MIRUS International Inc.

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INVERSINE AUHF Inverter Sinewave Filter

Tony Hoevenaars, PEng., MIRUS International Inc.

April 2019

What we will Discuss

- PWM Adjustable Speed Drive Inverters
- Problems Associated with PWM Inverter Operation
  - Long leads/cables
  - Overvoltage at motor terminals and reflective wave phenomenon
  - Motor Anti-resonance issue
  - Common-mode voltage issues, shaft voltage and bearing currents
- INVERSINE™ Advanced Universal Sine-Wave Filter
- Competitive Comparison
- Summary

Mirus Is Harmonic Mitigation

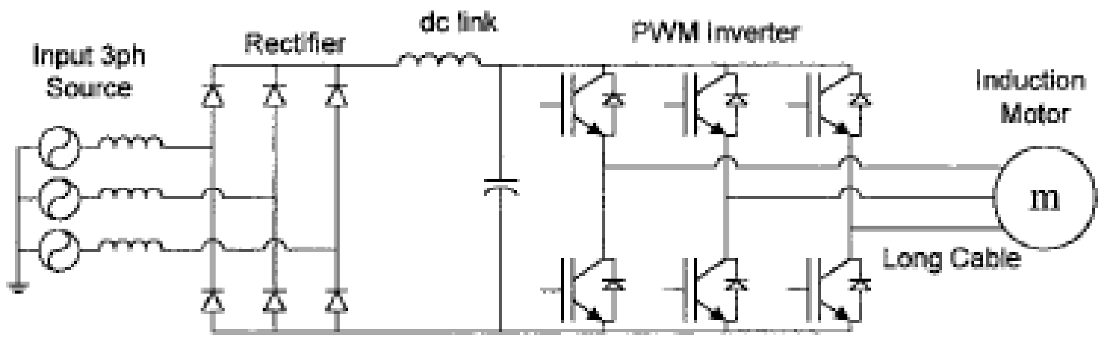
MIRUS International Inc. designs and develops world-class power quality improvement products for mission critical operations

Our solutions:

- Minimize disruption to the power supply
- Improve reliability
- Adhere to the strictest regulatory requirements
- Save energy and reduce operating costs

PWM Adjustable Speed Drive Inverters

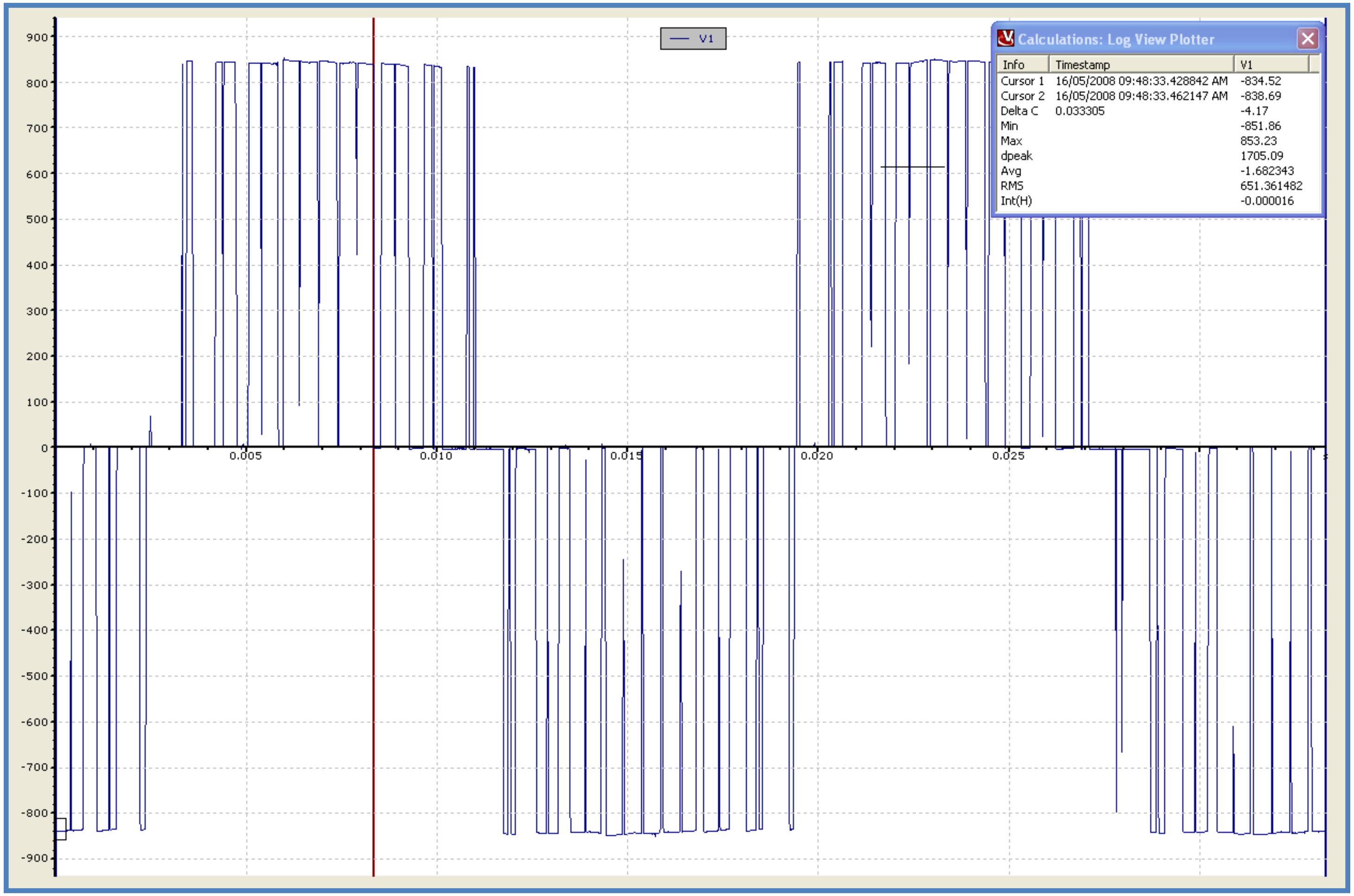
- Utilize Pulse Width Modulation (PWM) Inverters with high frequency switching of Insulated Gate Bipolar Transistors (IGBTs)
  – 2 to 8 kHz switching frequencies typical
  – Voltage rise time (dV/dt) rates of 6,000 V/μs typical (up to 20kV/μs is possible)
- Motors are designed to withstand stress of 1,000V/ μs



Conventional ASD system

Reference: “*An Evaluation of Mitigation Techniques for Bearing Currents, EMI and Overvoltages in ASD Applications*”, *IEEE IA Vol. 34, No.5 Sept/Oct.* 1998

ASD Normal Mode Output Voltage:
Typical PWM for 600V Inverter at 2 kHz



Voltage rise time ratio (dV/dt) = 4,400 V/µs

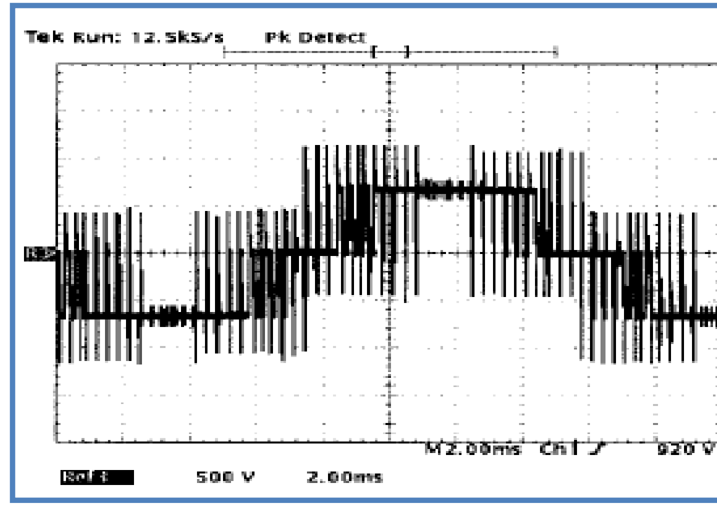
Peak voltage = 853 V (603V AC supply)

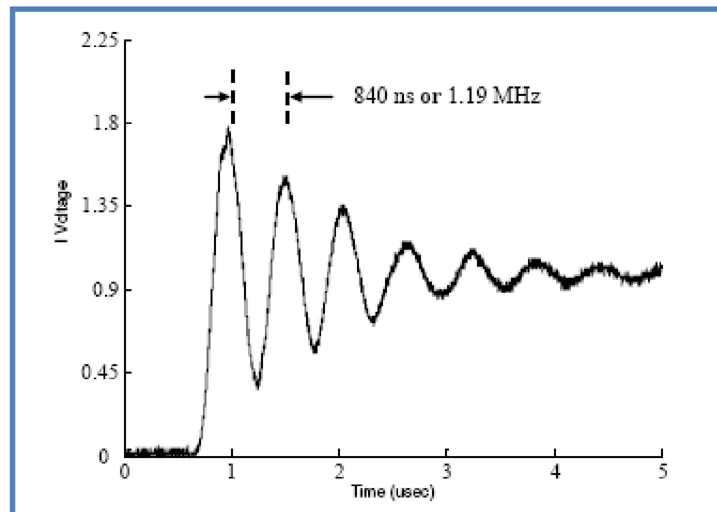
Problems Associated with Inverter Operation

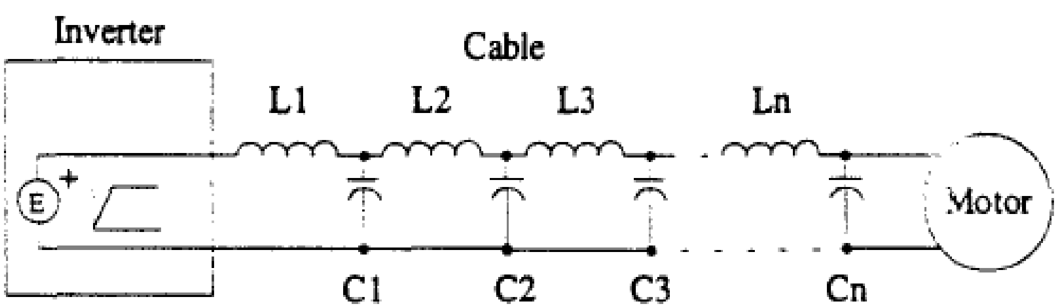
- Motor problems:
  - Motor terminal overvoltage (spikes) due to reflective wave phenomenon and motor anti-resonance
  - Excessive harmonic losses
  - Excessive noise
  - Stressed insulation leading to failures
  - Shaft voltage and Bearing currents leading to bearing failures
- High EMI and RFI
- Higher cost, inverter duty motors required
  - NEMA MG-1 Part 31.
- Special cables required to reduce leakage currents, deal with overvoltages, etc…

Reflective Wave Phenomenon with Long Cable Runs

- PWM pulses travel between inverter and motor behaving like traveling waves on transmission lines
- Leads to reflective wave phenomenon and overvoltage at motor terminals
  - Up to 2 x DC bus voltage of the drive
- Caused by high dV/dt of PWM pulse and mismatch between cable and motor surge impedance
- Worse with long cable runs and higher PWM switching frequency

