6-Pulse VFD with Lineator™ AUHF vs Active Front-End (AFE) Drive

Manufacturers of AFE Drives claim benefits such as, reduced line current harmonics, improved power factor and inherent regenerative capabilities when they're compared with standard 6-Pulse VFDs equipped with diode bridge rectifiers. But rarely discussed is the overall system efficiency, and the fact that current harmonics are much higher when measured above the 50th and that serious problems can result from the introduction of these higher frequency Supraharmonics. Supraharmonics include the range of frequencies from 2 kHz (40th harmonic at 50 Hz) to 150 kHz (2500th harmonic at 60 Hz). In the majority of drive applications, the reality is a properly designed Wide Spectrum Passive Filter, such as the Lineator AUHF, can outperform AFE Drives, especially when harmonics above 50th are taken into consideration.

Fig. 1a shows a typical AFE Drive topology. The problems associated with the operation of AFE rectifiers are related to the converter design characteristics, switching frequency and interaction with the power system. AFE Drives require a passive LCL filter ahead of the input bridge. The function of this filter is to reduce the switching frequency harmonics introduced by the IGBTs. All AFE manufacturers include LCL filters that are only minimally effective because a more effective filter would be much more expensive and physically larger. Both topologies have an input passive filter but the Lineator/6-Pulse VFD topology is simpler, more reliable and less expensive.

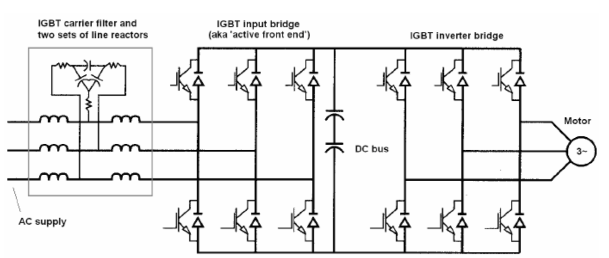


Fig. 1a: AFE Drive topology with LCL filter

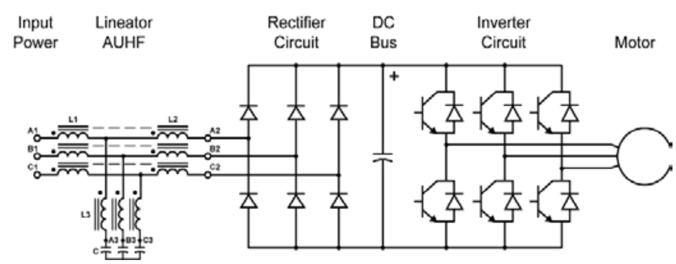


Fig. 1b: 6-Pulse Drive topology with Lineator AUHF

The following table provides a comparison between the two topologies:

Technical Challenge	Mirus Lineator AUHF with a 6 Pulse Rectifier VFD	AFE Drives and AC-AC Matrix Technology VFD's	Notes
Full Spectrum Harmonic Mitigation	Meets or exceeds IEEE Std519 and IEC 61000 series current harmonic limits over the entire frequency range, including Supraharmonics. (see Appendix B)	Typically meets current harmonic limits defined up to the 50th (3 kHz) but will introduce Supraharmonics in the 2 kHz to 150 kHz range due to IGBT switching frequencies.	For this reason, IEEE Std519-2014 allows for application above the 50th but unfortunately, this is rarely applied. See Appendix A for examples of AFE injection of high frequency harmonics.
Ground Leakage Current and Neutral-Ground Voltage (common-mode)	Since the Lineator AUHF is a passive harmonic mitigation device, there are no components to induce high frequency neutral-ground voltages (common-mode) and inject ground currents.	A direct consequence of the Active Front End drive is the introduction of high frequency common-mode noise into the ground system. This can be problematic in that it can cause ground fault trips and lead to excessive common-mode current flow in the ground and other inadvertent paths.	With long cable runs, VFD induced common-mode noise and ground currents are known to effect secondary cable and motor bearing integrity. But the use of IGBT technology in the active rectifier sections of AFE Drives has pushed this concern to the upstream side as well. (see Appendix A)

