Harmonic and Energy Saving Solutions

Reducing Generator Size and Fuel Consumption through Harmonic Mitigation

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Reducing Generator Size and Fuel Consumption through Harmonic Mitigation

What we will discuss:

- Case Study Background
- Generators and Harmonics
  - Requirements for Non-linear Loads, such as Variable Speed Drive Applications (VSD)
  - VSD Harmonics
  - How Source Impedance effects Current and Voltage Distortion
- Concept of Rightsizing a Generator under Non-linear Loading
- VSD Harmonic Mitigation Techniques
- 200HP Islanded Oil Pumping Case Study
  - Computer Simulations
  - Simulations vs measured values
  - Fuel and emissions reduction
- Conclusions

Case Study Background

Location: An unmanned, islanded oil pipeline pumping station near Cotulla, Texas

- 200 HP, 480V Pump with AC Variable Speed Drive (VSD) initially supplied by a 176 kW diesel generator
- VSD was equipped with AC line reactor to reduce harmonics
- After numerous problems including generator instability and several expensive VSD failures, the generator was increased to 500 kW on manufacturer's recommendation
- Some VSD problems still persisted so an harmonic mitigation solution for the VSD was analyzed and applied
- Application of harmonic mitigation paid back in 1½ mo

Generator Requirements for VSD Applications

- When generators supply non-linear loads, such as VSDs, many conditions need to be considered
  - Overheating of the generator due to additional harmonic losses
  - High voltage distortion as the harmonic currents pass through the source impedance of the generator
  - Excitation Control and Automatic Voltage Regulator (AVR) issues resulting in instability
  - Higher fuel consumption and emissions
- Standard solution recommended by generator manufacturers:
  - Oversize by 2x to 2.5x

Problem with Standard Solution

- Fuel consumption and emissions will increase further
  - Generator efficiencies drop when they are operated at more lightly loaded levels
  - Further impact on the environment
    - 1 USgal of diesel emits 9.1 to 13.2 kg of air contaminants *
  - Increase in operating costs
- Increase in capital costs
- Although slightly reduced, voltage distortion remains

* *Estimation of Carbon Footprints from Diesel Generator Emissions*, A Q Jakhrani et al, 2012 International Conference in Green and Ubiquitous Technology, 2011 IEEE

Generators and Harmonics

- Harmonic currents substantially increase losses in generator
- High generator source impedance results in high voltage distortion
  - a relatively 'weak' source
  - internal impedance (unsaturated sub-transient reactance or X"d) is typically 4x to 5x a transformer's impedance
- Generators do not produce a perfect sinusoidal voltage waveform even under linear loading, but with non-linear loading, it is substantially worse
- Engineers may specify a high X"d in an effort to reduce fault levels but this will increase voltage distortion
- AVR controls can malfunction when voltage distortion levels are high

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Variable Speed Drives and Harmonics

For simple diode bridge rectifiers:

$$h = np \pm 1$$

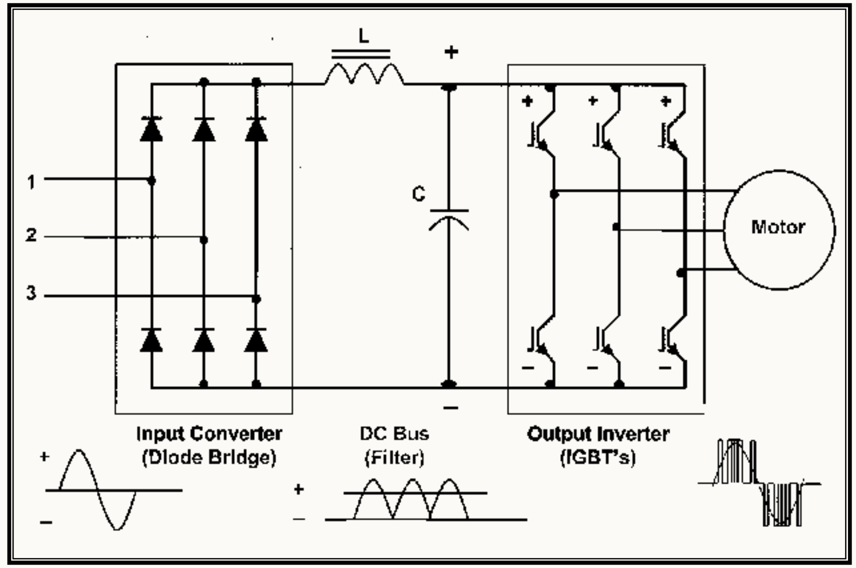
$$I_h = \frac{I}{h}$$

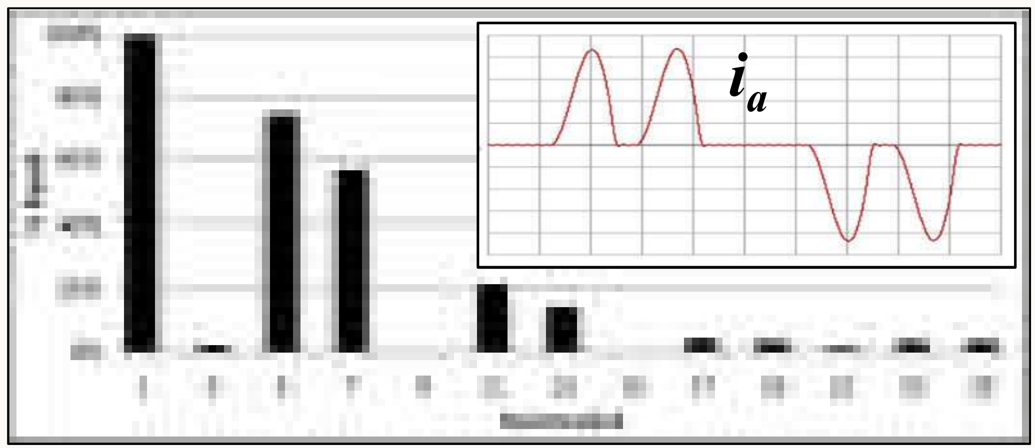
h = harmonic number
p = # of pulses in rectification scheme
n = any integer (1, 2, 3, etc.)
I_h = magnitude of harmonic current
(addition of DC bus cap increases I_h)

When,

p = 6

h = -- 5,7,--,11,13,--,17,19...





Current Waveform and Spectrum

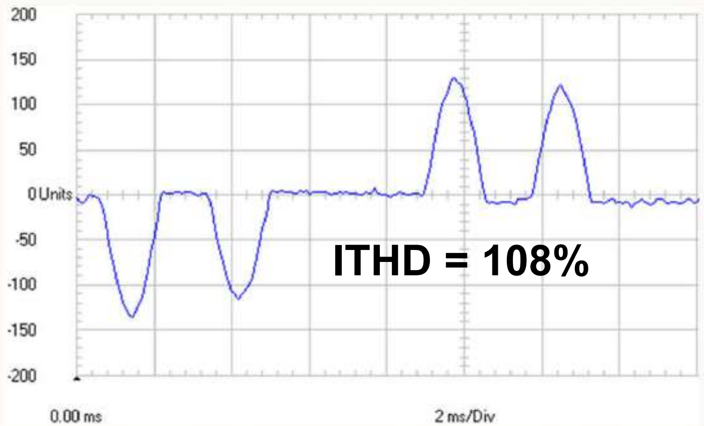
How Source Impedance Affects Harmonic Distortion

Low Source Impedance (Stiff)

