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MIRUS International Inc.

E.T.C.
Engineering Technology Conference 2025

Specificational Notes for VFD Secondary Circuit Design

HELSF – ETC Conference, April 16th, 2025

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Overview:

There are four VFD Secondary Circuit considerations that can compromise the life expectancy of VFD driven motors, cable installations, and load mechanical equipment:

- PWM Output Waveform Harmonics
- Resonance/Reflective Wave
- Transient Voltage Events
- Common Mode Noise

Line side VFD harmonics is a well understood condition with an IEEE standard that covers harmonic distortion/circuit design criteria, but no standard exists to cover the VFD output circuit design and performance requirements. This presentation will cover the above four conditions and discuss design options to avoid secondary circuit damage and extend the life cycle of the installation.

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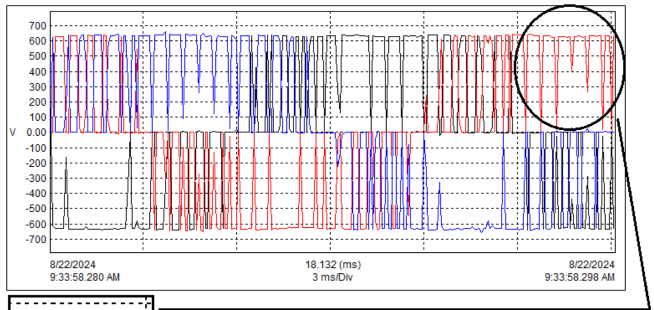
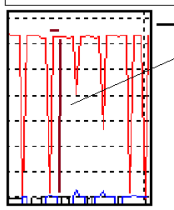
PWM Output Waveform Harmonics Discussion:

This is a wave-trace of a typical VFD output PWM waveform. As can be seen, there is a repetitive zero to peak voltage sequence exposing the secondary circuit components, cabling, and motor to high dv/dt stress. This is typically referred to as differential noise and will lower the life cycle of the load structures unless the load components are built to an "Inverter Duty" specification. Therefore, inverter duty rated motors and shielded inverter duty rated cables will be required. These enhancements are very expensive as compared to standard cable and standard induction motors.





The change in voltage as compared to time OV to peak voltage negative and positive sequence, dV/dT slope of the change creates significant dielectric stress on the entire secondary circuit and all electrical components within.

Secondary Inductors and dv/dt filters do not change this waveform, not addressing the dielectric stress created by the PWM output voltage waveform.

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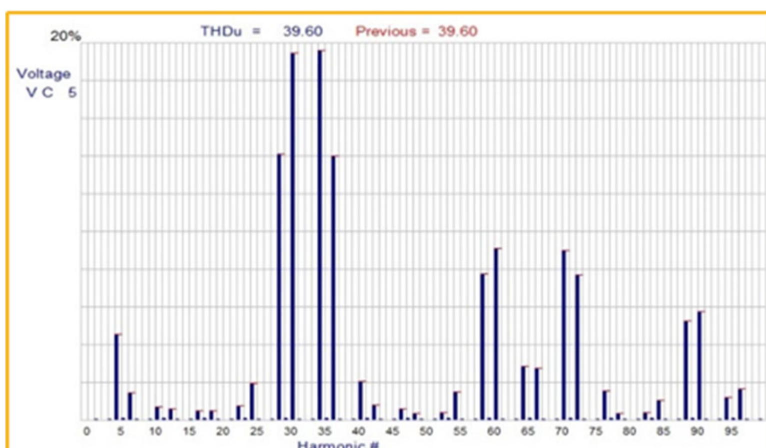
Specification Notes for VFD Secondary Circuit Design to Prevent Resonance & Common Mode Noise

The associated voltage distortion of a PWM waveform can be as high as 40% and will be centered around the switching speed of the inverter.

This harmonic source will generate elevated levels of eddy current loses and significant di-electric stress on components of the secondary circuit including the cable insulation systems and motors, as well as incremental heating due to harmonic injection.