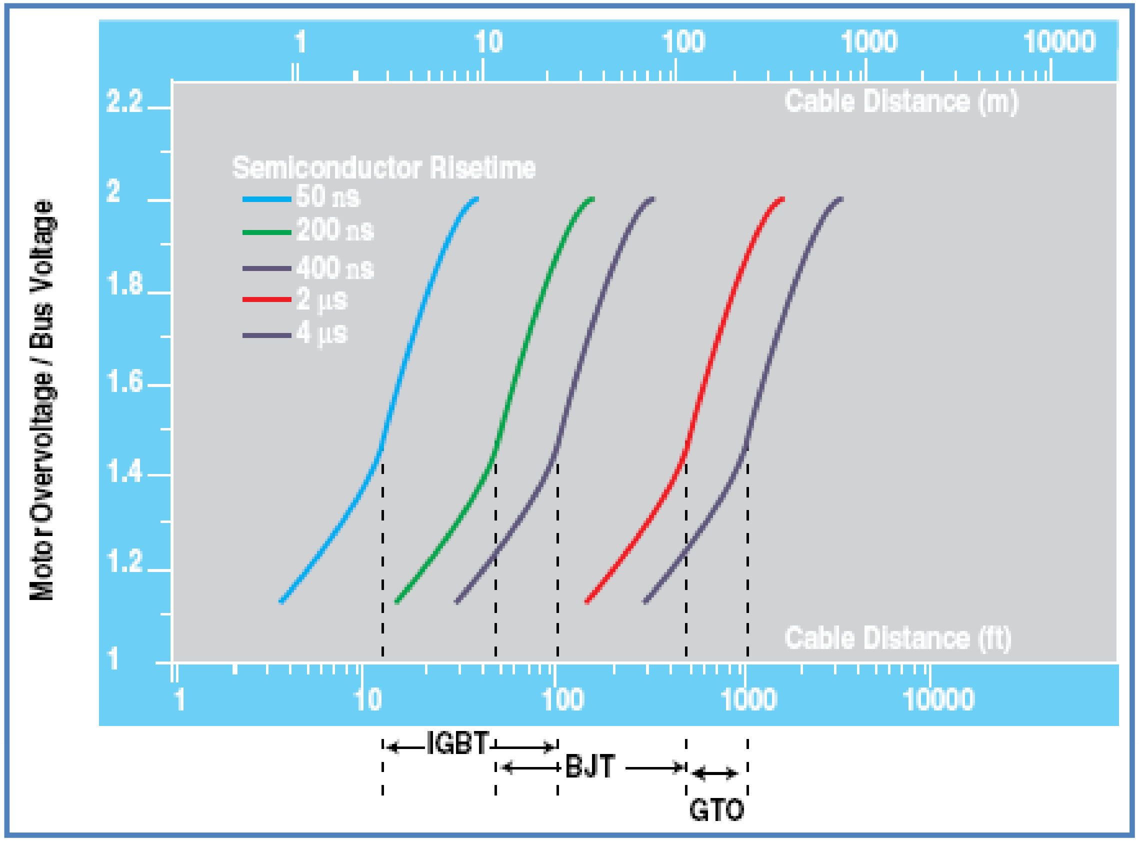






Reflective Wave Phenomenon (cont.)

- IGBT's allow for higher switching frequencies
- Even relatively short cable runs can cause problems:
  - Critical cable length for 500V/µs dV/dt is ~ 100m range (328 ft)
  - 1000 V/µs is 50m (164 ft)
  - 10,000 V/µs is 5m (16 ft)

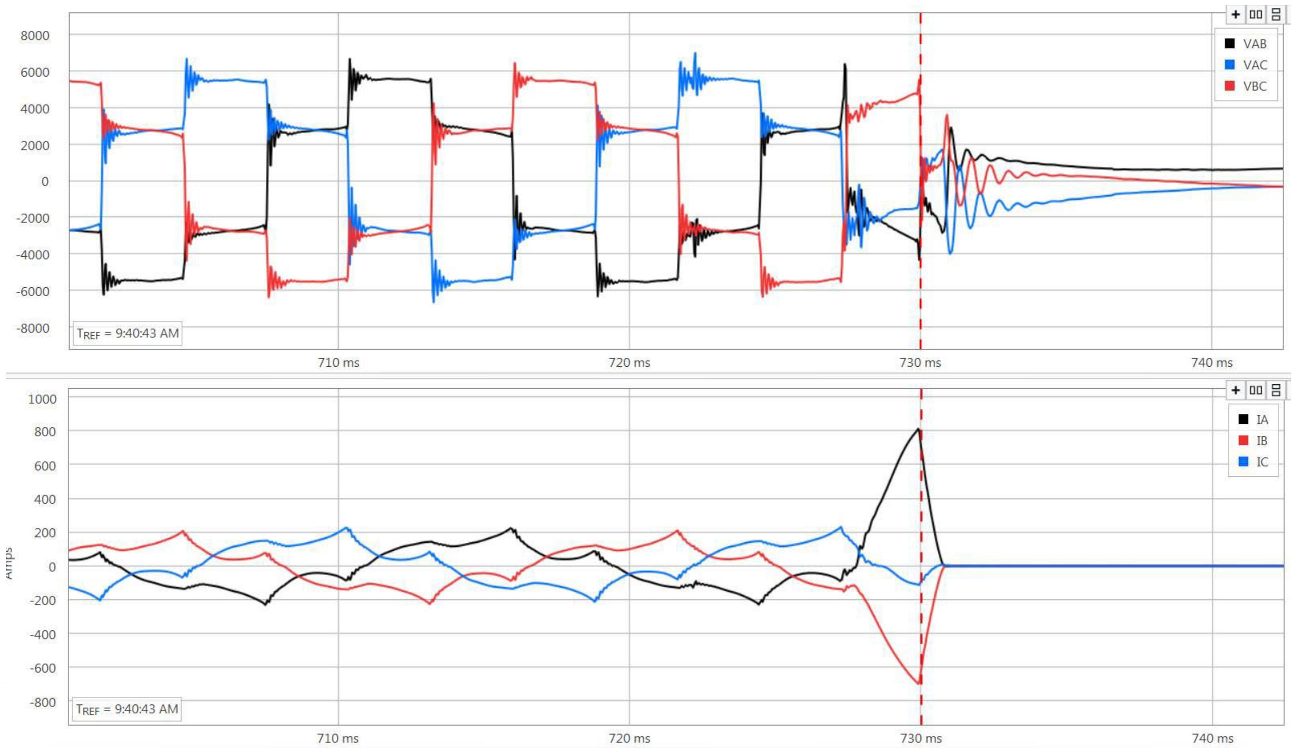


- Worse with higher surge impedance, small HP(kW) motors

Reference: AB App Note, *'Effective Motor Protection Against Reflected Wave Phenomenon'*

Overvoltage and Ringing in a 6-Step ESP Leading to Motor Failure

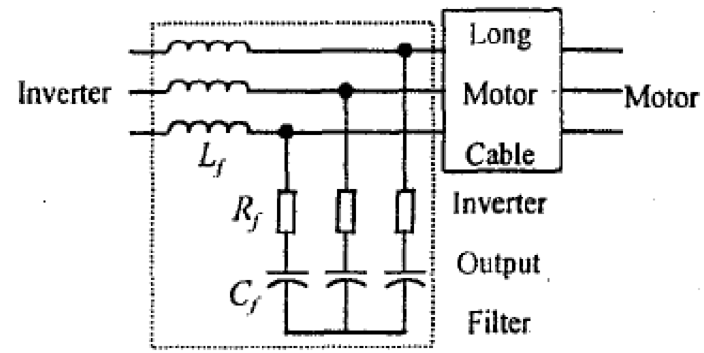
- 1100 HP ESP system operating in 6-Step mode with voltage distortion > 20% and obvious overvoltages and ringing
- Although there are only six voltage steps during each cycle, each step still has a fairly steep rise time resulting in voltage over shoot and ringing
- Resulted in premature motor failure
- In PWM operation without filtering, this would be more severe because it would occur many more times in the pulsed DC voltage
- But PWM with a sinewave filter is a good option



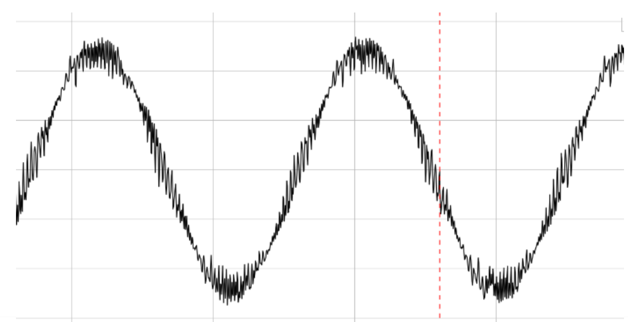
3-Phase Voltage and Current Waveforms on 6-Step ESP prior to and at Motor Failure

Conventional PWM Inverter Sinewave Filter

- Sinewave filters are low pass designs targeting the lowest PWM harmonic number with highest magnitude
  - These harmonics exist near the inverter switching frequency
  - Typically 2 to 8 kHz for ESPs
- For near sinusoidal voltage, the filter's tuned frequency must be well below the inverter's switching frequency and comfortably above its output fundamental frequency
  - Conventional design uses a minimum cutoff frequency of 10x fundamental and at least, 2 to 2.5x below the switching frequency
  - A 600 Hz cutoff frequency is often used for a 60 Hz inverter with a switching frequency above 2 kHz



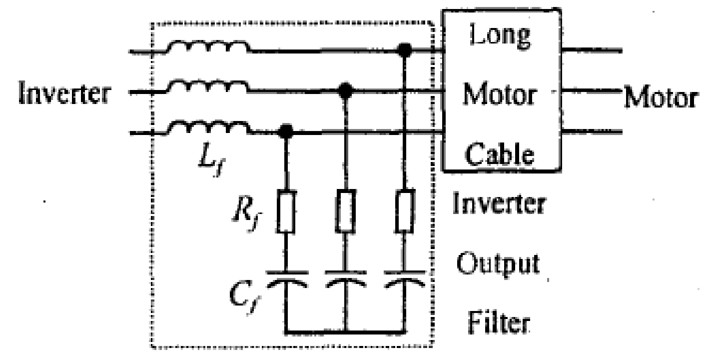
Second-order Inverter Sinewave Filter



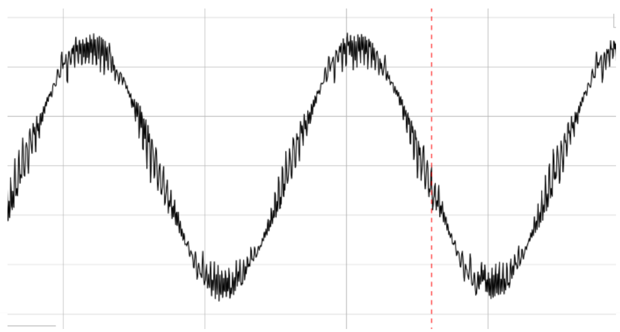
ESP PWM Output Voltage Waveform with Conventional Sinewave Filter

Conventional PWM Inverter Sinewave Filter (cont.)

