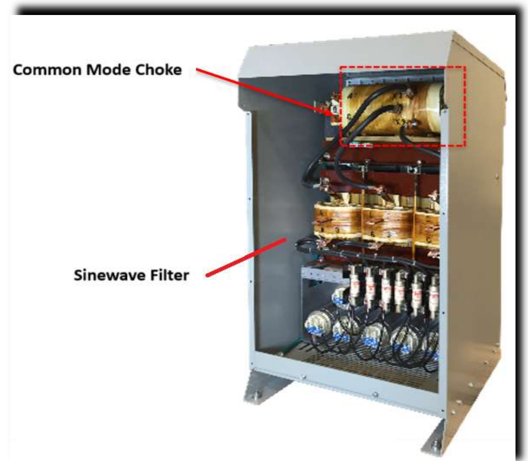
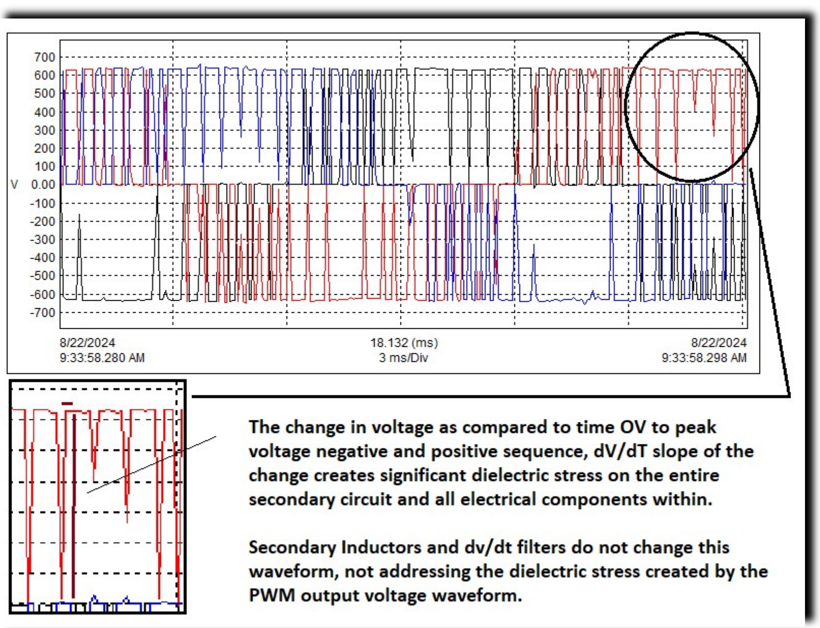
Engineering a well-designed VFD secondary circuit is a combination of dielectric stress reduction, and avoidance of reflective wave creation (ringing), both will compromise the life expectancy of the motor/load structure and can impact on the inverter operation and Variable Frequency Drive. Another key objective is to mitigate common mode nose (phase to ground) which can significantly compromise the motor/load via partial discharge across the bearing structures and can compromise the cable insultation due to phase to ground parasitic capacitance reactance. This condition can develop significant currents within the neutral and ground system, as well as induce ground and neutral voltage due to the resistance of the ground grid.

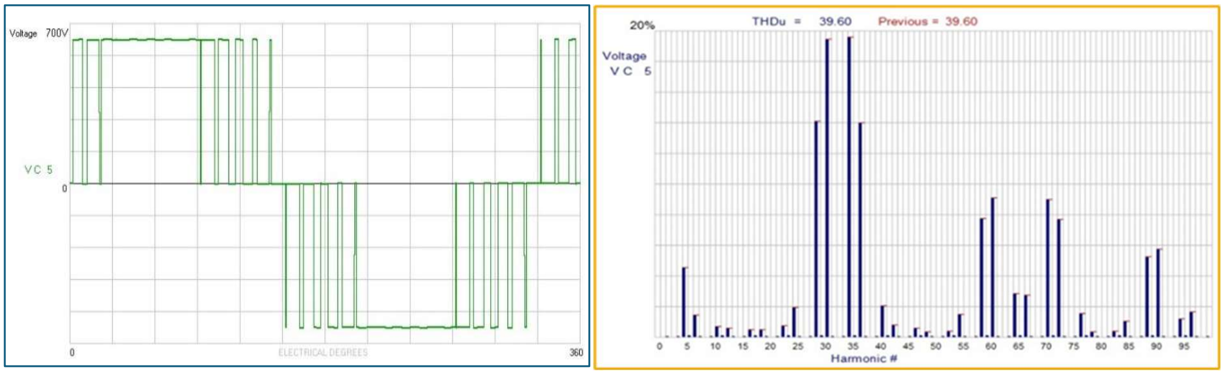




To the left is a wave-trace of a typical VFD output PWM waveform, as can be seen there is a repetitive zero to peak voltage sequence exposing the secondary circuit components cabling and motor to high dv/dt stress. This is typically referred to as differential noise and will lower the life cycle of the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

