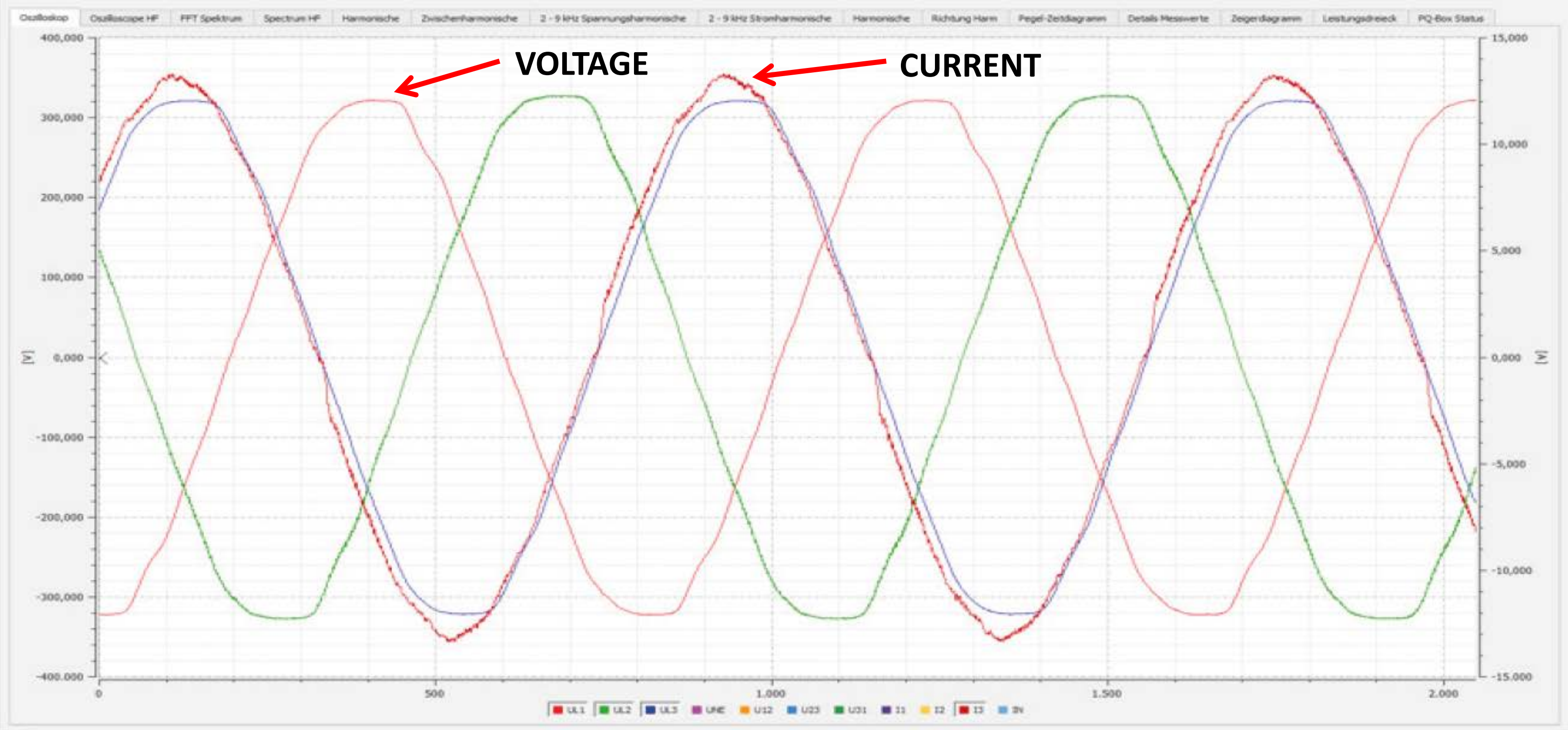


Fig. 3: Electric vehicle No. I connected to the outlet alone

- High frequency ripple on current drawn by charger

Voltage and Current Waveforms of EV Charger with 50 kHz Chopper Frequency

Reference:

1. Evaluating Supraharmonics up to 150 kHz in Electric Vehicles at the University of Applied Sciences Bingen, A-Eberle Power Quality document, 2016

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5 kW Inverter with 50 kHz Chopper Freq

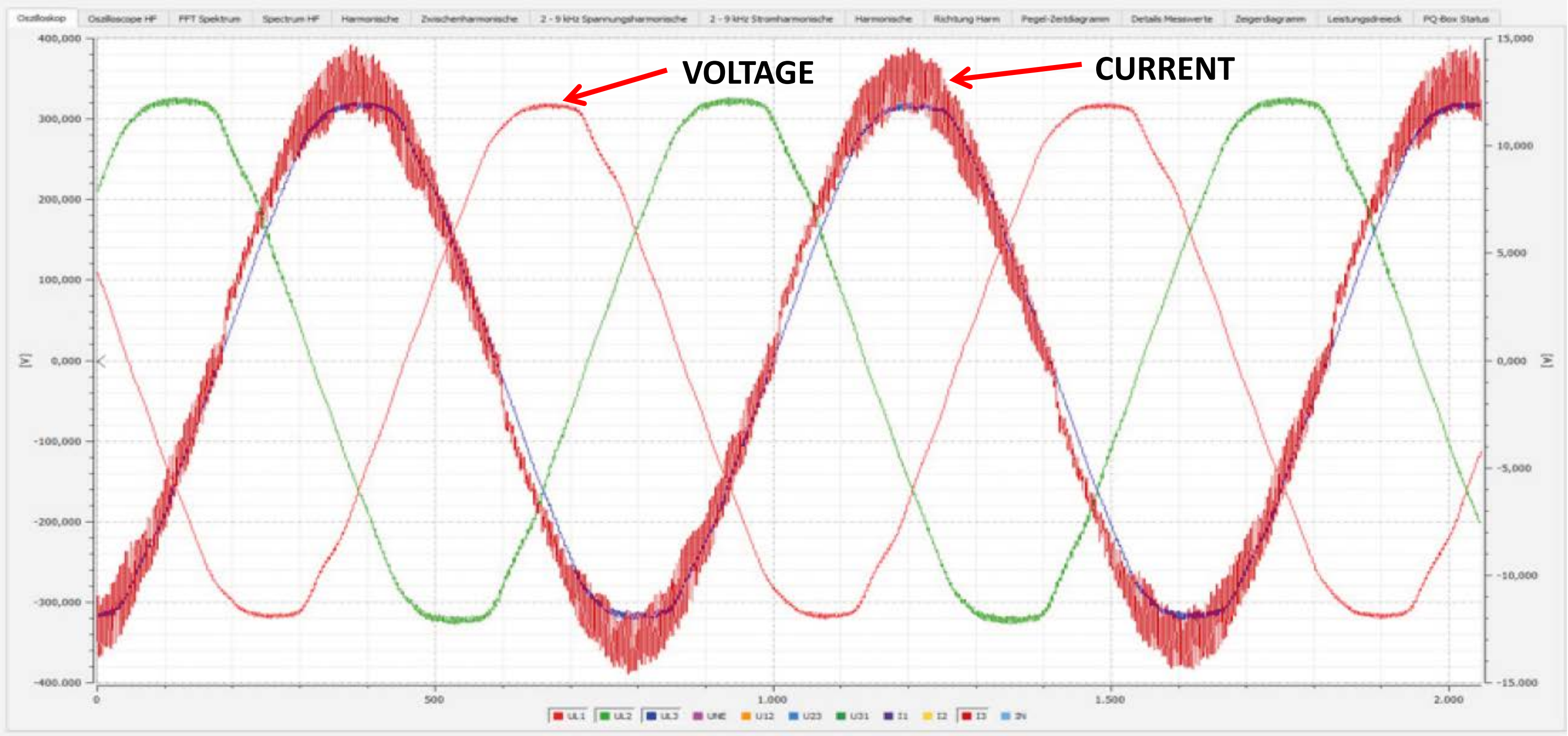

Fig. 4: Electric vehicles No. 1 and No. 2 connected in parallel to the charging station and the outlet