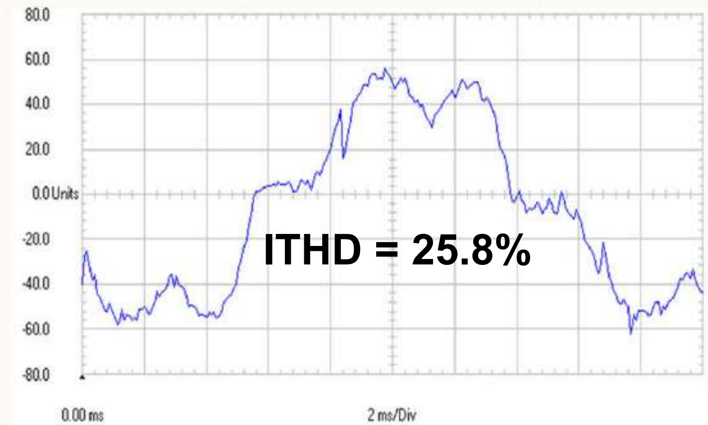
- Higher Current Distortion
- Lower Voltage Distortion

High Source Impedance (Weak)

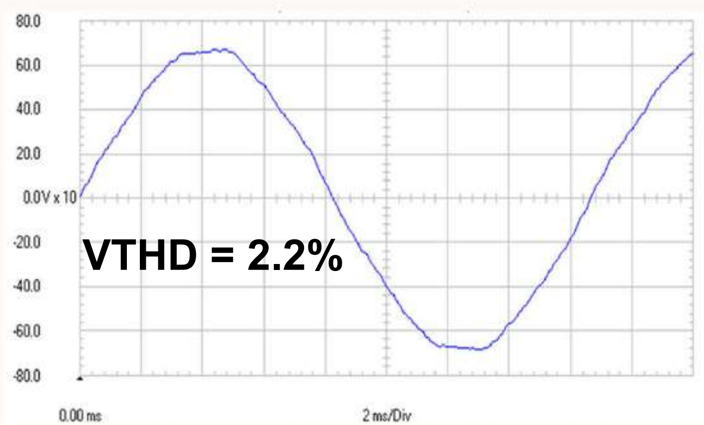
- Lower Current Distortion
- Higher Voltage Distortion



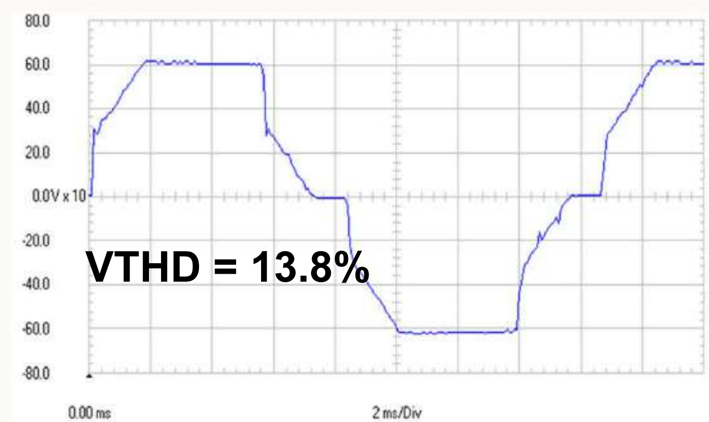
INPUT CURRENT OF 15 HP, 6-PULSE ASD ON A STIFF UTILITY SOURCE (ITHD = 108%)



INPUT CURRENT OF 15 HP, 6-PULSE ASD ON A WEAK GENERATOR SOURCE (ITHD = 25.8%)



INPUT VOLTAGE OF 15 HP, 6-PULSE ASD ON A STIFF UTILITY SOURCE (VTHD = 2.2%)



INPUT VOLTAGE OF 15 HP, 6-PULSE ASD ON A WEAK GENERATOR SOURCE (VTHD = 13.8%)

Concept of Rightsizing a Generator Under Non-linear Loading

- Traditional 'rule of thumb'
  - When VSDs represent more than 25% of the total load, they become cause for concern
  - When the amount is higher, greater oversizing is required
  - 2x to 2.5x oversizing is typical
- Oversizing can be avoided by applying effective harmonic mitigation
  - Reducing load ITHD to < 10% lowers derating requirement to 1.4x
  - For large non-linear loads or large quantities of smaller non-linear loads, harmonic mitigation should be considered

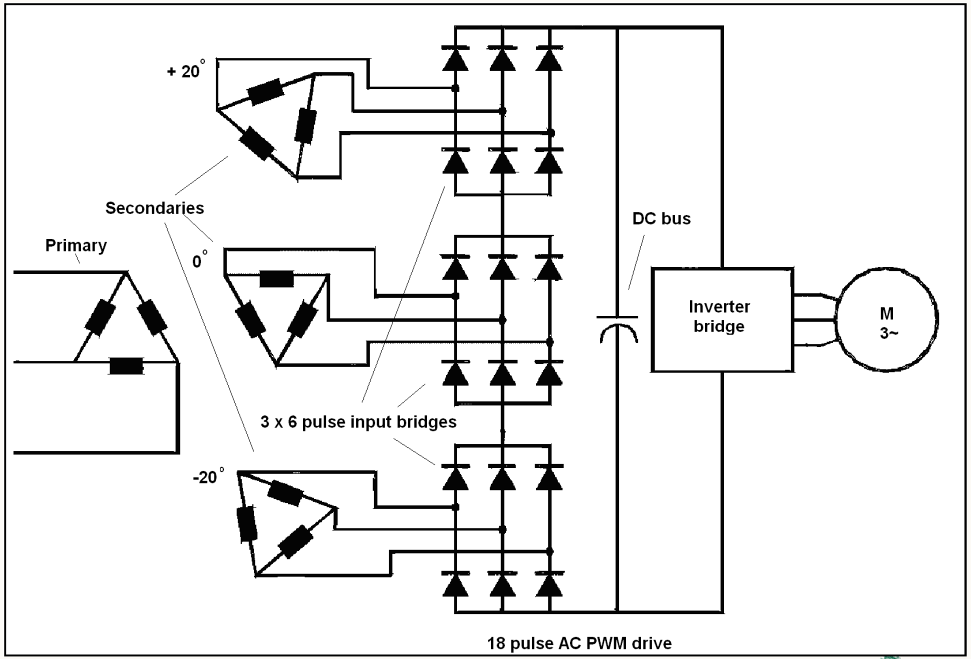
Ref: *Electric Power Application and Installation Guide – Engine and Generator Sizing,* Caterpillar, p53

VSD Harmonic Mitigation Techniques

- AC line reactors or DC chokes
  - Typically reduce harmonics by half but this is often not sufficient enough to prevent problems
  - 3% to 5% are typical impedances
  - Simply increasing the impedance further will have minimal effect and can cause voltage drop issues

VSD Harmonic Mitigation Techniques (cont.)