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PWM Output Waveform Harmonics Discussion:

- The injection of high frequency voltage harmonics into to the secondary circuit will introduce excessive eddy current loses and increase motor heating during operation.
- The high dV/dT associated with a PWM voltage source increases the associated dielectric stress on the entire secondary circuit, motor, and cable.
- This same dV/dT, depending on the secondary impedance characteristics, can create secondary circuit ringing/reflective wave conditions which can compromise the insulation P-P and P-G of the motor and cables.
- Without proper secondary circuit design, common mode noise can impact motor bearings via partial discharge and secondary cable runs due to parasitic capacitance, significantly reducing the life expectancy of motors and cables.

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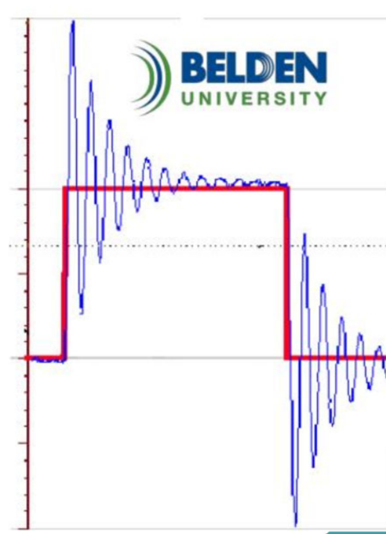
Resonance/Reflective Wave Discussion:

A very good explanation of reflective wave impacts is contained with the Eaton library. Here, they refer to it as ringing… As noted, it is a function of the dV/dt associated with inverter operation and confirms the relationship between dV/dt levels and cable lengths. I would suggest you download and read this applicational note as it is very insightful.

Eaton Application Note AP040013EN Effective August 2013

"… dV/dt also influences another phenomenon associated with long transmission lines which tends to cause a "ringing" effect, resulting in voltage peaks at the motor. Voltage peaks will begin at a small value and continue to increase in magnitude as cable length increases. Higher dV/dt levels cause the larger voltage peaks to develop at even shorter cable lengths. It is possible that voltage peaks might become as large as double the internal DC "Bus" voltage, corresponding to nearly 1500 volts peak for a 480 VAC rated AFD. Voltage peaks at this level are capable of damaging a standard motor."



Best Practices for VFD Cabling . Peter Cox P.Eng . Project Manager Belden Industrial Cable

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Resonance/Reflective Wave Discussion:

Output Reactors and dV/dT filters function to lower the dV/dT slope of the PWM waveform however the output is still a PWM waveform, and a significant dielectric stress factor will still exist. Functionally, these two devices are shifting the resonance point of the secondary circuit and do little to improve the energy efficiency of the secondary circuit and resonance/ringing effects can still be present.

Given that PWM output waveforms have characteristically high levels of dV/DT, the use of a sinewave filter is recognized as the most effective means for controlling resonance, ringing, and reflective wave conditions which impact the life expectancy of cables and motors.

The faster the switching frequency and longer the cable run length the greater the likelihood of developing reflective wave. Some studies have noted that ringing/reflective wave can be witnessed in cable runs as short as 50' at 480V. The resonance point is a function of the overall secondary impedance (not just the length of the cable) as well as the switching speed of the inverter.

The presence of ringing/reflective wave due to secondary circuit resonance is easy to diagnose. Simply take a scope trace of the secondary circuit voltage waveform during the ramp and at nominal speed to observe the presence of any instability and/or transient effects during the test cycle.