Technical Challenge	Mirus Lineator AUHF with a 6 Pulse Rectifier VFD	AFE Drives and AC-AC Matrix Technology VFD's	Notes
System Resonance Concerns and Compatibility with other Drive Topologies within the Distribution System	The Lineator AUHF is tuned well below the 5th (300 Hz) and away from 6-pulse, multi-pulse, or other passive rectifier harmonic frequencies. This avoids the potential for resonance with the power system. This allows Mirus to guarantee that the filter will … "Not resonate with other power system components."	The passive LCL-EMI/RFI filters within AFE Drives are always tuned above the 5th since they must target IGBT switching harmonics and higher. This makes the AFE Drive much more susceptible to resonance with the power system at harmonic frequencies that are introduced by other nonlinear loads, including 6-pulse and multi-pulse VFD's. As a result, AFE Drive literature does not guarantee against resonance with other power system components.	**Few engineers perform power system resonant frequency analysis since obtaining the information needed for an accurate analysis is extremely difficult. This places significant importance on the selection of a harmonic mitigation solution that inherently prevents resonance, such as Lineator AUHF. (see Appendix C)**
Energy Efficiency	The Lineator AUHF has extremely low losses with an efficiency of > 99%. As a series connected component, the combined total efficiency of the Lineator/6-pulse drive assembly is typically > 96.5%.	The total efficiency of most AFE Drives operating at a typically low IGBT switching frequency is between 94.5% and 95.5%. This is the result of additional losses introduced by the active rectifier IGBT operation. At higher switching frequency, the efficiency drops due to higher AFE losses.	**Comparing a Lineator AUHF paired with a 6-pulse drive, against an AFE Drive of the same manufacturer, the AFE is 1.5% to 2% less efficient. So not only is the AFE more expensive to purchase, it also has higher operating cost, which is a significant component in Cost of Ownership analysis. (see Appendix D)**
Considerations for Marine and other Generator Supplied Applications	The Lineator AUHF is purposely designed with an exceptionally low capacitive reactance to power ratio in order to ensure that the filter will not overexcite or create over-voltage issues in a Marine or other Generator supplied application. The Lineator is ABS certified for marine applications.	Generators, and other high impedance sources, are more likely to experience troublesome levels of voltage distortion at high frequencies when supplying AFE Drives. In addition, the passive LCL and EMI/RFI filter capacitors can interfere with automatic voltage regulators and other sensitive electronic devices, such as navigation and propulsion control, especially if resonance occurs.	**Electric propulsion and other marine VFD applications represent some of the greatest harmonic and resonance challenges. The combination of a 'weak', high impedance source, and nonlinear loads generating low or high frequency harmonics, makes designing a good harmonic mitigation strategy even more critical. (see Appendix A)**
Four Quadrant Regenerative Braking Application	A VFD equipped with a diode bridge rectifier does not have the ability to provide reverse power flow for regenerative braking operation. This remains true even when equipped with a Lineator AUHF.	AFE Drives are capable of four quadrant operation which allows for reverse power flow in applications where a motor can generate power rather than consume it, such as an elevator, pump jack or electric vehicle braking.	**If an application makes regenerative braking possible, an AFE Drive can be an attractive option. Generation of high frequency harmonics should still be taken into consideration and mitigated if possible.**

Appendix A: AFE Drives Introduce High Frequency Harmonics

In order to reduce input current harmonics, AFE Drives use IGBTs instead of a diode bridge rectifier. Current harmonics can be controlled through the switching action of the IGBTs but in so doing, switching frequency harmonics are introduced. Fig. 2 shows various measurements taken at a Paper Mill, equipped with AFE Drives, by the authors of a paper on 'Practical Problems Associated with the Operation of ASDs Based on Active Front End Converters in Power Distribution Systems' [1]. They compare Ph-to-Gnd voltages and input currents while operating the AFE Drives as simple 6-Pulse Rectifiers and in full AFE operation.

Both operations show Ph-to-Gnd voltage with high frequency components but during AFE operation these distortions are substantially worse. Input current measurements show much lower levels of low frequency harmonics than in 6-Pulse operation but the high frequency ripple is very obvious in the waveform and the spectrum reflects this ripple with higher bars around the 50th.

With a band of harmonics near the 50th, the IGBTs on these Drives would be switching at around 2 - 3 kHz. With higher switching frequencies, the harmonic band would move out to higher harmonic orders. In many cases, these are well above the 50th where almost all power quality analyzers do not measure. Despite AFE Drive manufacturers' efforts to ignore them, these higher frequency harmonics do certainly exist and most definitely can wreak havoc with connected equipment.