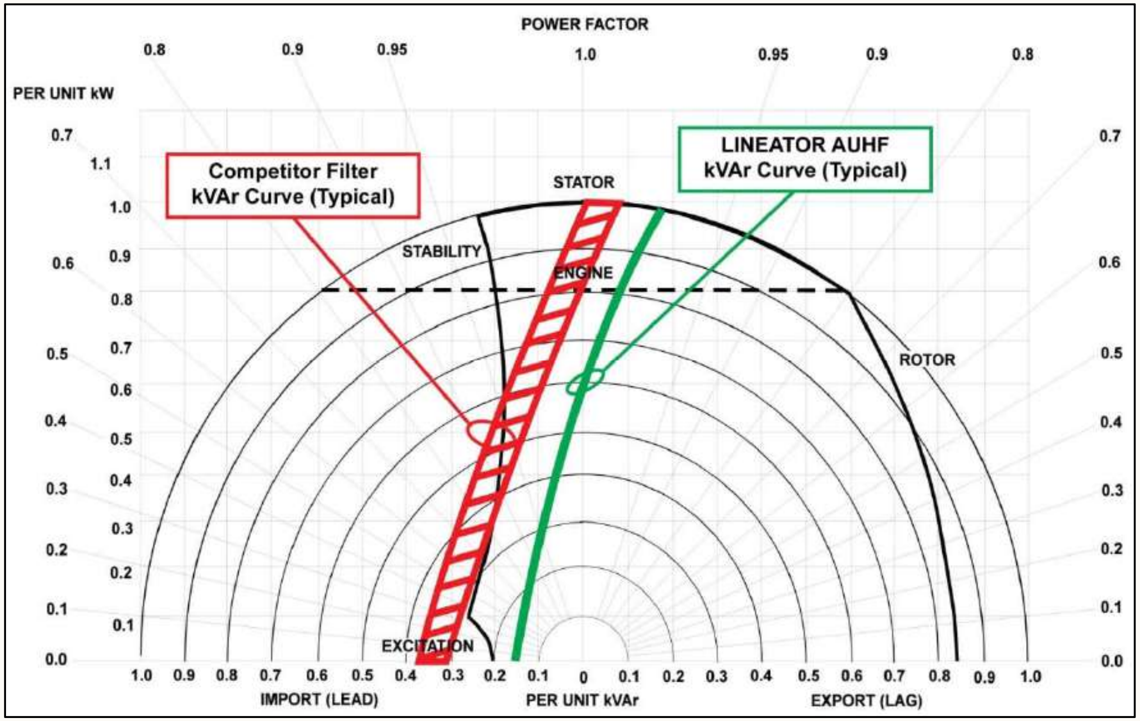
- Multipulse VSD (12-P, 18-P, 24-P, 36-P, etc.)
  - Transformer phase shifting creates harmonic cancellation
  - Effectiveness of phase shifting diminishes as pulse number increases
  - Voltage imbalance and voltage distortion reduces effectiveness
  - Transformer losses significantly lower VSD efficiency



Typical 18-P Configuration

VSD Harmonic Mitigation Techniques (cont.)

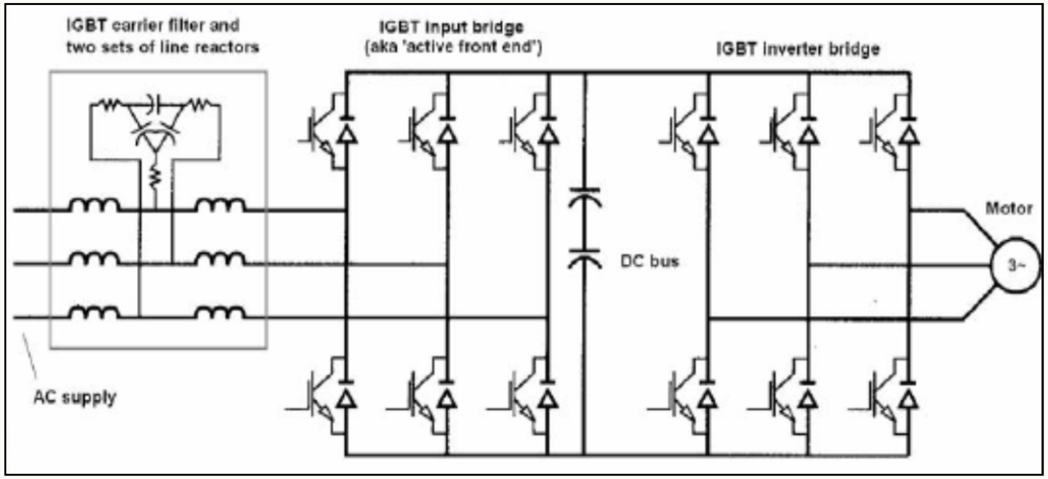
- Tuned passive filters
  - Target individual harmonics so multiple filters are required
  - Can be overloaded by upstream harmonics
  - High capacitive reactance can cause generator instability



Generator's Reactive Power Capability Curve

VSD Harmonic Mitigation Techniques (cont)

- Active Front-end VSD's
  - IGBT rectifiers replace diode bridge rectifiers
  - Input current harmonics up to the 50th are reduced but high levels of high frequency harmonics are introduced
    - ITHD levels are high when measured up to 100th
  - Introduce common-mode voltage
  - Almost 2x the losses of a standard 6-Pulse VSD
  - Expensive

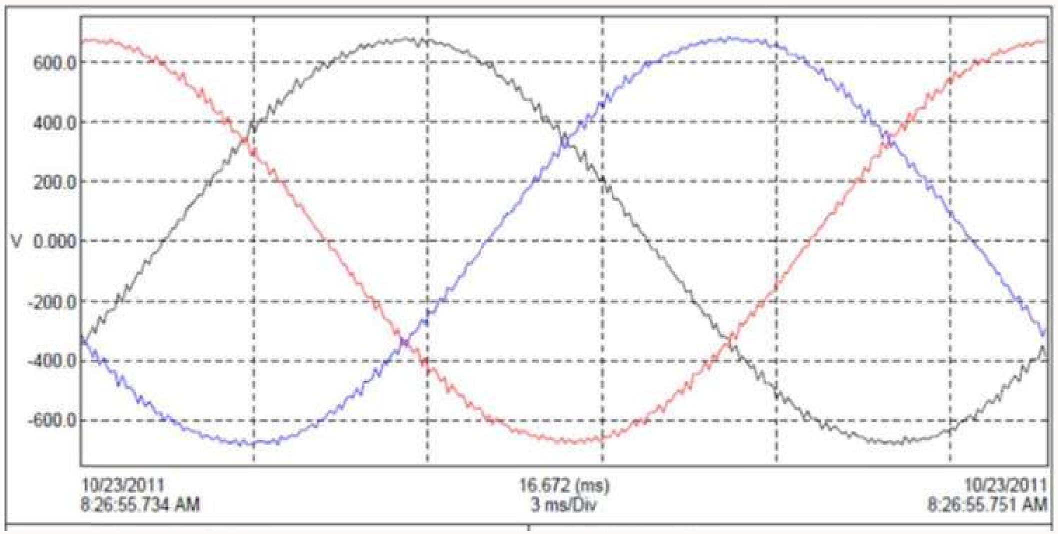


Active Front-end Drive Schematic

VSD Harmonic Mitigation Techniques (cont)

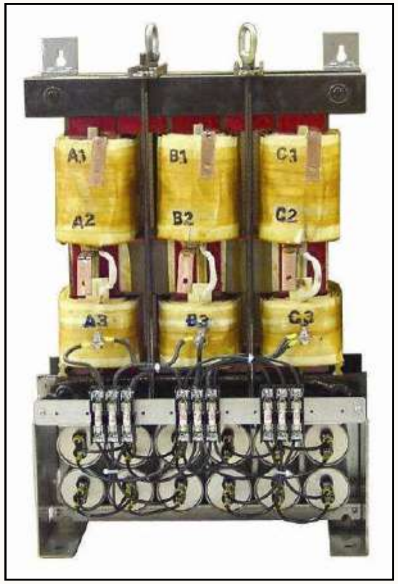
- Parallel Active Filters
  - Generate and supply non-linear loads with harmonic currents so that they do not need to be supplied by the source
  - Can introduce high levels of high frequency harmonics
  - All VSDs must be equipped with, at least, 3% AC reactor
  - Expensive