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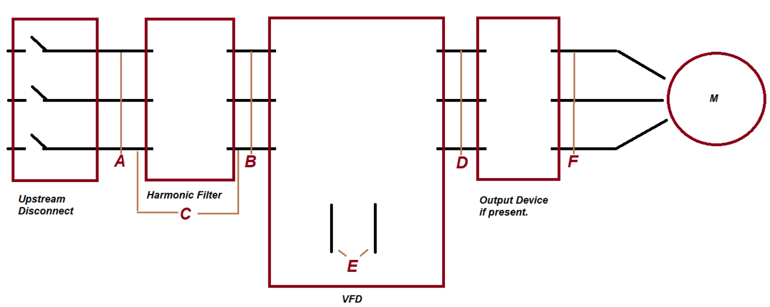
Resonance/Reflective Wave Discussion:

Resonance & reflective wave can occur on both the output of the VFD and between the DC bus capacitance and the source impedance. During the VFD start-up it is recommended to test the line and load side of the VFD at the same time per the diagram below:



A: Line Side harmonic measurement at nominal load to ascertain IEEE 519 compliance
B: VFD Line Side Testing, if there is no harmonic filter then this would functionally be test A.
C: A comparative test of line and load can be used to determine proper operation of the harmonic filter.
D: VFD Output Testing, to ascertain a normal and proper PWM output.
E: DC Bus measurement trace can document and confirm a stable DC bus voltage waveform.
F: Output device measurement, used to ascertain proper operation of the output inductor, dv/dt filter or Sinewave filter If there is no output device, then test point E, should be used to ascertain a proper output waveform w/o ringing or reflective wave.

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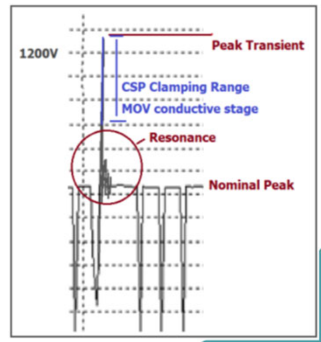
Transient/Surge Voltage Event Discussion:

Secondary VFD circuit Transient/Surge Protection is not often recognized or discussed, but it is quite often present when a reflective wave condition is present.

Functionally, it is an “Over-shoot of the PWM dv/dt” as shown in the graphic to the right.

The MOV topology CSP – Coordinated Surge Protection - will begin to conduct at ~950V with a full clamping at ~ 1500V, minimizing dielectric stress during the transient and surge event. When coordinated with the capacitance element of the sinewave filter, typical transients and surges have little effect on the motor, load, or the integrity of a VFD inverter.



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Transient/Surge Voltage Event Discussion:

The primary specificational criteria for selecting a properly coordinated transient/surge protector is to require the following:

- PEAK LET-THROUGH VOLTAGE: No greater than 1500V for 480V rated installations.
- PEAK SURGE CURRENT (PER MODE / PER PHASE): 480/600V applications -100 kA / 200 kA
- MCOV: 480V Applications - 550 L-L & L-G, 600V Applications: 840 L-L & L-G
- Low impedance internal circuitry designed with very low let through voltage levels coordinated below most harmonic filtered drive circuit withstand limits.
- Factory integrated within the sinewave filter/secondary protective assembly and installed with the shortest practical lead length to maintain a low let-through voltage.
- LED status lights factory installed on enclosure exterior.
- Two types of fusing: Component level thermal fusing and phase level fault current fusing.
- Metal oxide varistor (MOV) design with fast reaction time (<1ns).

WARRANTY: 15 years unlimited free replacement on CSP (Coordinated Surge Protection) component. When factory installed on Lineator AUHF harmonic filter product or an Inversine AUSF sinewave filter, the complete AUHF or AUSF filter product warranty is increased by an additional 24 months, i.e., 5 years total vs. 3 years.