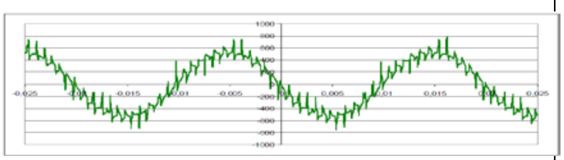
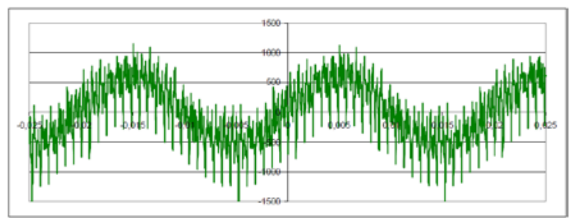
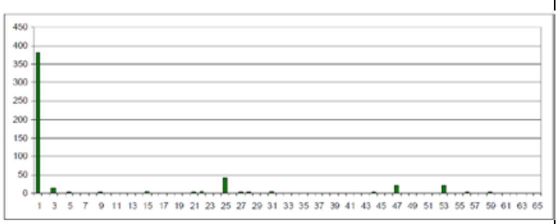
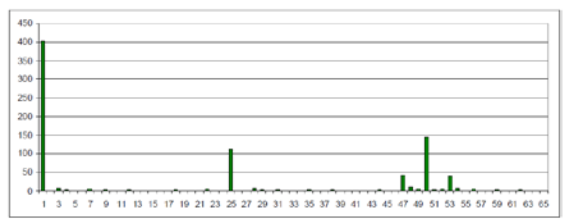
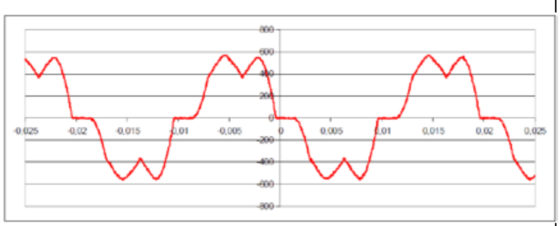
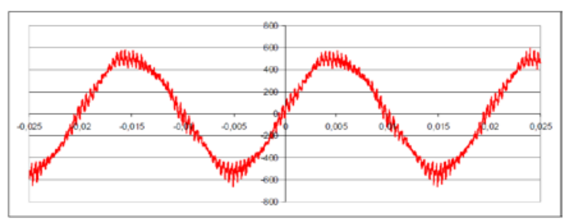
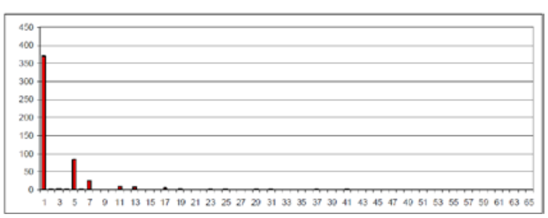
	Operating as a 6-Pulse Rectifier Drive	Operating as an Active Front-End Drive
Ph-to-Gnd Voltage Waveform		
Ph-to-Gnd Voltage Spectrum		
Input Current Waveform		
Input Current Spectrum		

Fig. 2: Variable Frequency Drive Voltage and Current Waveforms and Spectrums for an AFE Drive in a Paper Mill [1]

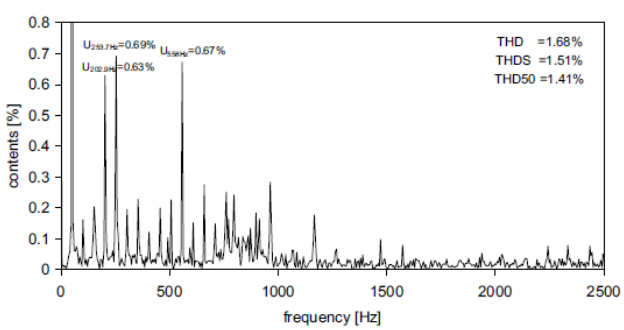
When AFE Drives are used on marine vessels with weak generator supplies, this problem can become even worse. The American Bureau of Shipping (ABS) has acknowledged this in several locations in Section 13 of its 'Guidance Notes on Control of Harmonics in Electrical Power Systems', such as:

iii) Total harmonic current distortion (Ithd), harmonic current spectrum up to 50th harmonic (or up to 100th for equipment with "active front ends") and total magnitude of total harmonic current per unit, per circuit and per installation at rated load, as applicable. [2]