Voltage waveform – VTHD <1%

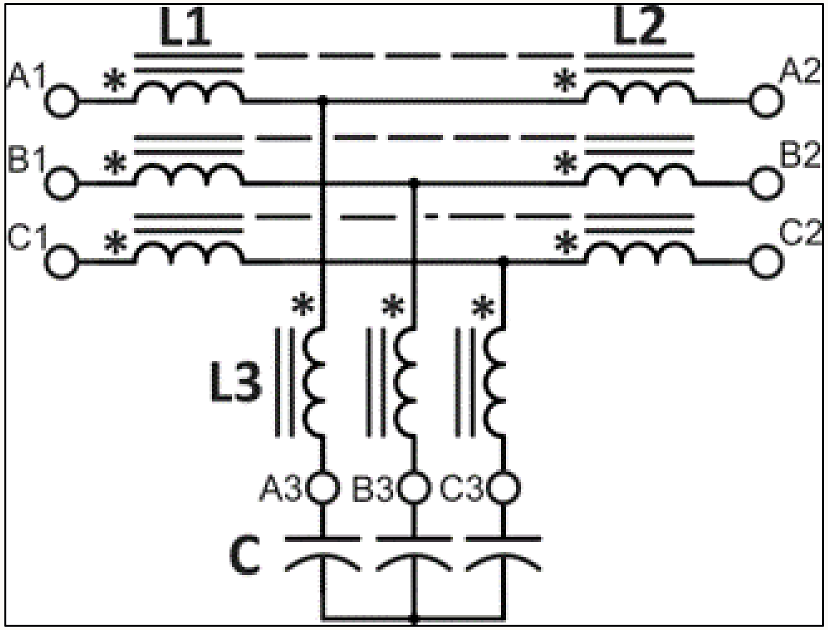


Voltage Ripple introduced by Active Filter

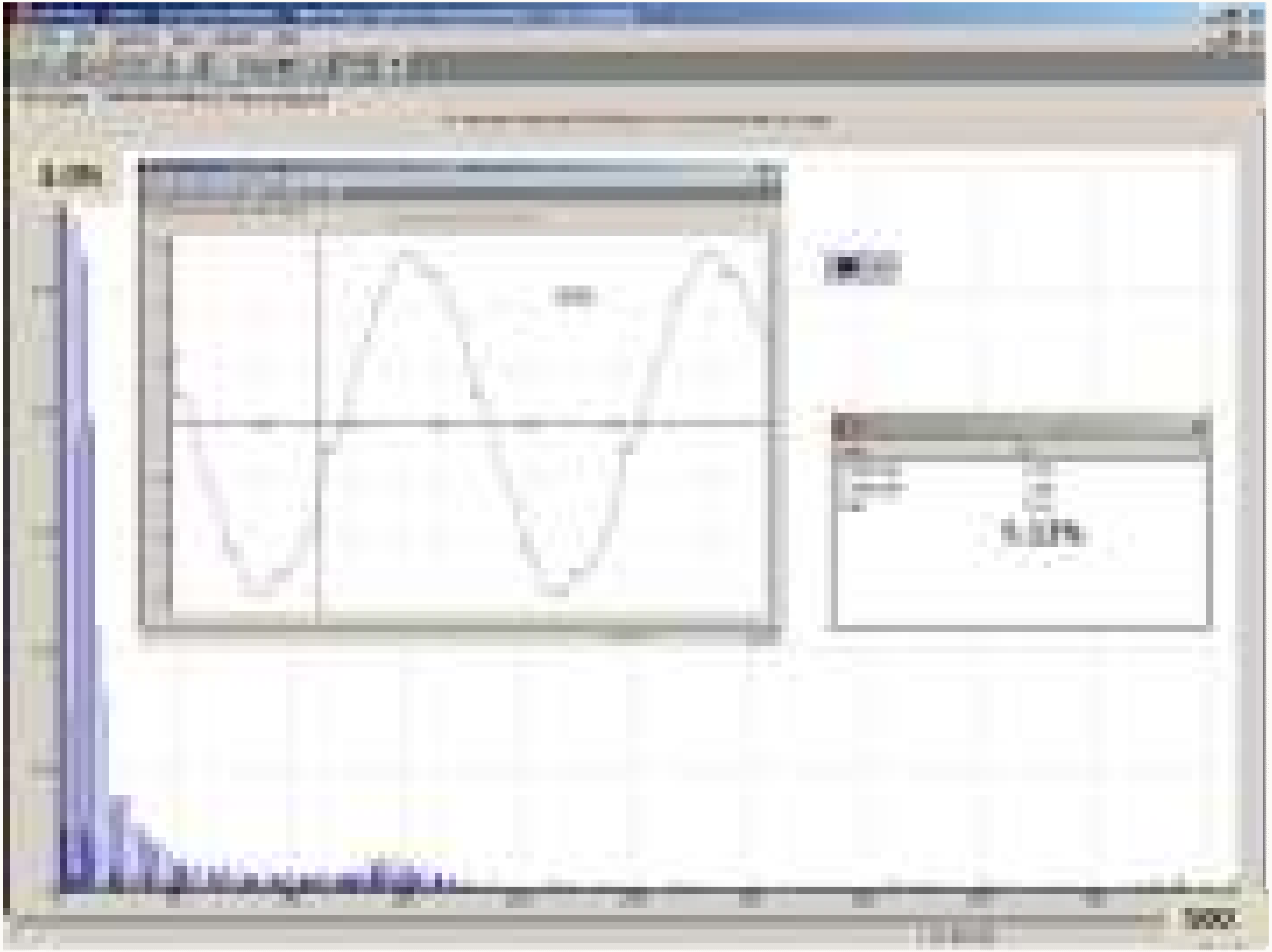
VSD Harmonic Mitigation Techniques (cont)



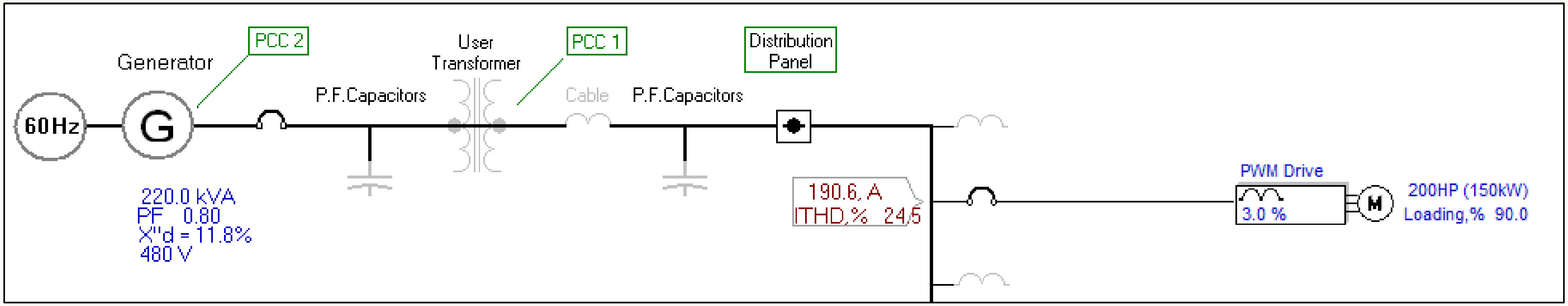
- Passive Wide Spectrum Harmonic Filter (WSHF)
  - Reduces full spectrum of characteristic harmonics generated by 6-Pulse VSD
  - Unique multiple reactor on common core
  - Very low capacitive reactive power to ensure generator compatibility
  - Input tuned below 5^{th} harmonic to prevent resonance with power system
  - Very high efficiency