- A second EV was connected in parallel with a 10 kHz chopper frequency
- High frequency ripple on current drawn by first EV charger substantially increased
- Ripple appears on voltage

Voltage and Current Waveforms of EV Charger with 50 kHz Chopper Frequency

Reference:

1. Evaluating Supraharmonics up to 150 kHz in Electric Vehicles at the University of Applied Sciences Bingen, A-Eberle Power Quality document, 2016

Passive Wide Spectrum Harmonic Filter – Lineator AUHF

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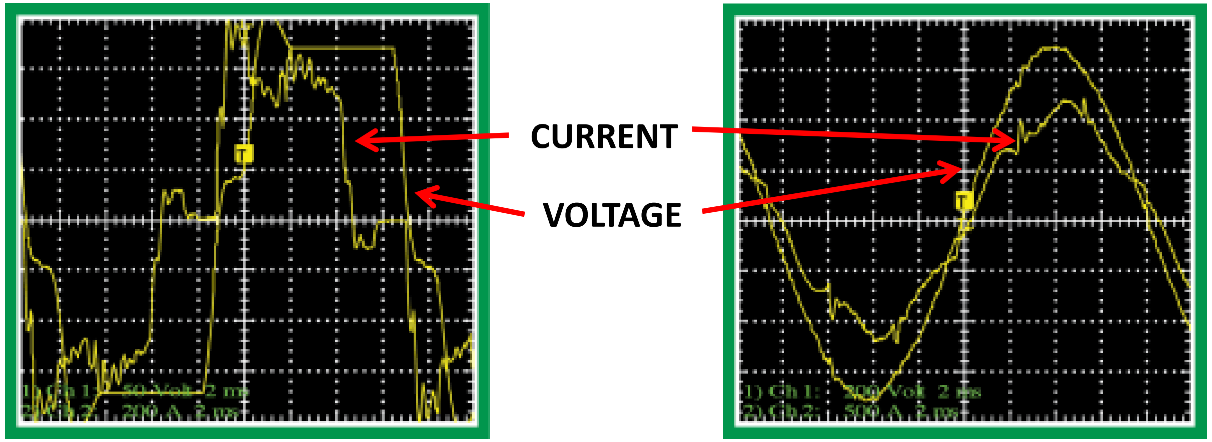


Input Without Filter Installed

Input With Filter Installed

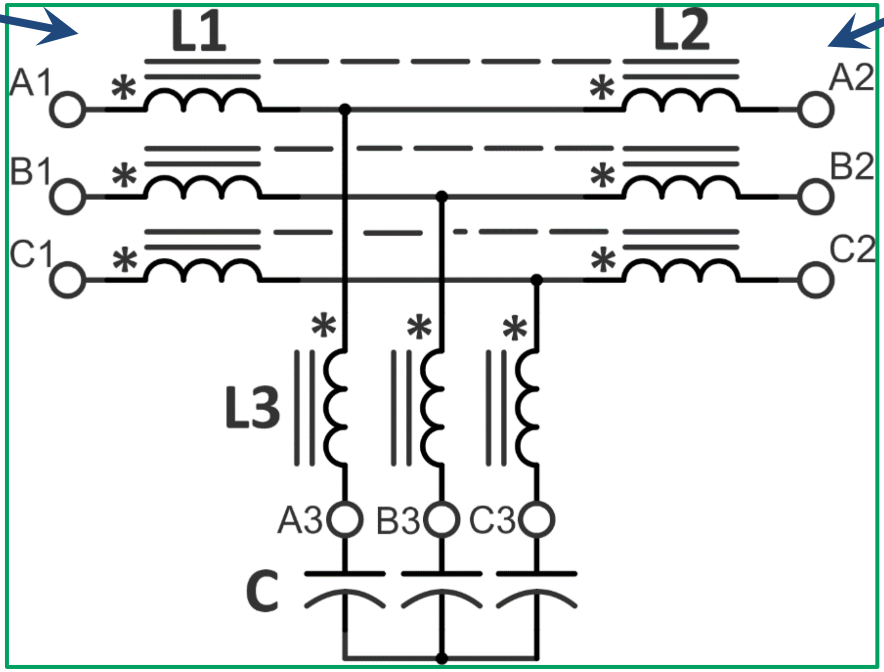
- Input harmonic filter for VSDs
- Better than 18-pulse or AFE performance with 6-pulse VSD
- 'Real-World Guarantee'
- Meets IEEE and IEC harmonic limits
- Near unity power factor
- Generator compatible
- Highest efficiency