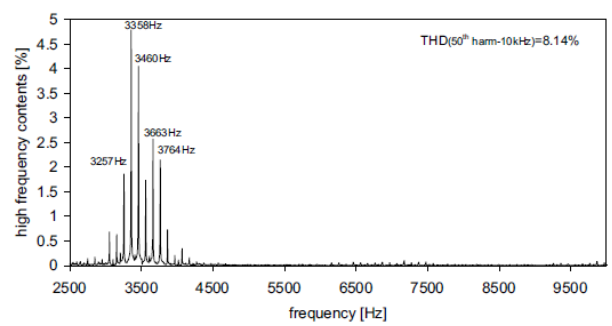
Fig. 3 shows frequency spectrums of the voltage at the Bridge Distribution Panel of a catamaran equipped with Main and Propulsion AFE Drives [3]. Measurements were taken over three frequency bands – up to 50th harmonic, 50th to 10 kHz and 10 kHz to 50 kHz. Although the voltage harmonics were very low in the lower frequency range (VTHD = 1.68%), they were very high in the frequency range above the 50th (VTHD = 8.14%) with a band around 3450 Hz (69th harmonic) produced by the AFE Drives operating at a 3.6 kHz switching frequency [3]. Most power quality analyzers that only measure up to the 50th harmonic would not have highlighted these high distortion levels.

These higher frequency harmonics will undoubtedly cause problems with connected equipment such as standard AC 6-Pulse VFDs, including those manufactured by the same supplier as the AFE Drives. The following statement is from the 'Practical Problems' paper sited earlier.

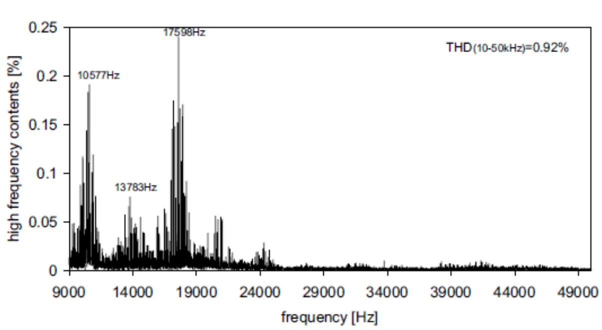
"From the power distribution point of view, the AFE rectifier operates as a current source, and as such injects high frequency current harmonics into the grid. If ASDs that use diode-based rectifiers (standard ASD) are connected to the same ac grid, the high frequency current components are pushed into their dc bus. This is due to the fact that they offer a low impedance path to these high frequency current components (due to the dc link capacitor presence), overloading the respective converter. Moreover, if the standard ASD is operating at light load, its dc bus voltage will tend to increase until the converter shuts down, hopefully by means of the dc link over voltage protection." [1]



a) Up to 50th harmonic (VTHD = 1.68%)



b) 50th harmonic to 10 kHz (VTHD = 8.14%)



c) 10 kHz to 50 kHz (VTHD = 0.92%)

Frequency bands	THD [%]
0-50kHz	8.38
0-50th harmonic	1.68
50th harmonic-10kHz	8.14
10-50kHz	0.92

d) Summary of VTHD at various frequency bands

Fig 3: Voltage harmonic spectrum of a Marine Vessel with Main and Auxiliary Propulsion AFE Drives [3]

The authors of [1] also noted that the high speed IGBT switching action of AFE Drives introduces ground leakage currents (common-mode) that can cause inadvertent operation of ground fault protection equipment. Fig. 4 shows the neutral-to-ground voltage and currents of an AFE Drive running in both 6-Pulse operation and AFE operation. High frequency common-mode noise increases substantially while in AFE operation.