VSD Harmonic Mitigation Techniques (cont)



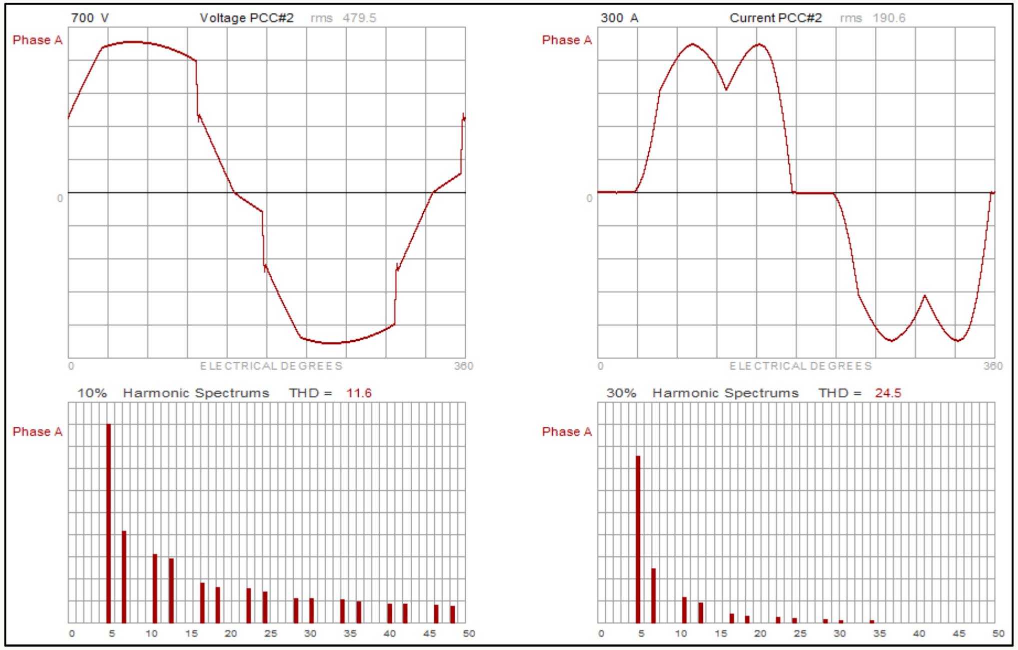
Computer Simulation of 200HP Pump on 178kW (220kVA) Generator – 3% Reactor (Original Configuration)



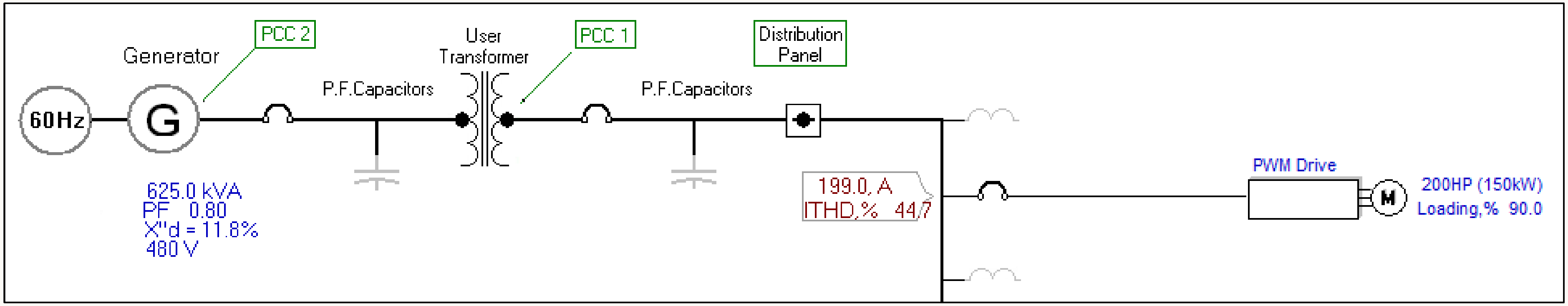
at PCC #2

VTHD, % = 11.6
ITHD, % = 24.5
Irms, A = 190.6
Isc/Iload = 12.1
Disp. PF = -0.96
True PF = 0.93
Isc,(kA) = 2.2
Active kW 147.3
kVA = 158.3
kVAR = 57.8

VTHD extremely high



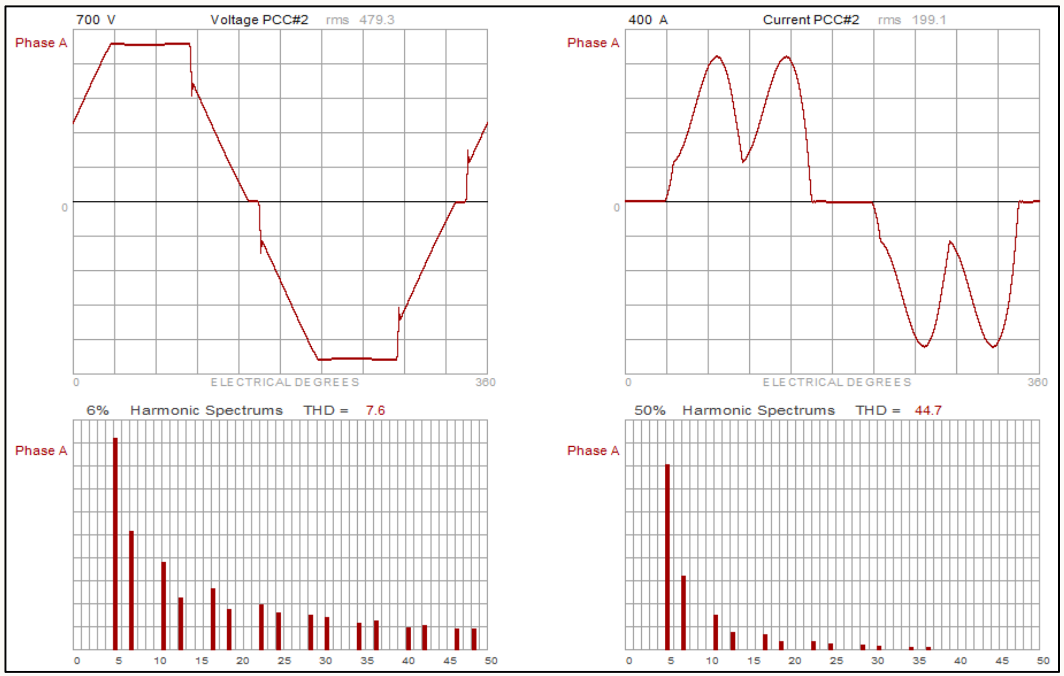
Computer Simulation of 200HP Pump on 625kVA (500kW) Generator – no mitigation