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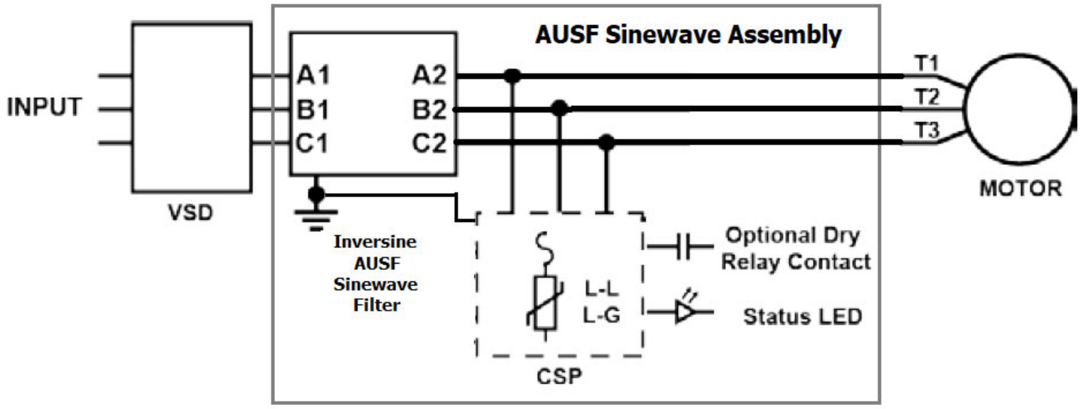
Transient/Surge Voltage Event Discussion:



Installation One-Line

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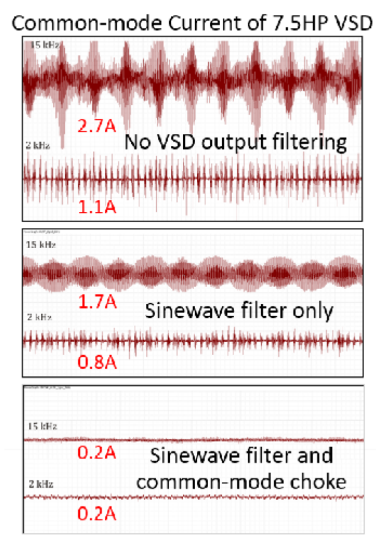
Common Mode Noise Discussion: Challenge

- The damage from common mode noise within the secondary circuit is created by partial discharge across the motor bearings and associated mechanical load structures, and parasitic capacitance compromising cable insulation to the system ground.
- The graphic to the right highlight's common mode levels on a 7.5 HP VFD highlighting the substantial high frequency currents associated with common mode noise within the secondary circuit. It also shows that a Sinewave filter is not a viable solution for the common mode challenge. As the motor HP/load increases, the associated CM noise current levels will increase in a non-linear growth rate.
- The remedy to avoid premature motor and cable failures is to eliminate potentially destructive dielectric stress (dv/dt) by converting the PWM waveform to a sinusoidal and using a Common Mode Choke to reduce common mode noise.



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Common Mode Noise Discussion: Challenge

- Common-mode is the phase-to-ground voltage that appears due to the instantaneous sum of the 3-phase voltages of the PWM inverter not being zero even when the sum of the average 3-phase voltages is zero.

- Common-mode voltages will induce common-mode currents to flow through parasitic capacitance in the motor and motor feeder cable. High frequency capacitive coupling exists across the motor bearings and between the feeder conductors or motor windings and ground.

- Common-mode currents can lead to premature motor bearing failure and cable insulation breakdown.

- The Common Mode Choke option will:
  - ~ Reduce shaft voltage and bearing currents
  - ~ Reduce cable leakage currents
  - ~ Reduce common-mode voltages throughout power system

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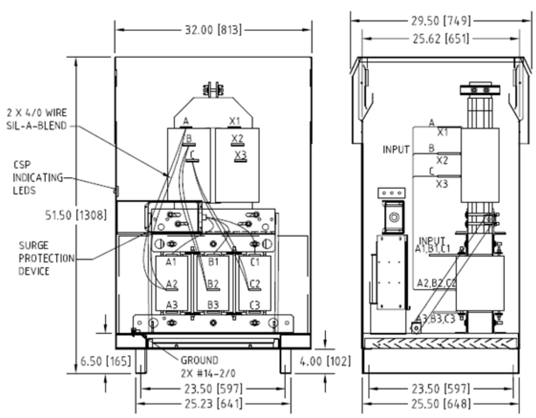
Total Secondary Circuit Solution: *Sinewave Filter, Common Mode Choke w/ CSP*



Front View Side View

If you combine the sinewave filter, common mode choke and coordinated surge suppression (CSP) into a single assembly/solution, the customer/user may be able to avoid the need for shielded inverter duty rated cables and utilize standard induction motors versus inverter duty rated motors while increasing the efficiency and life cycle of the secondary installation and ***reducing the overall cost of the project***.