Passive Wide Spectrum Harmonic Filter – Lineator AUHF

Multiple windings on a common core

High impedance L1 winding

Compensating winding L2 improves performance without increasing voltage drop



Input tuned below 5th to prevent importation of upstream harmonics

Output tuned near 7th to remove load side harmonics

Unique reactor design allows for smaller cap bank to reduce voltage boost and reactive power at no load

250kW WSHF-HP Performance PWM VSD

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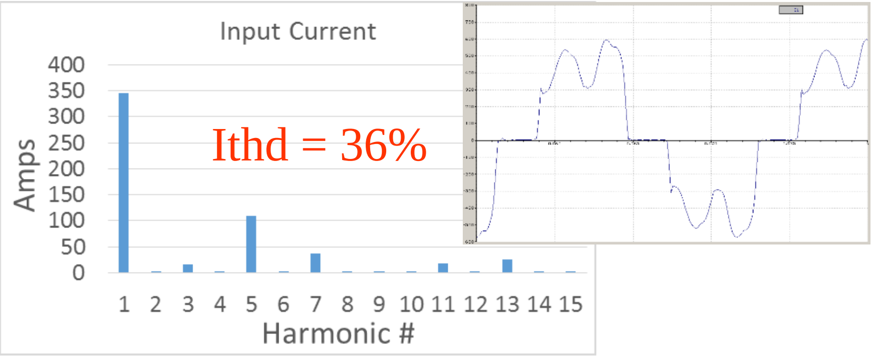
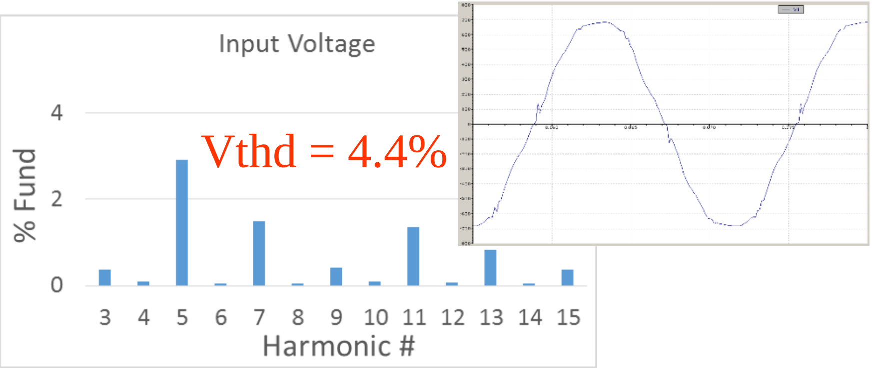
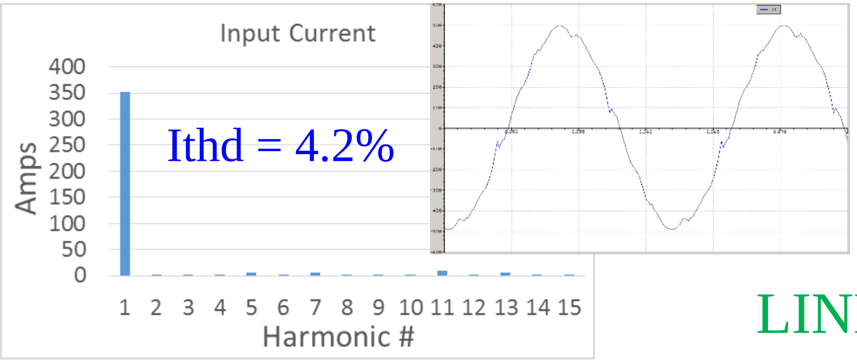
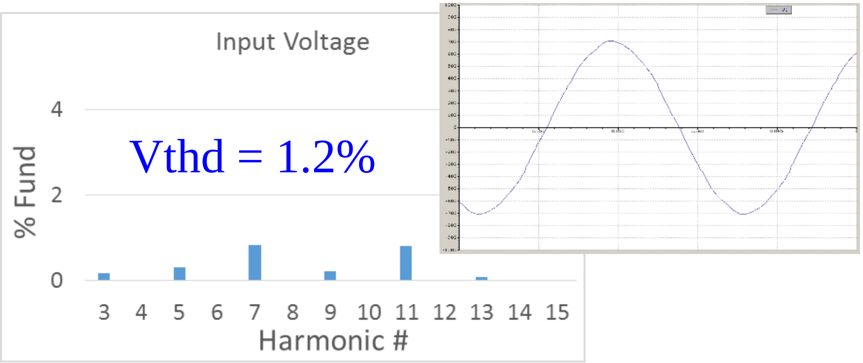
With Reactor