- It is important to prevent potential resonance of the filter with cable and motor impedances
  - Resistors are often added to produce a second-order RLC network
  - Resistors increase losses and filter cost so some manufacturers offer designs without resistors that often perform poorly and fail prematurely
  - Often significant levels of high frequency voltage ripple remain



Second-order Inverter Sinewave Filter

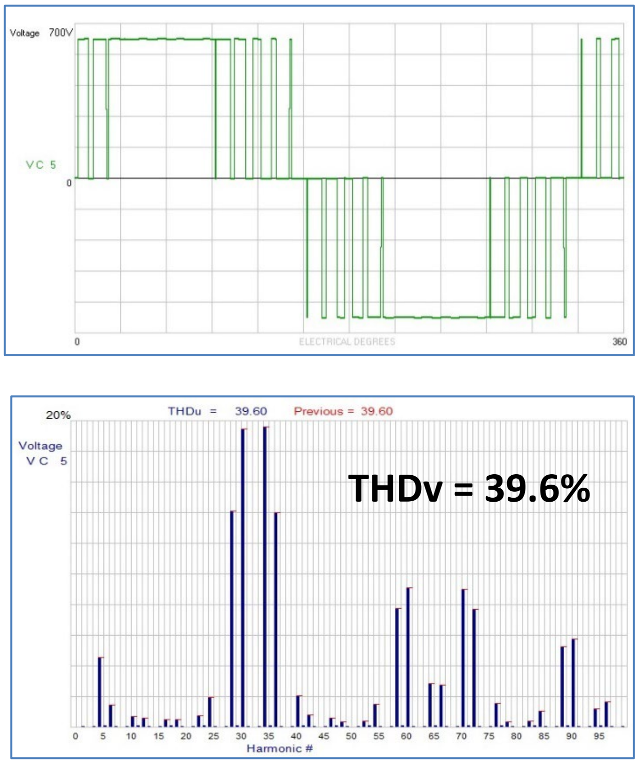


ESP PWM Output Voltage Waveform with Conventional Sinewave Filter

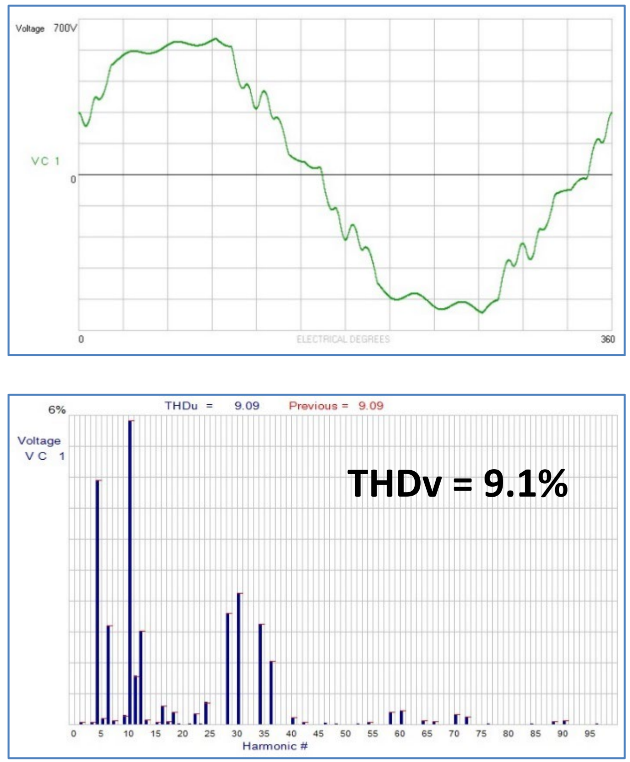
Conventional Sinewave Filter Computer Simulations – 200HP, 480V, 60Hz ESP

MIRUS International Inc.

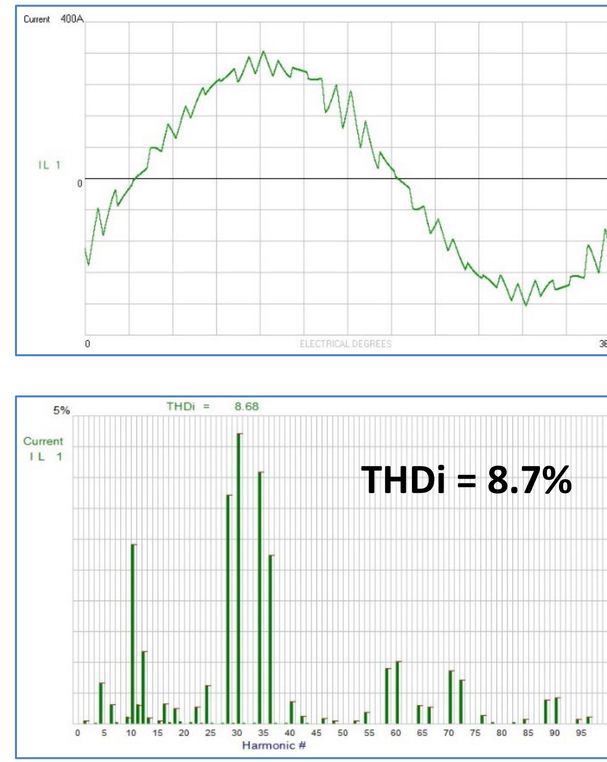
Sinewave Filter Tuned to 10x Fund (600 Hz) with 2 kHz Switching Frequency



Inverter Output PWM Voltage Waveform and Spectrum



Sinewave Filter Output Voltage Waveform and Spectrum

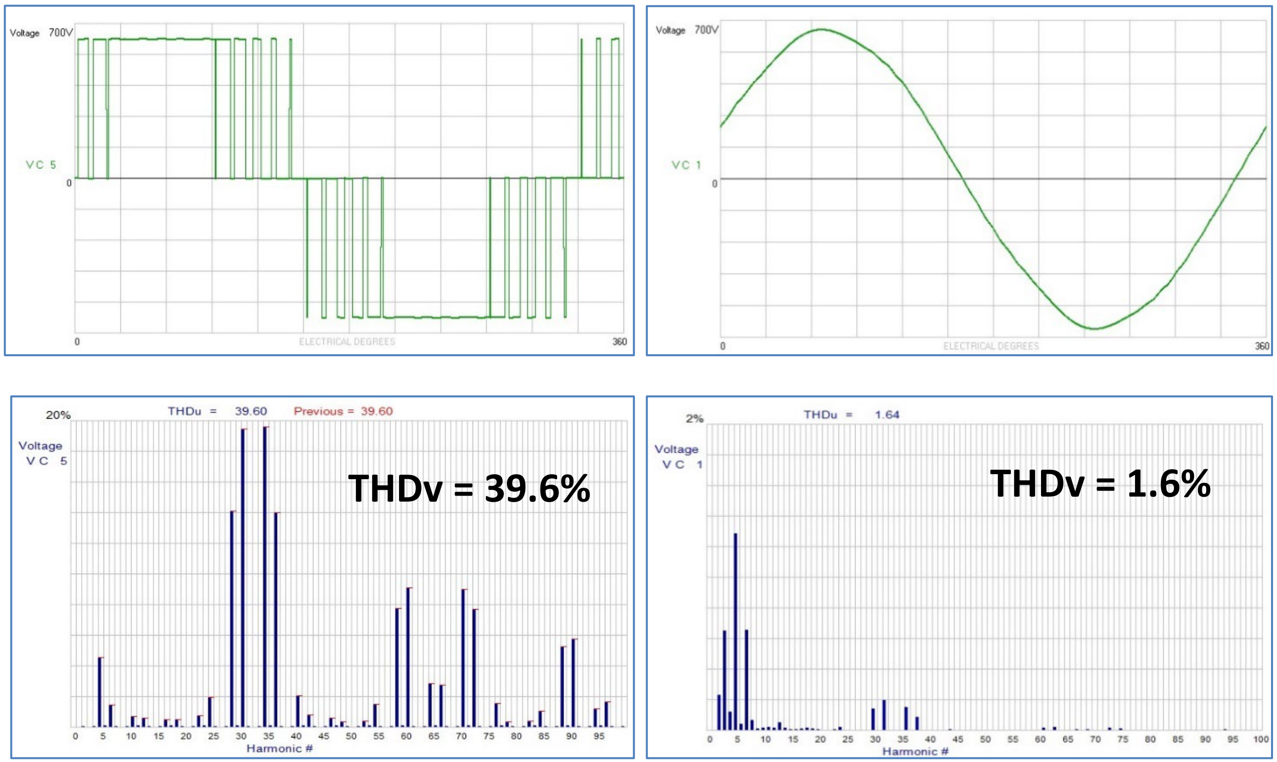


Sinewave Filter Output Current Waveform and Spectrum

New Sinewave Filter Computer Simulations – 200HP, 480V, 60Hz ESP

MIRUS International Inc.

Sinewave Filter Tuned to 3x Fund (180 Hz) with 2 kHz Switching Frequency



Inverter Output PWM Voltage Waveform and Spectrum

Sinewave Filter Output Voltage Waveform and Spectrum

Substantial improvement in voltage distortion, voltage drop and power factor

New Sinewave Filter Improves PF and Reduces Inverter Current

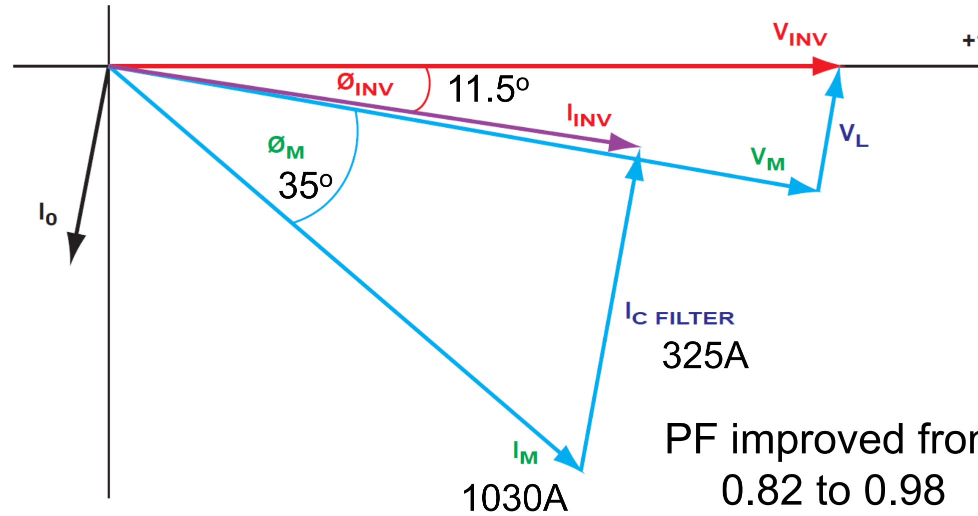
MIRUS International Inc.