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Sinewave Filter with Common Mode Choke: Potential Cable & Motor Savings

	Shielded Inverter Duty Cable: 3C 350 MCM w/Ground					XHHW: 1C 350 MCM with single #3 Ground per conduit run					
Distance from Drive to Motor	Associated Cable Length	Typical Minimum Cable Purchase	$/Foot	Cable Cost without a minimum purchase Requirement	Cable Cost based on 1000' reel minimum	Associated Cable Length	No Minumum Cable Purchase Typ.	$/Foot 1C 350 MCM with Ground Conductor avg.	XHHW Cable Cost	Cable Cost Savings 1000"/reel minimum using XHHW versus Inverter Duty Rated Cable	Cable Cost Savings w/o minimum reel purchase using XHHW versus Inverter Duty Rated Cable
50'	50	1000	$ 72.90	$ 3,645.00	$ 72,900.00	150	150	$ 10.75	$ 1,612.50	$ 71,287.50	$ 2,032.50
100'	100	1000	$ 72.90	$ 7,290.00	$ 72,900.00	300	300	$ 10.75	$ 3,225.00	$ 69,675.00	$ 4,065.00
150'	150	1000	$ 72.90	$ 10,935.00	$ 72,900.00	450	450	$ 10.75	$ 4,837.50	$ 68,062.50	$ 6,097.50
200'	200	1000	$ 72.90	$ 14,580.00	$ 72,900.00	600	600	$ 10.75	$ 6,450.00	$ 66,450.00	$ 8,130.00
300'	300	1000	$ 72.90	$ 21,870.00	$ 72,900.00	900	900	$ 10.75	$ 9,675.00	$ 63,225.00	$ 12,195.00
500'	500	1000	$ 72.90	$ 36,450.00	$ 72,900.00	1500	1500	$ 10.75	$ 16,125.00	$ 56,775.00	$ 20,325.00
750'	750	1000	$ 72.90	$ 54,675.00	$ 72,900.00	2250	2250	$ 10.75	$ 24,187.50	$ 48,712.50	$ 30,487.50
1000'	1000	1000	$ 72.90	$ 72,900.00	$ 72,900.00	3000	3000	$ 10.75	$ 32,250.00	$ 40,650.00	$ 40,650.00

Typical Cost of Mirus Inversine Sinewave Filter with Common Mode Choke @ 200HP/480V = $10,670 w/o freight Designation: AUSF-CMC

The difference in motor cost between non inverter duty rated and inverter duty rating is $1,200.00 for a 200 hp vertical motor. $57997.00 for a Std. Induction Motor vs. $59214.00 for an Inverter Duty Rated Motor

Beldon 29534 350-3C-2000V UL, 1000V C (UL) cost $72.90/foot, Minimum purchase by most distributor outlets, 1000' per reel

Single conductor 350 MCM XHHW-2 cost $10.11 per foot. A #3 ground is needed at $1.92 per foot. So, the comparison for cable costs per foot so averaging the ground would result in a $10.75/ft average with the ground