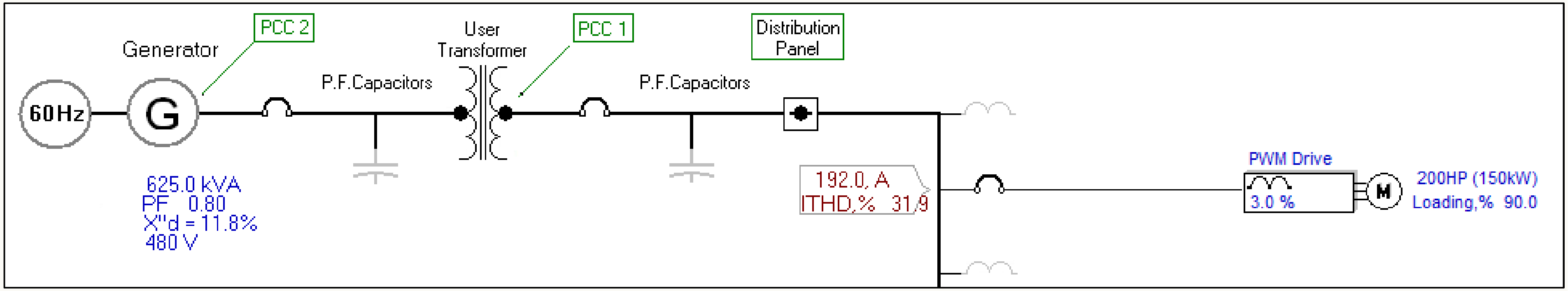
VTHD still exceeds 5%

at PCC #2

VTHD, % = 7.6
ITHD, % = 44.7
Irms, A = 199.1
Isc/Iload = 35.1
Disp. PF = -0.98
True PF = 0.89
Isc,(kA) = 6.4
Active kW 147.4
kVA = 165.2
kVAR 74.6



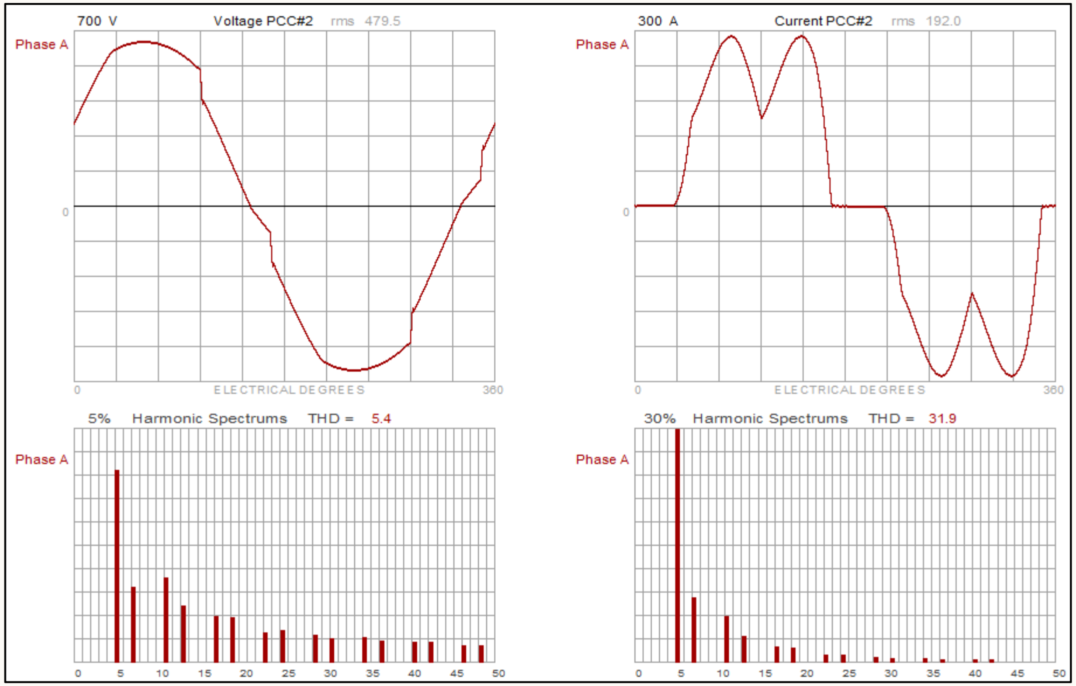
Computer Simulation of 200HP Pump on 500kW Generator – with 3% AC line reactor



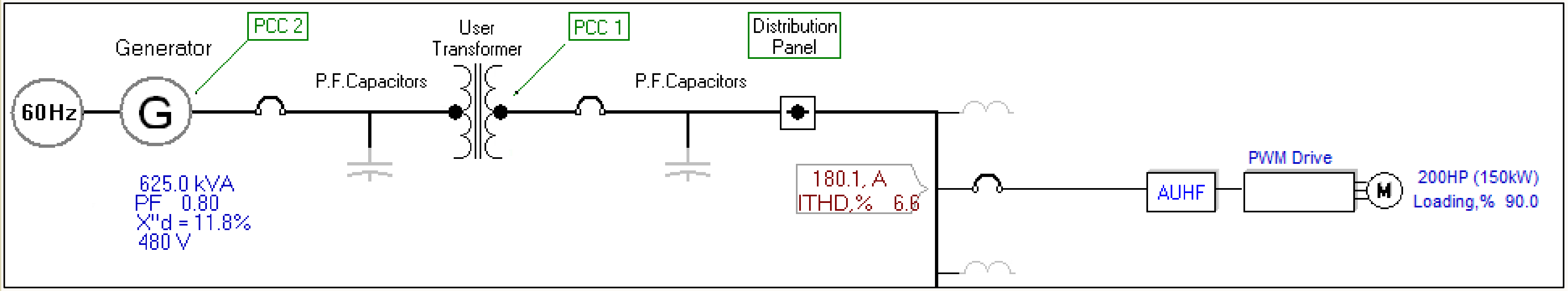
VTHD still exceeds 5%

at PCC #2

VTHD, % = 5.4
ITHD, % = 31.9
Irms, A = 192.0
Isc/Iload = 34.8
Disp. PF = -0.97
True PF = 0.92
Isc,(kA) = 6.4
Active kW 147.3
kVA = 159.4
kVAR 61.1



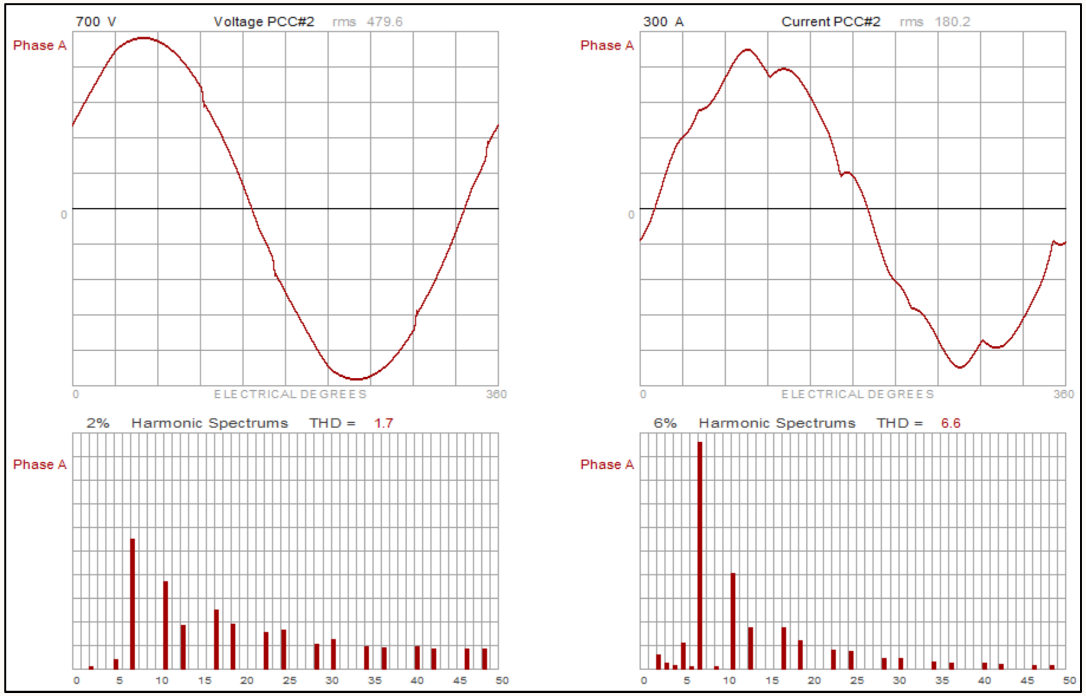
Computer Simulation of 200HP Pump on 500kW Generator – with WSHF