- Filter capacitors supply most of the inductive reactive power of motor
- Power Factor is improved to near unity

$$PF = \cos(\text{Ø})$$
$$\text{Ø} = cos^{-1}(PF)$$

- Voltage drop of the filter choke is kept as low as possible
- The resulting RMS current of the inverter is smaller with the filter than without
- Reduces need to oversize VFD for motor

1100HP, 480V, 60Hz ESP



PF improved from 0.82 to 0.98

I_{INV} reduced by 14%

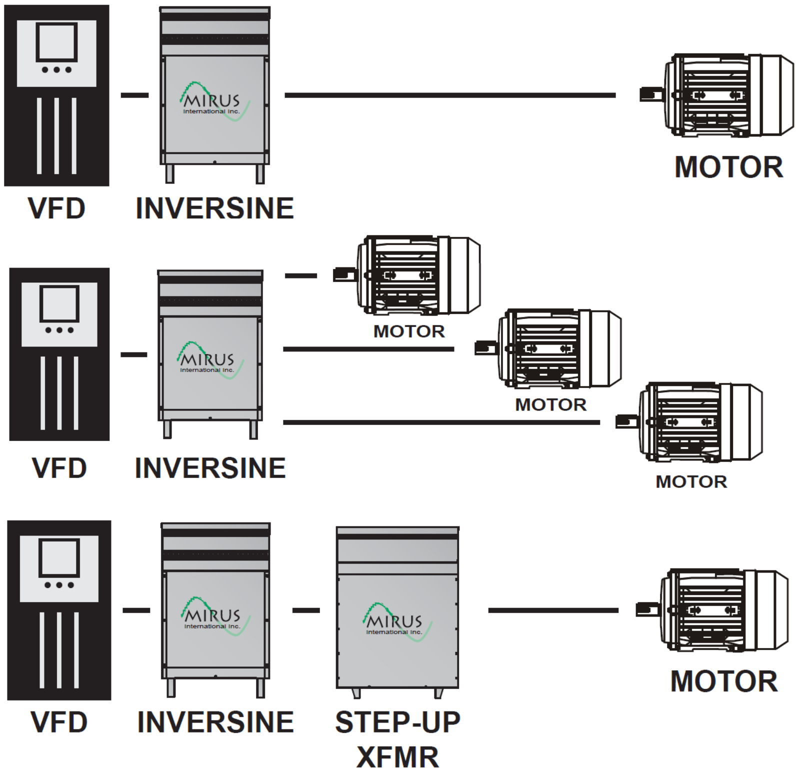
V_{INV} = voltage at the inverter output
V_M = voltage at the motor
V_L = fundamental voltage drop along the cables to the motor
I_{INV} = current at the inverter output
I_M = current at the motor
I_O = no load motor current
$I_{C\ FILTER}$ = capacitive current of the filter

INVERSINE™ Advanced Universal Sinewave Filter (AUSF)

- Low pass filter with cutoff frequency well below the lowest harmonic frequency of the inverter voltage resulting from PWM
  - Filters out high frequency currents while allowing lower frequency fundamental currents to pass
  - < 3% voltage harmonic distortion
  - < 5% current harmonic distortion
  - Without the need for damping resistors
- Prevents
  - Transient overvoltages at motor terminals
  - Additional motor losses
  - Excessive motor noise

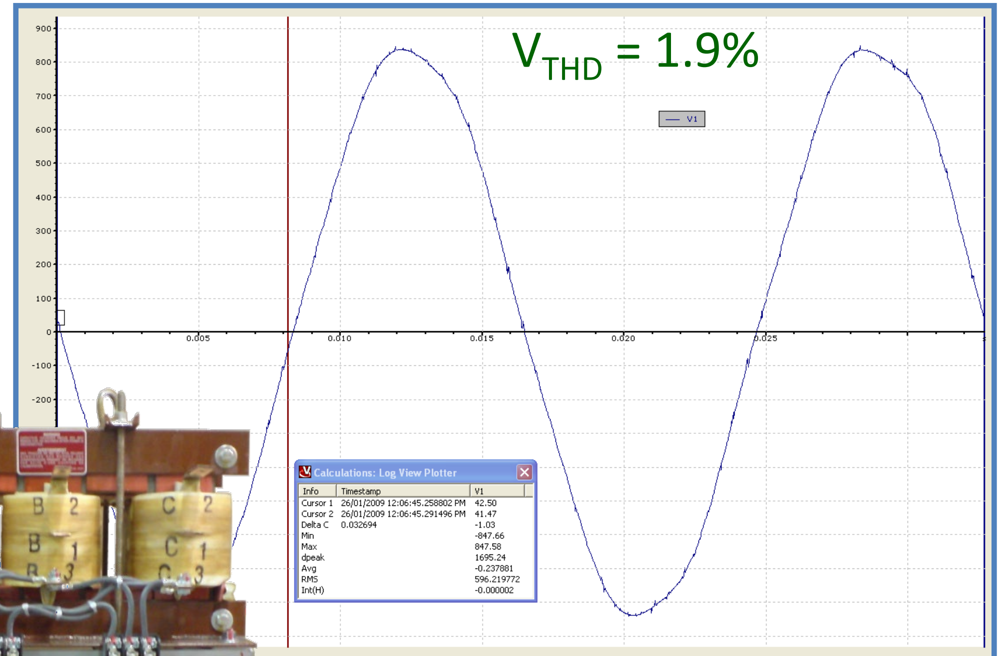
INVERSINE AUSF Applications

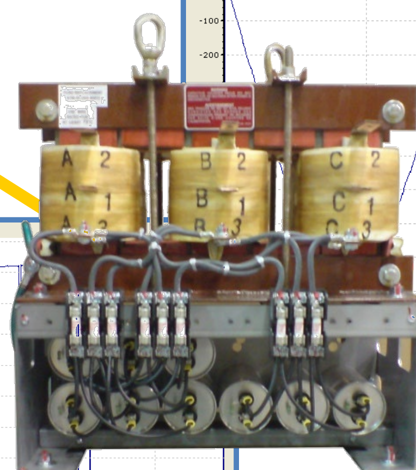
- Motor which has inadequate insulation for ASD duty
- Motor cable length is long, especially ESPs for Oil & Gas and Irrigation
- Number of parallel motors
- Specific requirements for peak voltage level and dV/dt rise time ratio
- To reduce motor noise
- Inverter duty cables not used
- Maximum safety and reliability (ie. Explosion Proof applications)

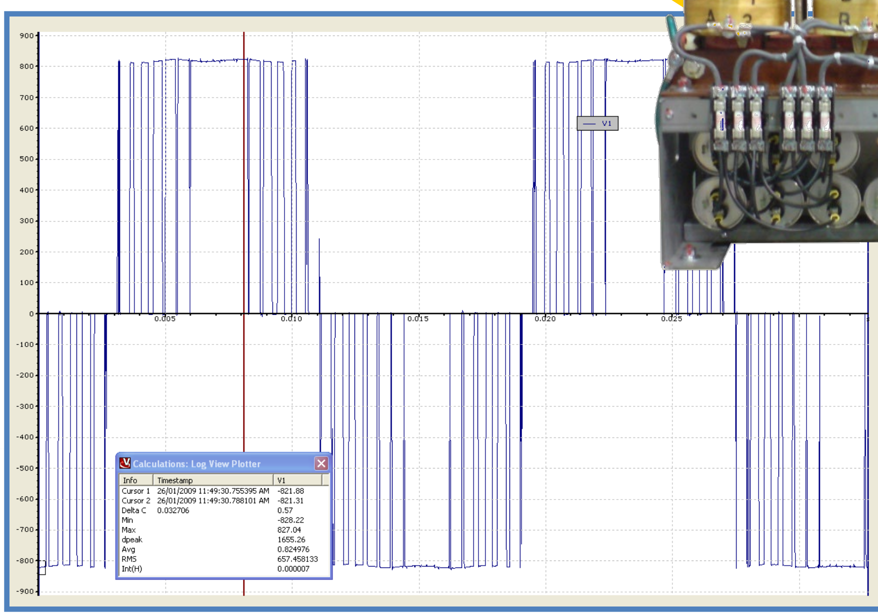


INVERSINE AUSF Performance (Voltage)

< 3% VTHD Typical

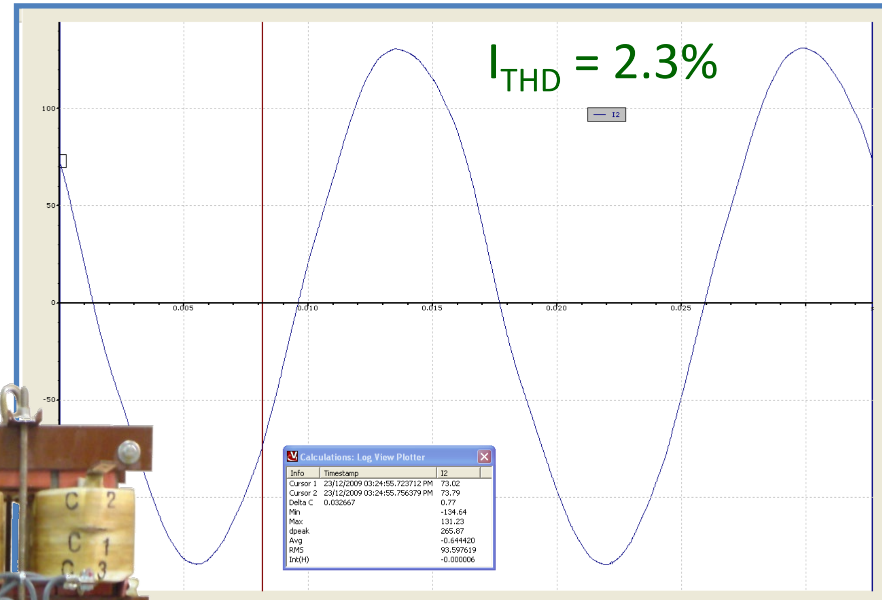


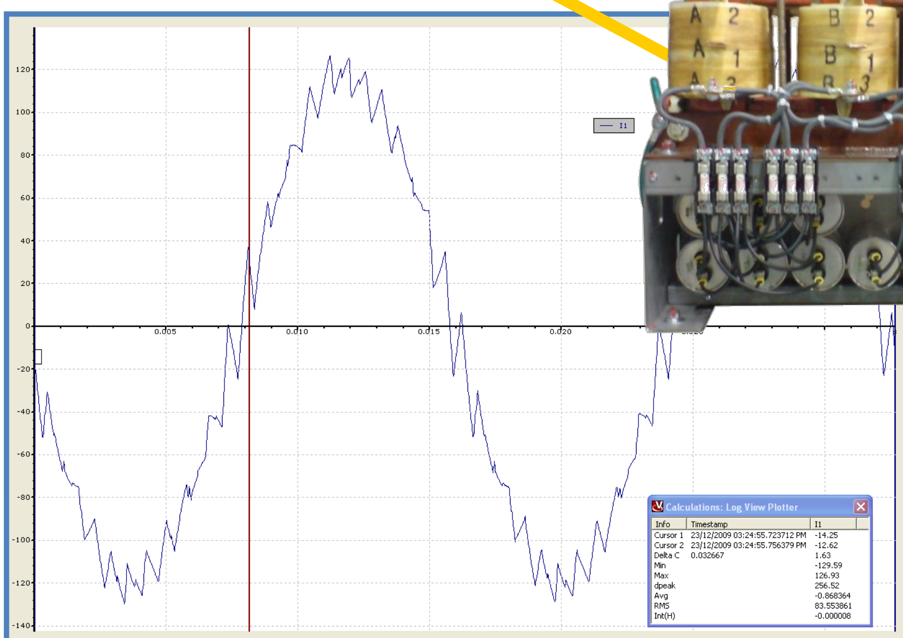


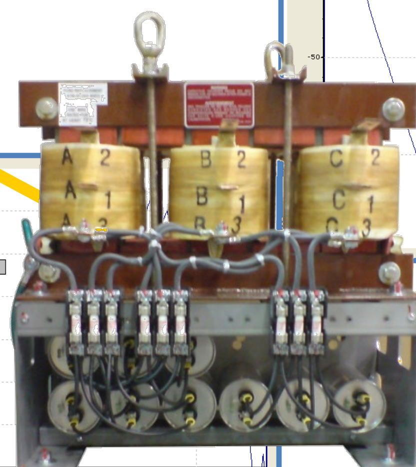


INVERSINE AUSF Performance (Current)