Assumed same labor and conduit Cost for both installations

Distance from Drive to Motor	Inverter Duty Motor Cost	Induction Motor Cost	Motor Cost Savings	1000'/reel minimum Cable Cost Saving	No Minimum/Reel Cable Cost Saving	Less AUSF-CMC Inversine Sinewave Filter Cost	Cable & Motor Cost Saving based on using XHHW versus Inverter Duty Rated Cable - 1000" Reel	Cable & Motor Cost Saving based on using XHHW versus Inverter Duty Rated Cable - no Minimum Reel Length	Output Reactor Saving: $2063.00 Estimated	Output DV/DT savings: $2675.00 Estimated
50'	$ 59,214.00	$ 57,997.00	$ 1,200.00	$ 71,287.50	$ 2,032.50	$ 10,670.00	$ 61,817.50	$ (7,437.50)	$ (5,374.50)	$ (4,762.50)
100'	$ 59,214.00	$ 57,997.00	$ 1,200.00	$ 69,675.00	$ 4,065.00	$ 10,670.00	$ 60,205.00	$ (5,405.00)	$ (3,342.00)	$ (2,730.00)
150'	$ 59,214.00	$ 57,997.00	$ 1,200.00	$ 68,062.50	$ 6,097.50	$ 10,670.00	$ 58,592.50	$ (3,372.50)	$ (1,309.50)	$ (697.50)
200'	$ 59,214.00	$ 57,997.00	$ 1,200.00	$ 66,450.00	$ 8,130.00	$ 10,670.00	$ 56,980.00	$ (1,340.00)	$ 723.00	$ 1,335.00
300'	$ 59,214.00	$ 57,997.00	$ 1,200.00	$ 63,225.00	$ 12,195.00	$ 10,670.00	$ 53,755.00	$ 2,725.00	$ 4,788.00	$ 5,400.00
500'	$ 59,214.00	$ 57,997.00	$ 1,200.00	$ 56,775.00	$ 20,325.00	$ 10,670.00	$ 47,305.00	$ 10,855.00	$ 12,918.00	$ 13,530.00
750'	$ 59,214.00	$ 57,997.00	$ 1,200.00	$ 48,712.50	$ 30,487.50	$ 10,670.00	$ 39,242.50	$ 21,017.50	$ 23,080.50	$ 23,692.50
1000'	$ 59,214.00	$ 57,997.00	$ 1,200.00	$ 40,650.00	$ 40,650.00	$ 10,670.00	$ 31,180.00	$ 31,180.00	$ 33,243.00	$ 33,855.00

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Sinewave Filter with Common Mode Choke: Energy Savings

kWh Energy Charge Rate	Operating hours 24hr/day x 30 days/month	kW based on 200HP motor operated at 90% Load (kW)	kWH	Potential Monthly Energy Operating Cost	Potenital Annual Energy Operating Cost	2% Energy Improvement /Month	5% Energy Improvement /Month	Potential 2% Annualized Savings	Potential 5% Annualized Savings
$0.08	720	135	97200	$7,776.00	$93,312.00	$155.52	$ 388.80	$ 1,866.24	$ 4,665.60
$0.10	720	135	97200	$9,720.00	$116,640.00	$194.40	$ 486.00	$ 2,332.80	$ 5,832.00
$0.12	720	135	97200	$11,664.00	$139,968.00	$233.28	$ 583.20	$ 2,799.36	$ 6,998.40
$0.14	720	135	97200	$13,608.00	$163,296.00	$272.16	$ 680.40	$ 3,265.92	$ 8,164.80

Notes:

We have assumed an average 90% loading on the load, changes to this utilization level will imnpact on the actual savings.

The 2% - 5% range is provided for reference only, the actual circuit impedance and other load circuit factors will determine the actual savings.

The range of the kWh energy rates is typical in most applications but can change based on overall peak demand charges and other rate scaled factors.

The potential for energy savings due to the efficiency enhancement of the secondary circuit due to the elimination of the losses associated with a PWM waveform and common noise losses can provide additional savings on top of the initial installation cost saving previous discussed. Typically, depending on the secondary circuit physical characteristics, a 2% - 5% energy saving can be realized.