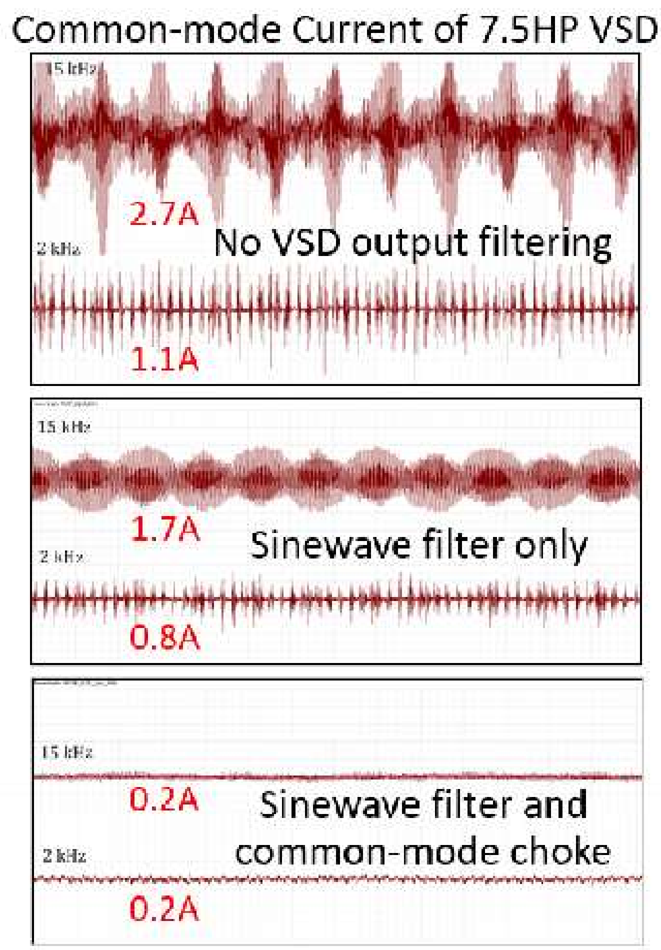
Secondary inductors and dv/dt filters do not change the functional dielectric stress within the system, they are simply attempting to "detune" the secondary circuit to avoid reflective wave/ringing/resonance. They also do little to avoid Common Mode Noise applicational challenges.

Copyright © 2024-09-27 Five Star Electric, 11135 Iota Drive, San Antonio, TX 78217



Typical Voltage Waveform and Spectrum from a typical Inverter PWM Output

Common Mode Noise 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/VSD highlighting the substantial high frequency currents associated with common mode noise within the secondary circuit. It also shows that a Sinewave filter alone is not a viable solution for the common mode challenge. As the motor HP/load increases, the associated CM noise current levels will increase significantly. 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 waveform and the use of a Common Mode Choke is required. This combination eliminates both differential and common mode dielectric stress associated with PWM inverter VFD/VSD secondary operations.

In most cases, the addition of the Sinewave filter and Common Mode Choke is more than offset by cost saving by the ability to utilize Standard Unshielded Cable and Standard Induction Motors versus Inverter Duty components. In addition, adding a Mirus AUSF Sine wave filter can increase the efficiency of the output circuit from 2% - 5% due to the elimination of eddy currents and secondary PWM losses associated with the mitigation of the voltage distortion of the PWM waveform harmonic spectrum.

See cost savings potential with a payback analysis from utilization of a Sinewave filter w/CMC and the material savings by utilizing XHHW Type 2 cable versus Inverter Duty rated cable and a Std. Induction Motor versus an Inverter Duty rated Motor, as well as potential operating costs reduction due to operating efficiencies enhancement in **Appendix A**.