VTHD well below 5%

at PCC #2

VTHD, % = 1.7
ITHD, % = 6.6
Irms, A = 180.1
Isc/Iload = 35.4
Disp. PF = -0.99
True PF = 0.99
Isc,(kA) = 6.4
Active kW = 147.8
kVA = 149.6
kVAR = 23.3



Computer Simulation vs Measured Values - 200HP Pump on 500kW Generator

Computer Simulation

	No Harmonic Mitigation	With 3% AC Reactor	With WSHF
VTHD	7.6%	5.4%	1.7%
ITHD	44.7%	32.0%	6.6%
Current (Amp)	198.8	191.5	180.3
Real Power (kW)	147.2	146.9	148.3

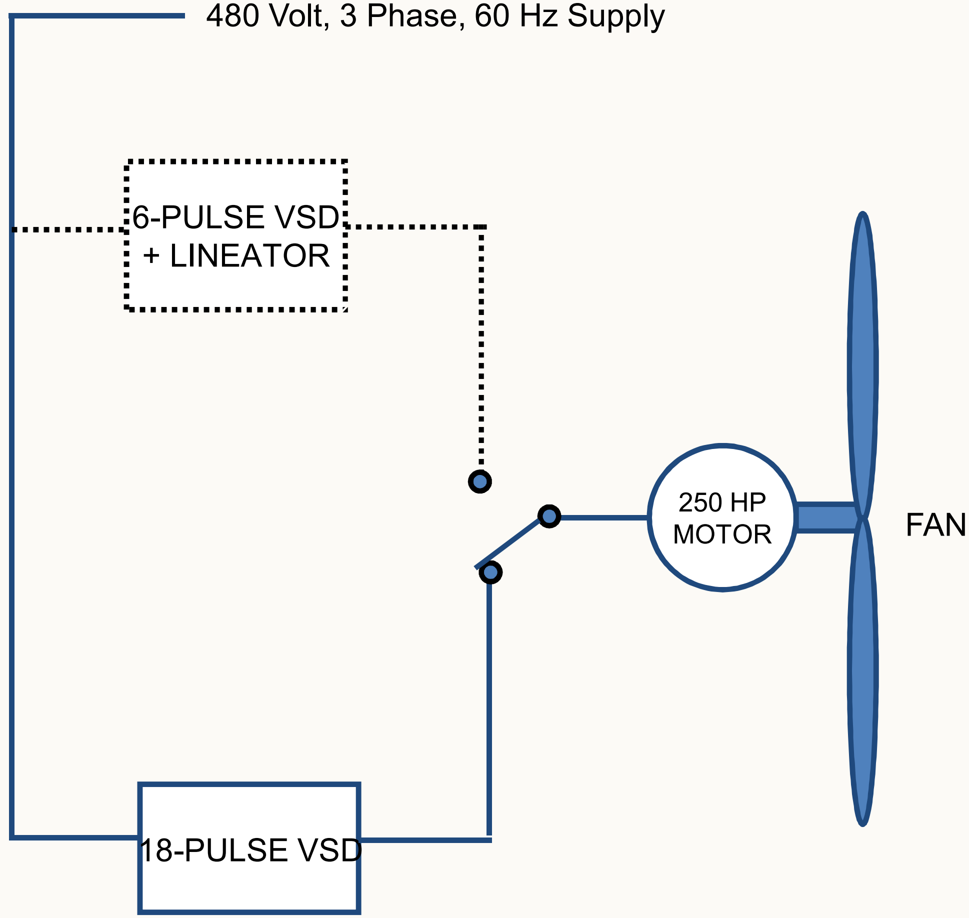
Measured Values
at 240 BPH

	With 3% AC Reactor	With WSHF
VTHD	6.0%	2.3%
ITHD	23.7%	5.7%
Current (Amp)	181	137
Real Power (kW)	137.5	111.5

Lower measured power consumption likely due to improved operation of pump with application of Wide Spectrum Harmonic Filter

Another Application where WSHF Improved VSD Performance

Skydiving Simulator Energy Savings Analysis: 18-Pulse VSD vs 6-Pulse with Lineator Harmonic Filter