< 8% ITHD Typical







INVERSINE and the Inverter Power

INVERSINE	OTHERS
Low insertion loss resulting in lower voltage drop – < 2.5% of rated voltage	Standard LC filter insertion loss is 10% of rated voltage
No damping resistors required	Damping resistors often required to limit resonance
Highest efficiency > 99%	Often lower than 98% efficiency
VTHD improved to < 3%	VTHD < 5% but not always reached
Improves PF at VFD output	PF at VFD remains low

Common-Mode Voltage

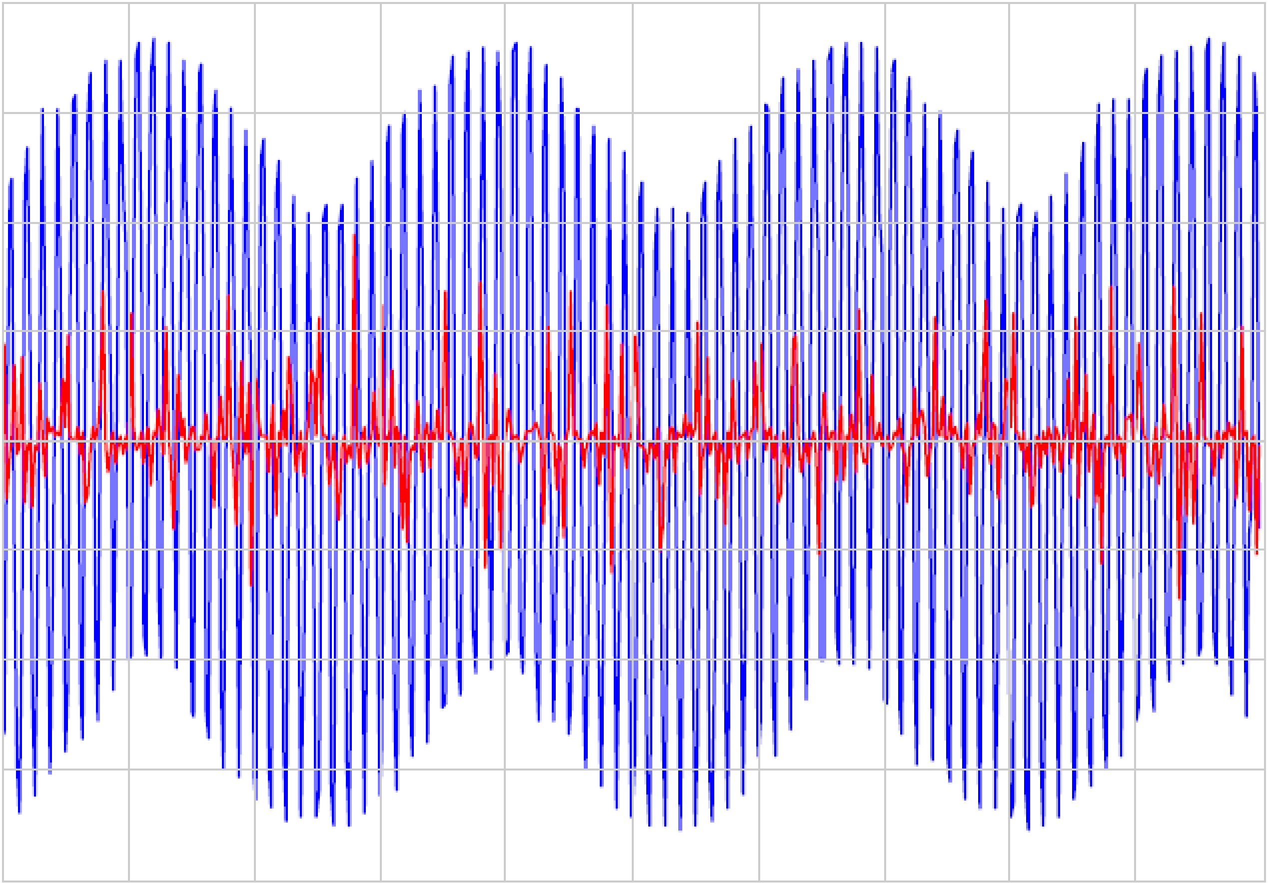
- Motor neutral voltage on a balanced 60Hz or 50Hz utility sine-wave system is zero
- But motor neutral on ASD due to rectangular PWM pulses at high frequency is never zero
  - Although sum of average 3-ph voltages is zero, an instantaneous sum of 3-ph voltages is not zero resulting in neutral point shift voltage (Common-Mode Voltage)
- Common-Mode voltage induces shaft voltage and generates bearing currents in motor
- Common-mode currents cause motor bearing failures and other motor issues

Reference: *'Inverter Driven Induction Motor Bearing Current Solutions' IEEE PCIC-2002-08*

Measured ASD Neutral-Ground Voltage

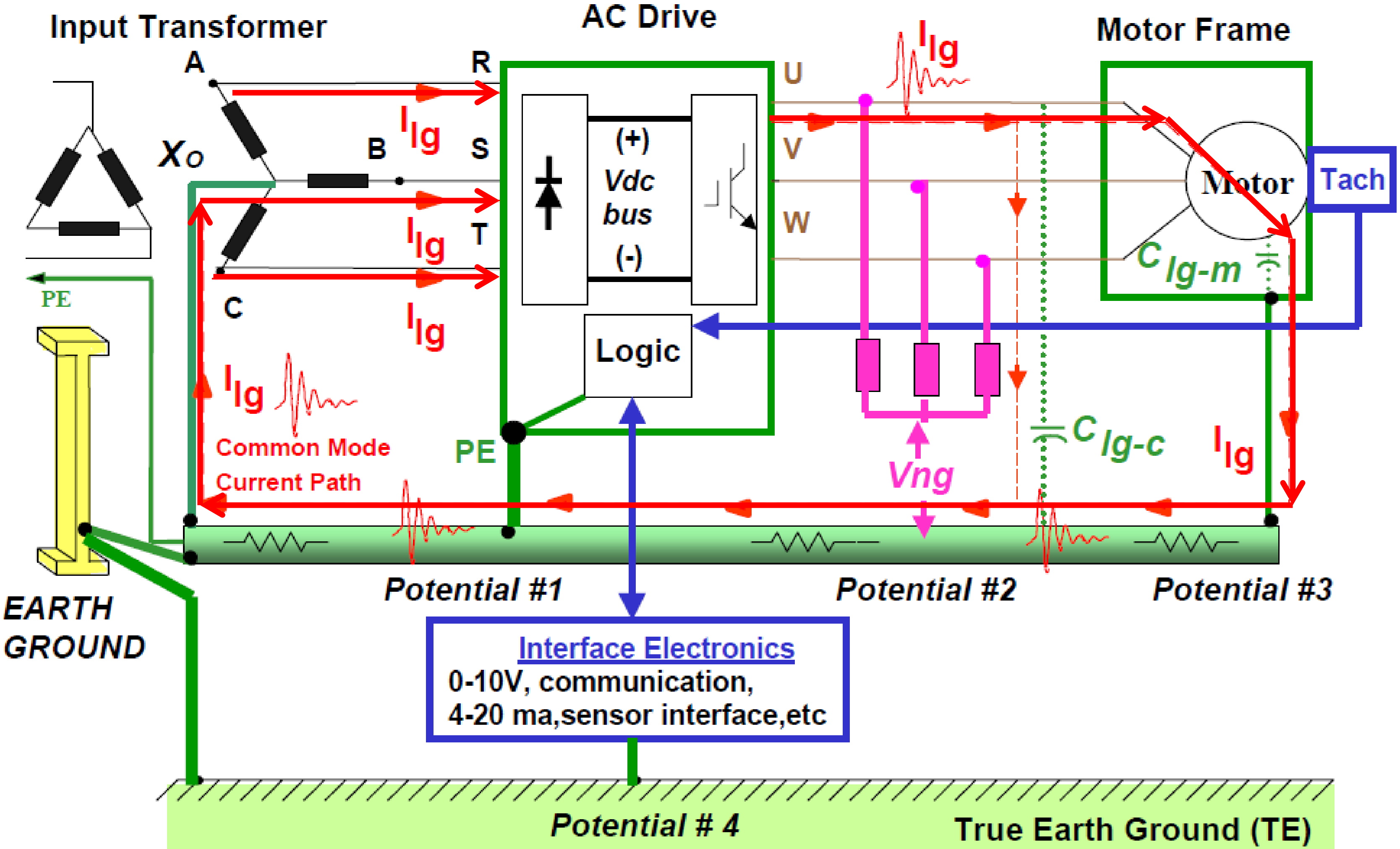
V_{ng} neutral-to-ground voltage

I_{lg} CM current



Parasitic Line-Gnd Common-Mode Path in a Solidly Grounded ASD System

EMI EMISSIONS of MODERN PWM AC DRIVES
Gary L. Skibinski, Russel J. Kerkman, and Dave Schlegel
IEEE Industry Applications Magazine, November/December 1999, pp. 47-81.