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Specificational Notes for VFD Secondary Circuit Design to Prevent Resonance & Common Mode Noise

Key Specificational Points: Clean Power VFD's w/ Sinewave Filter & Common Mode Choke Assembly

- Output voltage waveform dV/dT stress and voltage overshoots characteristic for PWM inverter must be eliminated and suppressed without the need for snubber resistors, or auxiliary power electronic circuits.
- The sinewave filter shall have efficiency of no less than 99% and shall be suitable for application with PWM inverters that have carrier frequencies between 1.5 kHz to 8 kHz and motor leads up to 15,000 feet.
- The sinewave filter shall be tuned to 180 Hz versus 600Hz for differential noise mitigation of the 5^{th} and 7^{th} voltage distortion frequencies to enhance efficiency of the secondary circuit. Total voltage distortion shall be < 3% Vthd. The capacitive reactance of the sinewave filter at the load shall compensate for motor inductive reactive power such that power factor at the PWM inverter output is improved to 0.97 or better and will lower overall filter insertion loss (i.e. voltage drop) to < 3%.
- The sinewave filter cut-off frequency shall be set approximately three (3) times the max allowed fundamental frequency of the PWM inverter to attenuate the carrier components at the rate of >40db per decade while minimizing the absorption of fundamental current by the filter.
- The sinewave filter shall eliminate the effects of reflected wave phenomenon. The need for VFD-rated cables and inverter duty motors will be eliminated when the common-mode option is included.
- Inductors shall be air-gapped to control magnetic saturation. The inductance shall remain above 50% of its nominal value for any overload not exceeding 200% of rated current.
- Include common-mode choke option (CMC) to reduce the effects of common-mode currents on motor bearings and cable insulation.
- *Option: Coordinated Surge Suppression (CSP) with a minimum 100 kA withstand to lower transients and voltage overages.*

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Questions?

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Presenter/Author Biography

Michael McGraw –Primary Author : Currently Business Development and Engineering Services Five Star Electric. Previously US Regional Manager for Mirus International, from 2018 – 2022, Independent Engineering representative for Mirus International from 2009 – 2018, and President and Founder of NSOEM, Inc. 1996 - 2018 He is a member of the IEEE – IAS and has previously published IEEE papers presented at the PCIC 2010, 2014, 2015, 2016, 2018, 2019 & 2024.

Austin Miller Co-Author: currently serves as the Power Quality Sales Manager at Mirus International Inc., overseeing the U.S. market. Before joining Mirus International Inc. in 2023, he gained valuable experience as an application engineer specializing in power system harmonics at CTM Magnetics. He is a member of the IEEE.

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Technical References:

(Publication Date Order)

- *Eaton Application Note AP040013EN Effective August 2013*
- *IEEE/PCIC Paper PCIC-2018-43, Active Harmonic Mitigation – What the Manufacturers Don't Tell You.*
- *A Practical Guide to Partial and Staged Harmonic Mitigation Strategies, MIRUS-TP006-A, Michael A McGraw, 05/12/2020*
- *The Need for Harmonic Modeling and Mitigation in Generator Applications Mike McGraw USA National Sales Manager, Mirus International Inc. Dated 06/24/2021*
- *An 'Intuitive Understanding' of Electrical Harmonics: A Conversation, Mike McGraw USA National Sales Manager, Mirus International Inc. Dated 03/08/2021*
- *Understanding the Relationship between Current Total Harmonic Distortion (iTHD) and Total Demand Distortion (TDD) in IEEE Std 519-2014, Group Paper - Mirus International Dated 03/30/2023*
- *Tutorial - Harmonic Challenges for Distribution Grid Design, 3 Hour IEEE Tutorial, IEEE/PES WNC Chapter, 03/05/2024*
- *FSE Document: FSE Output-TD001 2024/11/29 : Specificational Notes for VFD Secondary Circuit Design to Prevent Resonance & Common Mode Noise*
- *FSE - Electrical Harmonics 101: An Overview of the Fundamentals of Electrical Harmonics and Discussion of Mitigation Strategies.*
- *FSE - Electrical Harmonics 102: A Further Review of Electrical Harmonics and Discussion of Mitigation Strategies with Discussion of VFD Secondary Circuit Design Considerations.*

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