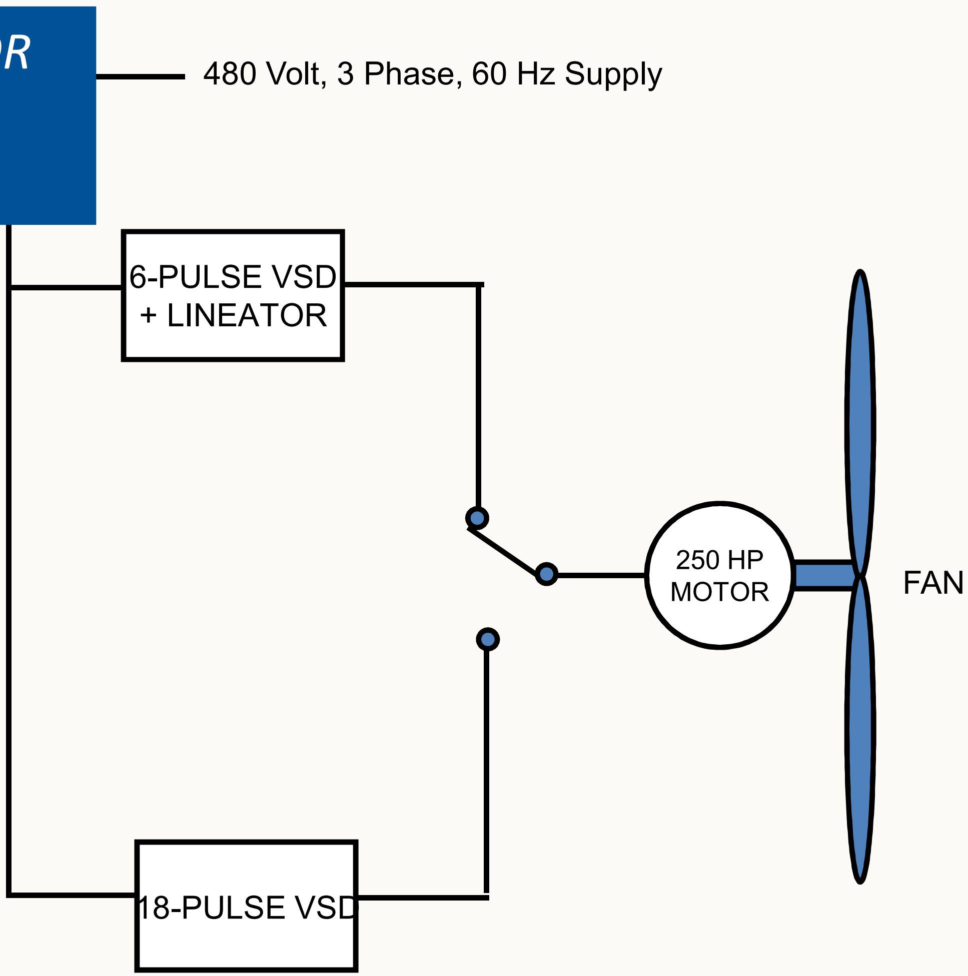


Fan (RPM)	Drive (Hz)	18-Pulse (kW)
818	55.92	152.47
889	60	190.03

With WSHF Drive Hz and Load kW are Reduced

KW SAVED WITH 6-PULSE VSD + LINEATOR
at 889 RPM : 6.89kW
at 818 RPM: 9.2kW

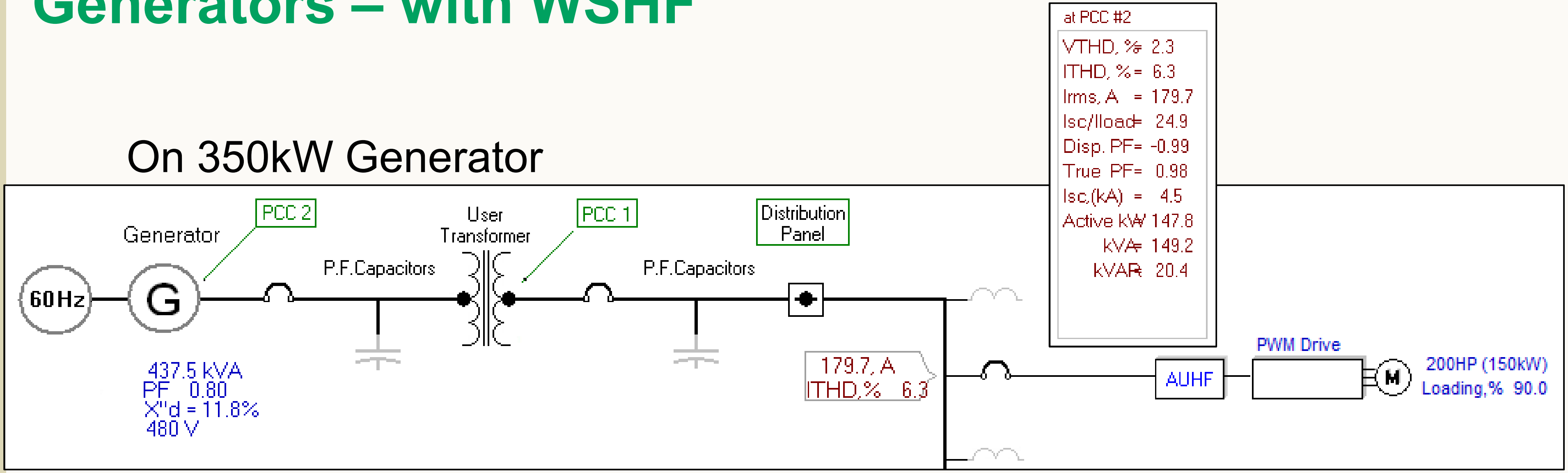
Fan (RPM)	18-Pulse VSD		6-Pulse VSD + Lineator	
	Drive (Hz)	kW	Drive (Hz)	kW
818	55.92	152.47	55	143.27
889	60	190.03	60	183.14



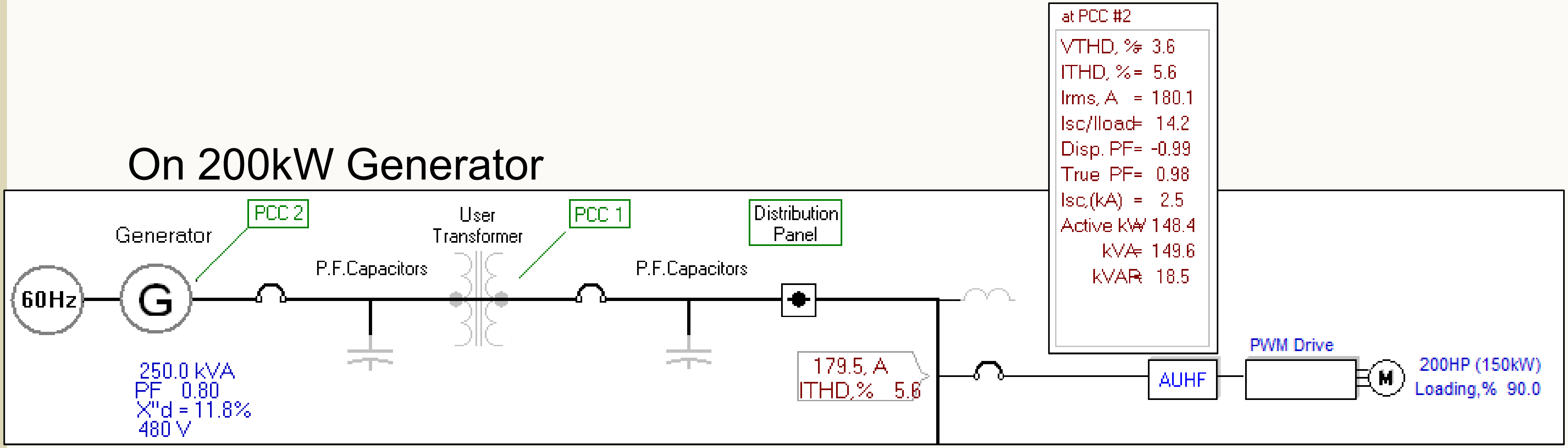
6-PULSE DRIVE + LINEATOR saved 3.5% to 6% of energy needed to run fan

Computer Simulation of 200HP Pump on Smaller Generators – with WSHF

On 350kW Generator



On 200kW Generator



Field Measurements vs Computer Simulation for 200HP Pump with WSHF on 350 kW Generator

	Computer Simulation	Field Measurements
VTHD	2.3%	2.5%
ITHD	6.3%	5.8%
Current (Amp)	179.7	144
Real Power (kW)	147.8	117.6
Apparent Power (kVA)	149.2	118.9
Reactive Power (kVAR)	20.4	17.4
True PF	0.98	0.99

Once again, lower measured power consumption likely due to improved operation of pump with application of Wide Spectrum Harmonic Filter

Comparison of 500kW and 350kW Generator Supplying 200HP Pump Operating at 240 BPH

	500 kW (with AC Reactor)	500 kW (with WSHF)	350 kW (with WSHF)
Load (kW)	137.5	111.5	117.6
Load %	27.4	22.2	39.2
Fuel Consumption Rate at % Load (gal/hr)	11.8	10.1	7.3
Fuel Consumption at 24 hrs/day, 30 days/mo (gal/mo)	8,496	7,272	5,256
Fuel Cost (USD/mo)	$32,285	$27,634	$19,973
Fuel Savings (USD/mo)	N/A	$4,651	$12,312
% Savings	N/A	14.4%	38.1%
Emissions* ($kgCO_2/hr$)	120	103	74
Monthly Emissions ($kgCO_2/mo$)	86,400	74,160	53,280
Monthly Emissions Reduction ($kgCO_2/mo$)	N/A	12,240	33,120

- Fuel cost - $3.80 USD/gal
- WSHF paid back in 1 ½ months on fuel savings alone
- Emissions calculated at 10.2 kg/gal*
- Generator replacement easily justified on fuel savings
- With generator replacement, emissions reduction is equivalent to the operation of 84 automobiles*

* *Estimation of Carbon Footprints from Diesel Generator Emissions*, A Q Jakhrani et al, 2012 International Conference in Green and Ubiquitous Technology

Conclusions

- For generator applications, consideration must be given to the amount of non-linear loading and the harmonic distortion these loads will introduce
- 'Rule of thumb' sizing practices require more than doubling the generator capacity when supplying non-linear loads
- This leads to much higher installation and operating costs and excessive emissions
- Even with oversizing, voltage distortion often still causes operational problems with sensitive equipment, such as VSDs
- By applying effective harmonic mitigation, the need to oversize can be eliminated while providing fuel/energy savings and lower emissions throughout the life of the installation

Questions or Comments