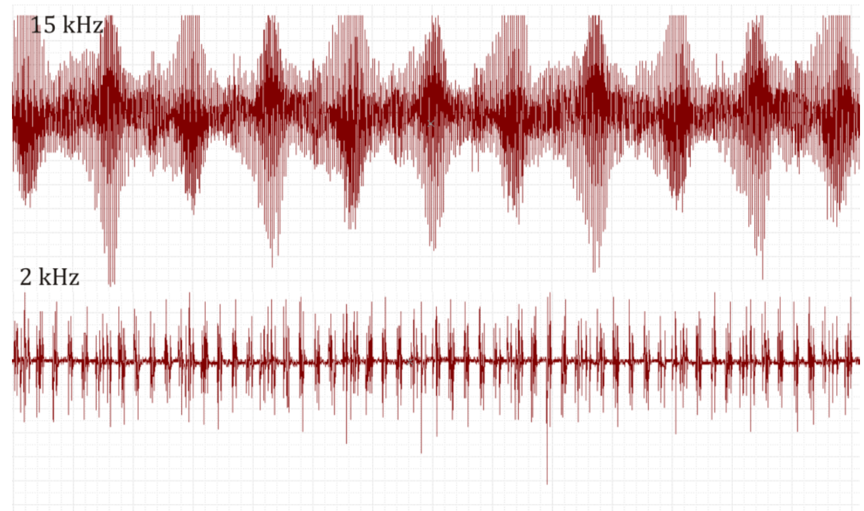


INVERSINE AUSF with CM Choke

- Standard INVERSINE differential mode filtering
  - < 3% VTHD
- Built-in common-mode choke
  - >25 dB attenuation in switching frequency range (2 - 8kHz)
  - > 40dB in 100kHz to 1MHz frequency range
  - Reduce common-mode voltages throughout power system
  - Reduce shaft voltage and bearing currents
  - Reduces cable leakage current
  - Reduces EMI/RFI

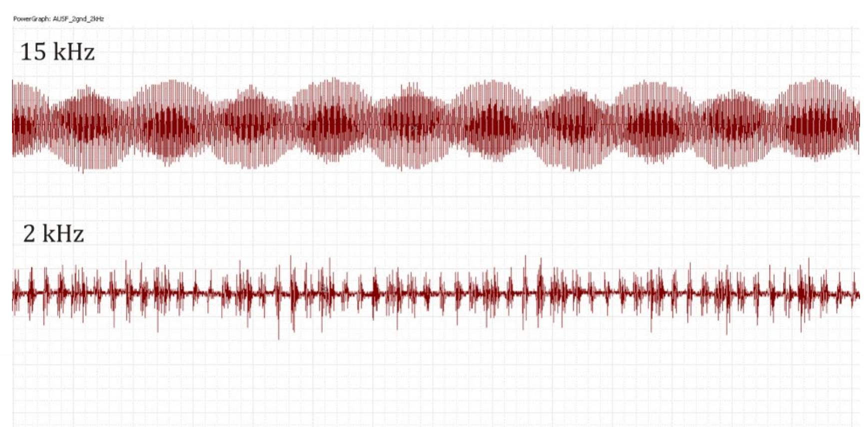
Common-Mode Testing – 7.5 HP VFD

- Common-mode current without sinewave filter or common-mode choke
  - 15 kHz = 2.690A
  - 2 kHz = 1.112A



- Common-mode current with sinewave filter
  - 15 kHz = 1.733A
  - 2 kHz = 0.756A

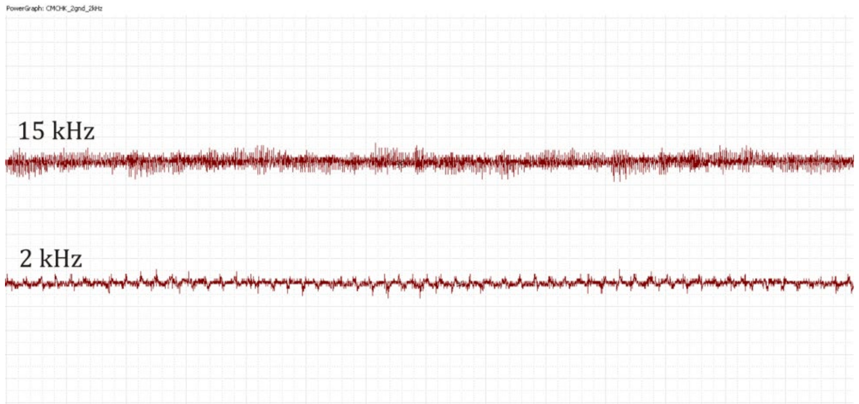
  (up to 1.5x reduction)



Common-Mode Testing – 7.5 HP VFD

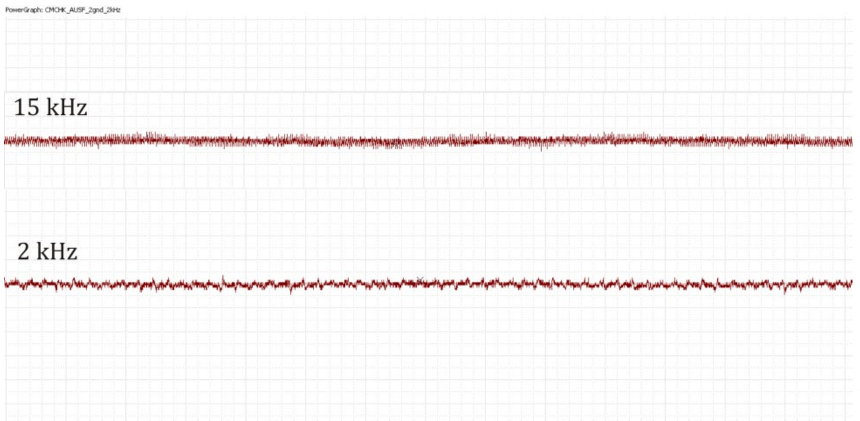
- Common-mode current with only common-mode choke
  - 15 kHz = 0.353A
  - 2 kHz = 0.238A

  (up to 7.5x reduction)



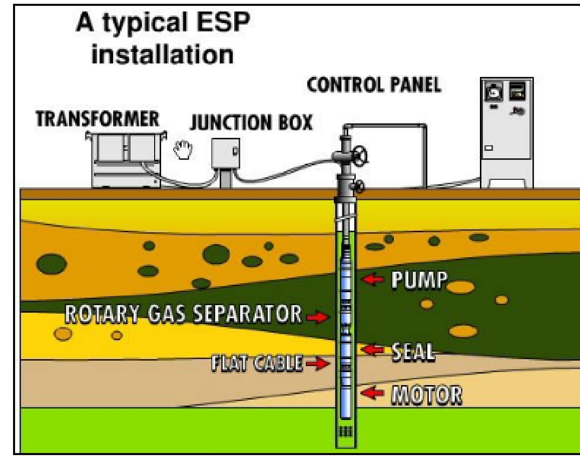
- Common-mode current with sinewave filter and common-mode choke
  - 15 kHz = 0.229A
  - 2 kHz = 0.202A

  (up to 10x reduction)



Case Study 1 – Sinewave Filter Replacement in Midwest USA Oilfield Retrofit

200HP, 480V Inversine Sinewave filter replaced an existing filter on an electrical submersible pump (ESP)

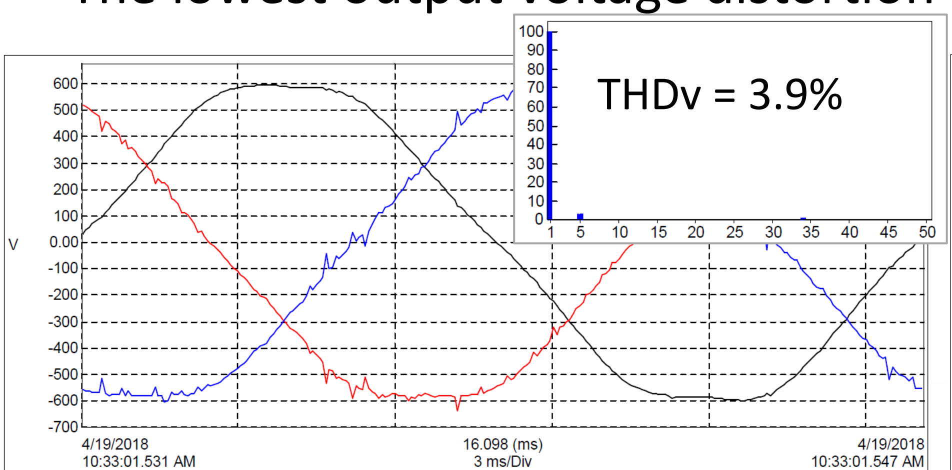


Challenge:

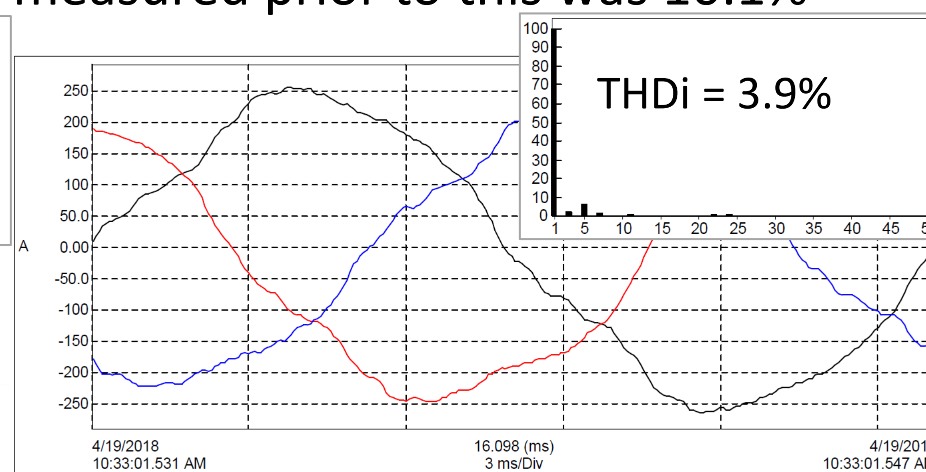
- Capacitors on existing filter were failing frequently and performance was poor

Results:

"The lowest output voltage distortion measured prior to this was 10.1%"



VFD Output Voltage



VFD Output Current

Case Study 2 – Sinewave Filter Replacement in Midwest USA Oilfield Retrofit

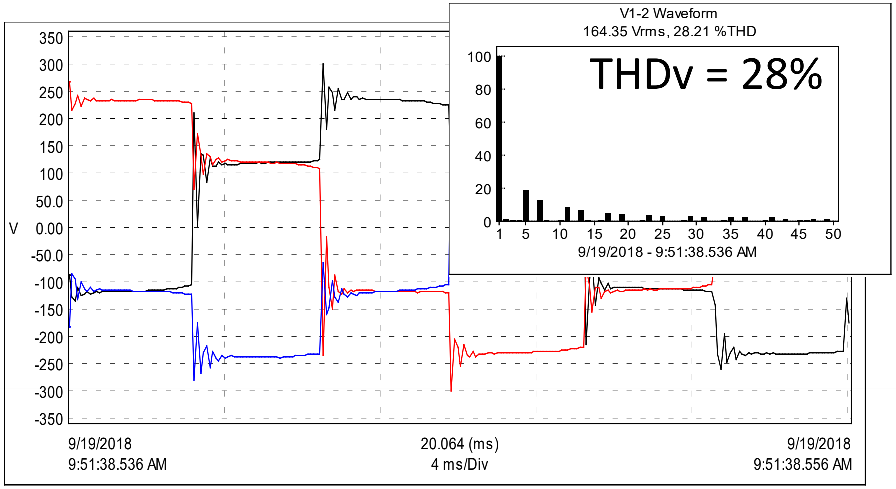
1100HP, 480V Inversine Sinewave filter replaced an existing filter on an electrical submersible pump (ESP)

Challenge:

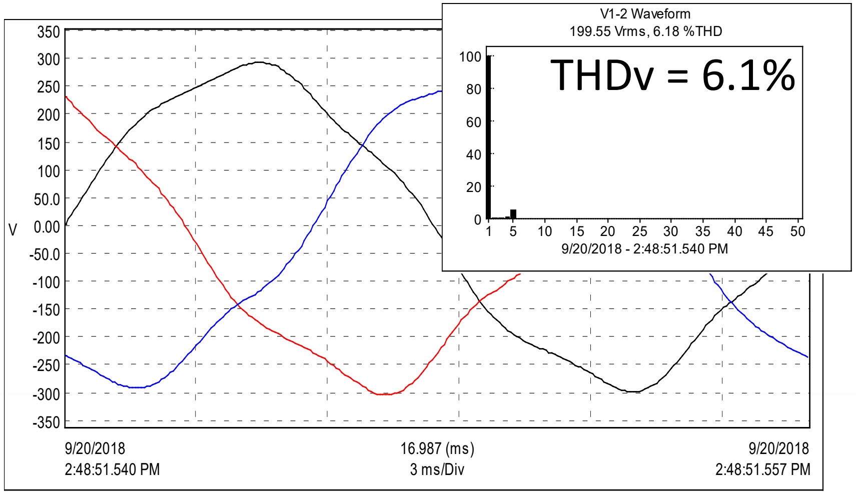
- Motors failing in 6-Step Operation

Results:

- Total elimination of overvoltages and ringing
- < 3% voltage drop (other filters > 10%)



Voltage to Motor in 6-Step Mode

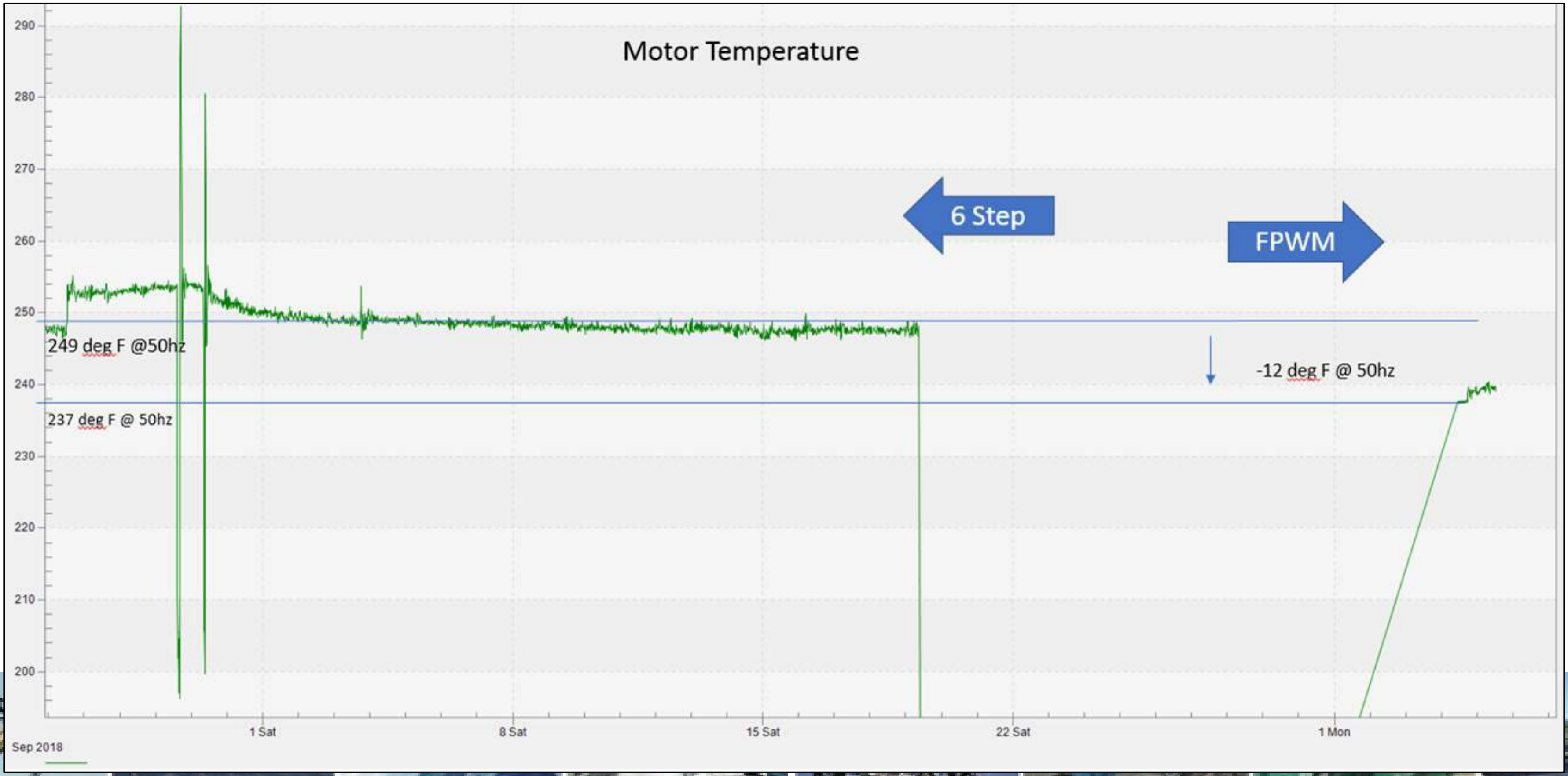


Voltage to Motor in PWM with Filter

Case Study 2 – Sinewave Filter Replacement in Midwest USA Oilfield Retrofit (cont.)

Results (cont.):

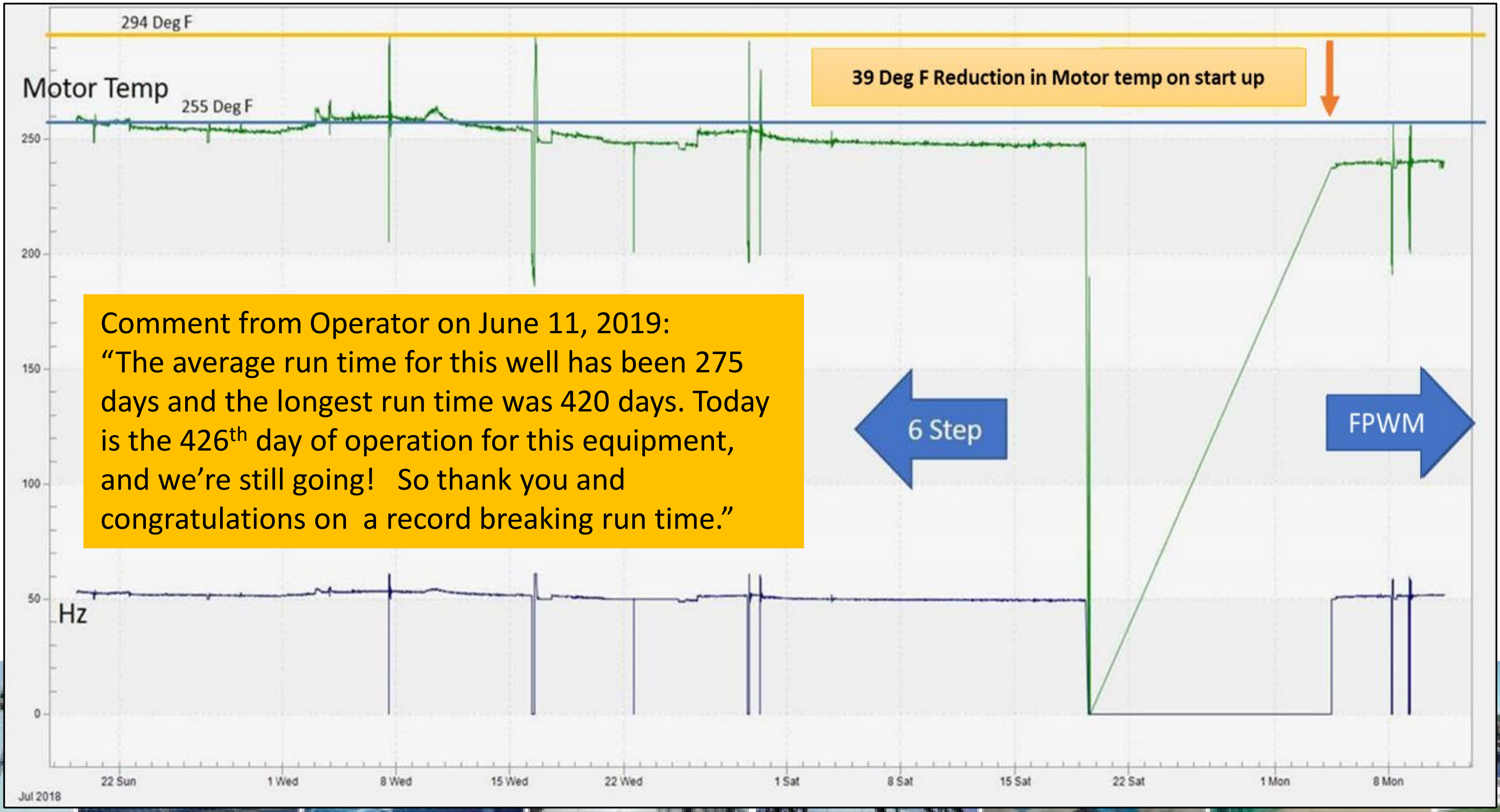
Motor Temperature Reduction with 1100HP, 480V Inversine Sinewave Filter: 12° F at 50Hz Operation



Case Study 2 – Sinewave Filter Replacement in Midwest USA Oilfield Retrofit (cont.)

Results (cont.):

Drop in Motor Operating Temperature with 1100HP, 480V Inversine Sinewave Filter: 39° F at Motor Startup



Comment from Operator on June 11, 2019:
"The average run time for this well has been 275 days and the longest run time was 420 days. Today is the 426th day of operation for this equipment, and we're still going! So thank you and congratulations on a record breaking run time."

Case Study 2 – Sinewave Filter Replacement in Midwest USA Oilfield Retrofit (cont.)