With LINEATOR-HP

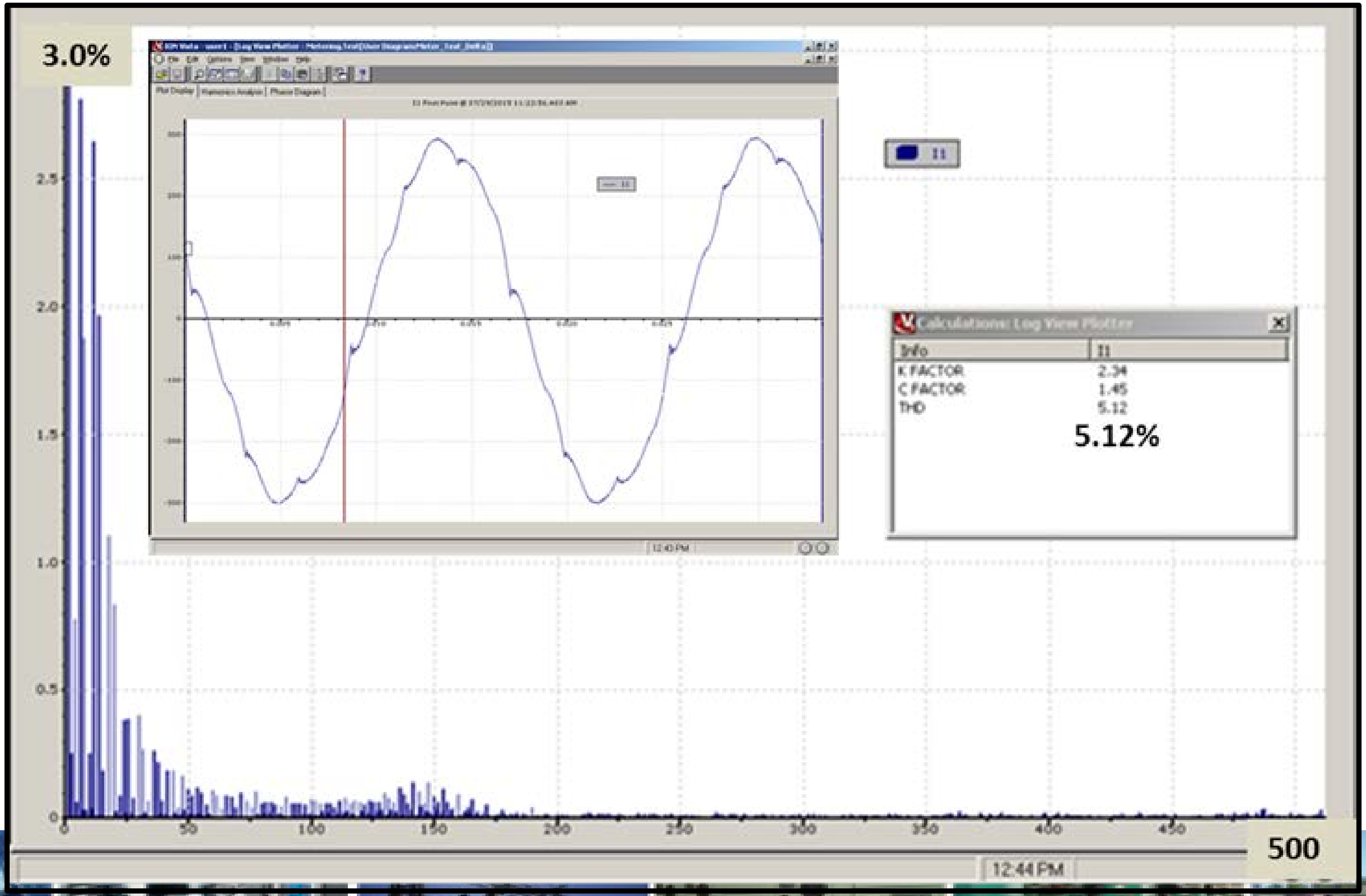




	Current Harmonics (Amps)																	
	RMS		5th		7th		11th		13th		Ithd		Itdd		K-factor		PF	
Load	w/o	With	w/o	With	w/o	With	w/o	With	w/o	With	w/o	With	w/o	With	w/o	With	w/o	With
Full	369	352	110	5.0	37	4.9	19	9.5	25	6.1	36%	4.2%	36%	4.2%	8.9	1.5	0.94	0.98
75%	275	257	83	4.8	35	6.6	16	8.1	17	3.9	37%	5.2%	28%	3.9%	9.3	1.7	0.94	1.00
50%	188	171	67	3.5	27	5.7	5.6	5.6	14	3.9	44%	6.1%	22%	3.0%	10	2.2	0.92	1.00
30%	123	108	48	2.8	27	5.9	4.1	3.3	9.2	1.8	55%	7.8%	16%	2.4%	17	2.4	0.88	0.96
25%	109	92	55	2.4	34	5.8	5.3	2.7	7.3	1.8	77%	8.7%	19%	2.2%	17	2.6	0.79	0.93

Lineator AUHF Performance – Current Harmonics up to 500th

- Treats entire spectrum of harmonics
- No introduction of high frequency harmonics unlike Active Front End drives and Parallel Active Filters



Summary and Conclusions

- EV Charger rectifiers are non-linear loads and therefore, generate harmonics
- EV Supply Equipment for Public Charging stations with Level 2 or 3 chargers require harmonic mitigation to meet harmonic limit standards
- Consideration should be given to both Low Frequency Harmonics and High Frequency Supraharmonics
- 6-Pulse Rectifers equipped with a Wide Spectrum Harmonic Filter will meet Harmonic Standards without introducing Supraharmonics
- Multipulse Passive Rectifiers may not meet Harmonic Standard requirements
- Chargers with Active Rectifiers may meet Low Frequency requirements but will likely introduce high levels of Supraharmonics

Thank You

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