Copyright © 2024-09-27 Five Star Electric, 11135 Iota Drive, San Antonio, TX 78217

FIVE STAR ELECTRIC POWERED BY INNOVATION	**Specificational Notes for VFD Secondary Circuit Design to Prevent Resonance & Common Mode Noise**

<u>If you combine the Sinewave Filter and Common Mode Choke into a single assembly/solution, the customer/user can avoid the need for Shielded Inverter Duty rated cables and utilize Std. Induction motors versus Inverter Duty rated motors while increasing the efficiency and life cycle of the secondary installation.</u>

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. The CSP option, when ordered, will provide a drive assembly 5 Year Warranty Standard.
• Integrated Drive Manufacturer Reference: Five Star Electric AS7 or AS100 CP-AUSF-CMC or equal approved prior to bid.

SALES	DIRECT DIAL	CELL	E-MAIL
Mark Hajda - San Antonio TX	210-568-8940	210-627-3023	mark@vfd.com
Shannon Lux - San Antonio TX	210-568-8928	210-870-0099	shannon@vfd.com
Mike McGraw (Application Engineering)	X	713-208-8534	mmcgraw@vfd.com
Chuck Stewart– Austin TX	X	830-832-0525	chuck@vfd.com
Patrick McGinty – Houston TX		281-467-9113	pmcginty@vfd.com
Jason McKinley – Houston TX	X	713-516-4078	jason@vfd.com
Tery Lewis – Western Texas	X	806-252-9700	tlewis@vfd.com
Jack Dolman – Northern TX	X	469-563-8943	jdolman@vfd.com

Reference Materials:

- Improving Motor Performance and Runtime in ESP Applications with Novel Sinewave Filter SPE-204493-MS: Anthony (Tony) Hoevenaars, P. Eng & Michael McGraw Mirus International, Colt Burley & Elizabeth Bierhaus Denbury Onshore.
- PPT: Mirus International - Available Models and Options for MIRUS Passive Harmonic Filters, 02/03/2022
- A Practical Application of a Sinewave Filter to Resolve to Resolve ESP Motor Failures, PCIC 2019-34, Anthony Hoevenaars P. Eng – Mirus International, Mike McGraw – Mirus International, Colt Burley Denbury Onshore LLC.
- AUSF-TS001-A0: Mirus International Advanced Universal Sinewave Filter (AUSF) – Typical Specification
- SA-Water 2019 Sinewave Filter Project – Test Data Program
- Mirus Series AUSF Inversine Sinewave Filter versus dV/dT Filter Discussion: San Antonio Water Authority Case Review, Aron Sekula - Five Star Electric, San Antonio & Mike McGraw – Mirus International

Copyright © 2024-09-27 Five Star Electric, 11135 Iota Drive, San Antonio, TX 78217

Appendix A: Cost Payback Example 480V/200HP

- The typical minimum cable length purchase for Beldon Shielded Inverter Cable is 1000 foot, an analysis of both secondary circuit distance and a review of the cost of a 1000' cable reel length minimum purchase has been included. *When considering a minimum cable reel length, under all distance considerations there is an immediate payback utilizing a Mirus AUSF-CMC filter saving significant project costs even up to 1000 cable lengths.*
- If the AUSF-CMC filter is being utilized versus an inductor or dv/dt filter the immediate breakeven is just above 150' distance between the VFD and motor.

	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	Cable Cost Savings w/o minimum reel purchase using XHHW versus
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

The key to the AUSF-CMC is the integrated Common Mode Choke, which other manufacturers do not normally offer due to cost considerations. To utilize the XHHW unshielded cable and Std. Induction Motors, you must mitigate both the differential mode noise and common mode noise to eliminate the dielectric stress and parasitic capacitance that will impact on the secondary circuit.

With considerations of additional efficiencies from the Sinusoidal waveform feeding the secondary circuit and motor load, there could be a efficiency improvement within the operation of the loads and an associated energy savings which can result in a 2% - 5% improvement. The schedule below highlights the additional energy savings payback on top of the payback noted below...

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 energy saving enhances the payback of adding a Sinewave Filter w/ Common Mode Choke and additional future energy cost savings making this circuit design a prudent engineering requirement.

Copyright © 2024-09-27 Five Star Electric, 11135 Iota Drive, San Antonio, TX 78217