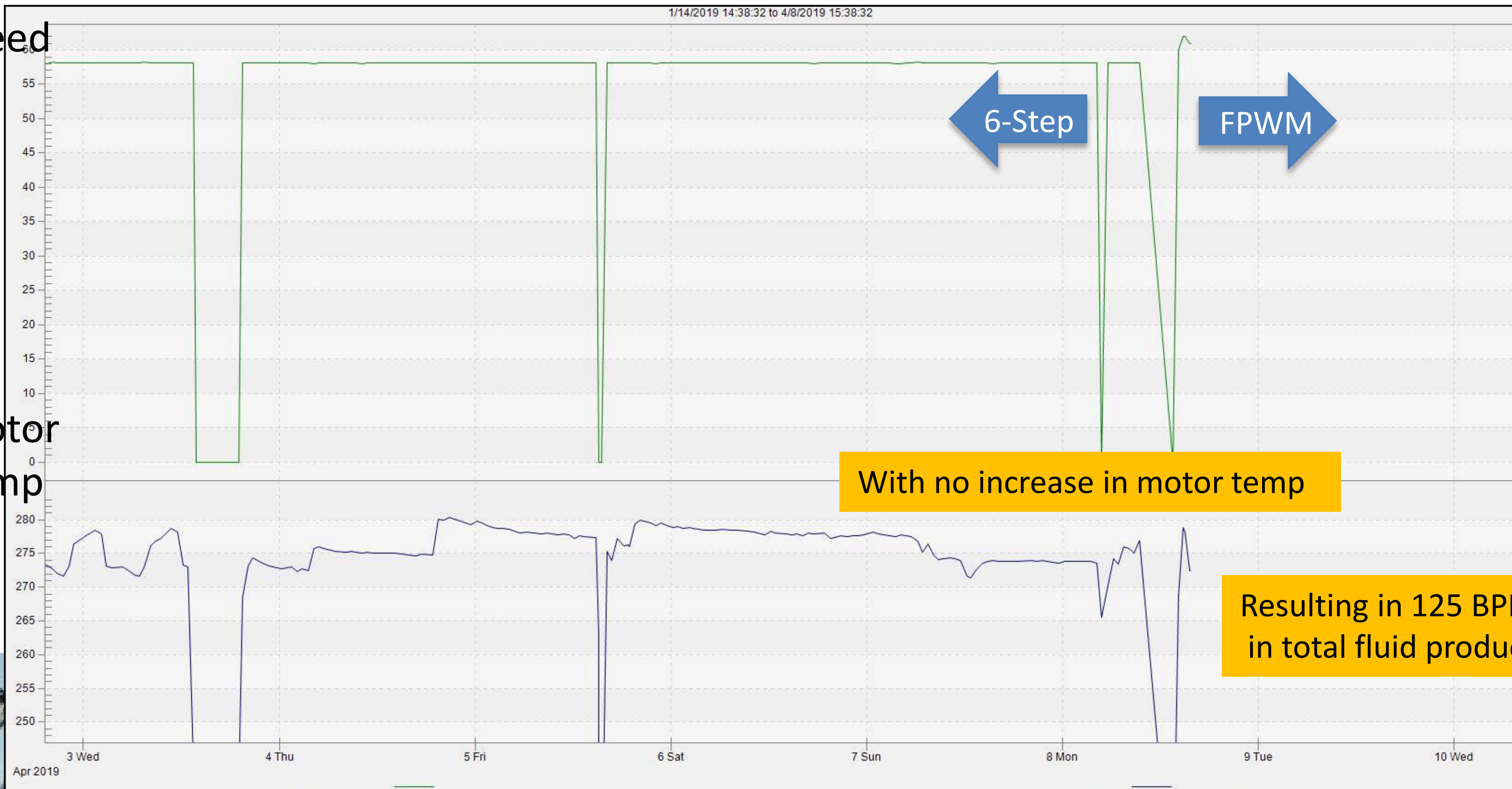
Results (cont.):

At a second site where a similar 1100HP, 480V Inversine Sinewave Filter was installed

Max VFD Speed increased to 62 Hz from 58Hz

VFD Speed

Motor Temp



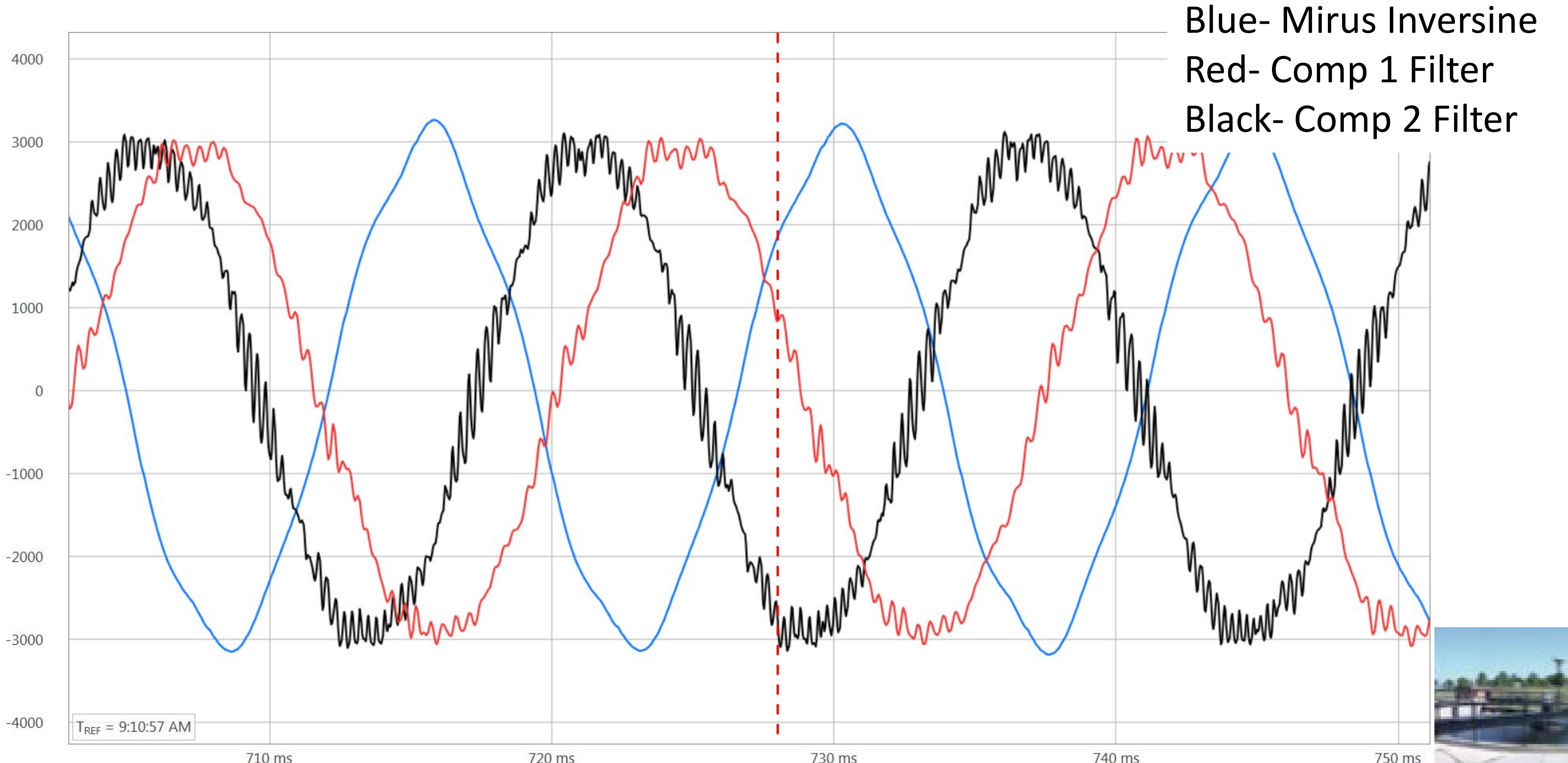
With no increase in motor temp

Resulting in 125 BPD increase in total fluid produced

Case Study 2 – Sinewave Filter Replacement in Midwest USA Oilfield Retrofit (cont.)

Results (cont.):

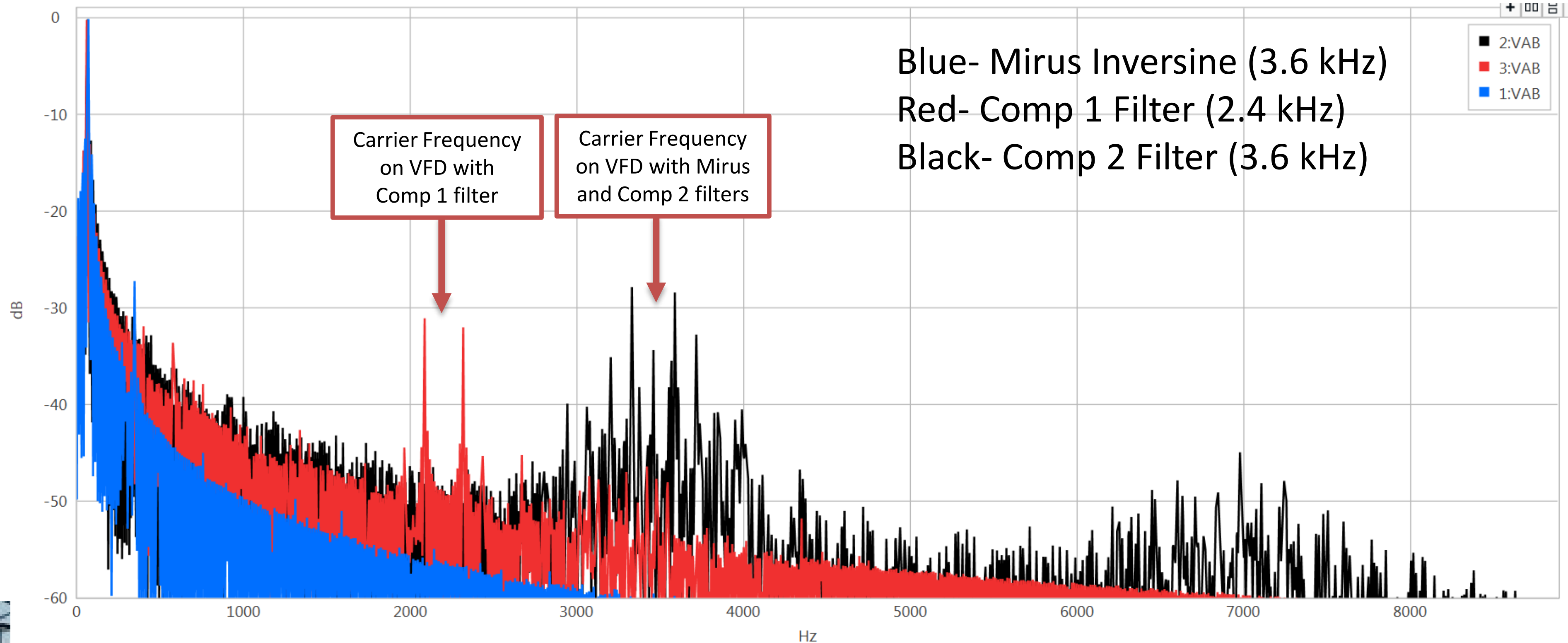
Voltage Waveform comparison of Mirus Inversine vs two other competitive sinewave filters in similar ESP applications

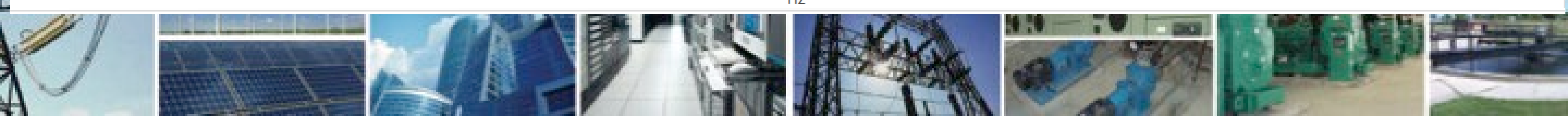


Case Study 2 – Sinewave Filter Replacement in Midwest USA Oilfield Retrofit (cont.)

Results (cont.):

Voltage Spectrum comparison of Mirus Inversine vs two other competitive sinewave filters in similar ESP applications





Summary

- The use of PWM Drives can lead to motor problems, cable issues and high EMI/RFI
- Mirus INVERSINE Advanced Universal Sine-Wave Filter will eliminate or reduce these problems by:
  - Substantially reducing voltage rise time (dV/dt)
  - Converting output voltage to near sinewave (<3% VTHD)
  - Lowering harmonic losses and temperature in motor
  - Reducing motor and cable insulation stress
  - Reducing motor noise
- Available common-mode blocking option will:
  - Reduce shaft voltage and bearing currents
  - Reduce cable leakage currents
  - Reduce common-mode voltages throughout power system

Discussion

Questions and feedback

Contact: Garrett Sandwell

info@vibescorp.ca

also check a related article titled "**Learn About Shaft Currents**"

Thank You

MIRUS International Inc.

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(Fan Doctor®)

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