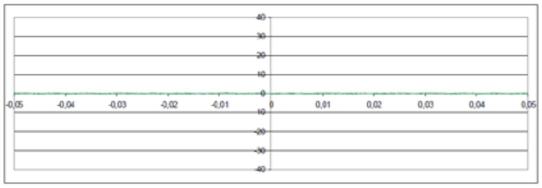
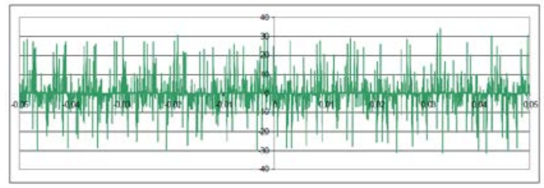
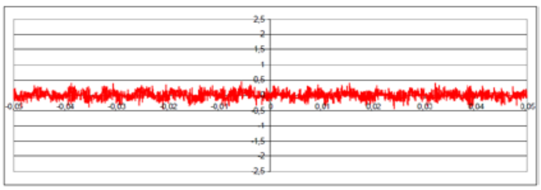
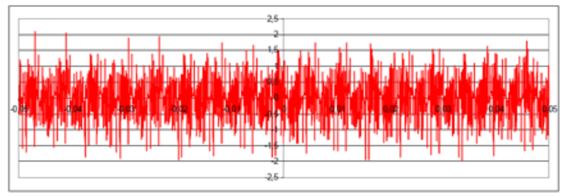
	Operating as a 6-Pulse Rectifier Drive	Operating as an Active Front-End Drive
N-to-Gnd Voltage		
N-to-Gnd Current		

Fig. 4: Variable Frequency Drive Neutral-to-Ground Voltage and Current for an AFE Drive in a Paper Mill [1]

Appendix B: Lineator AUHF Provides Equivalent Levels of Reduction in Low Frequency Harmonics (up to the 50th) as the AFE Drive without Introducing any High Frequency Harmonics

Lineator AUHF is a series connected, wide spectrum, passive harmonic filter designed to eliminate harmonics generated by 3-phase, 6-Pulse variable frequency drives. It performs as well as an Active Front End Drive in reducing harmonics in the low frequency range (up to 50th harmonics) while substantially outperforming AFE in the high frequency range. Lineator will provide some reduction in high frequency harmonics while the AFE Drive actually introduces these more damaging harmonics into the power system as described earlier.

The Lineator AUHF consists of a reactor with multiple windings on a common core and a relatively small capacitor bank (Fig. 5). This design exploits the mutual coupling between the windings to improve harmonic mitigation performance making it far superior to conventional passive filter solutions. To prevent importation of upstream harmonics, the resonant frequency, as seen from the input terminals, is near the 4th harmonic, comfortably below the predominant harmonics of 3-phase rectifiers.

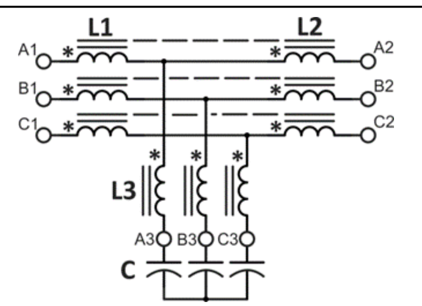


Fig. 5: Lineator AUHF Wide Spectrum Passive Filter Schematic

One key advantage of the unique reactor design is that it allows for the use of a significantly smaller capacitor bank (< 15% reactive power as a percent of the full load rating). This reduces voltage boost and reactive power at no load to ensure compatibility with generators. All other passive harmonic filter solutions introduce higher capacitive reactive power at light loads (typically 30% to 40%). Even the LCL filters on AFE Drives have higher capacitive reactance than the Lineator AUHF.

The filter is connected in series between the main supply and the drive. Current Total Harmonic Distortion (ITHD) is typically reduced to < 6% (a < 5% ITHD version is available) when applied to a 6-pulse AC PWM drive regardless of whether the drive is equipped with an AC or DC reactor or no reactor at all.

Lineators can be applied to AC drives with diode or SCR pre-charge input rectifiers ranging in size from 5HP/4kW to 3500HP/2600kW. They can be applied to single or multiple drives but only drive loads should be connected as the filter is designed specifically for rectifier operation. The filter can usually be retrofitted to existing drives without the requirement for drive modifications, whether for single drive or for multiple drive applications. A model is also available for operation on fully controlled SCR bridges, as used in DC Drives.

Figures 6 and 7 provide typical performance results measured in our Harmonics & Energy Lab on a Lineator AUHF. They show voltage and current waveforms and spectrums at the input to the Lineator measured up to the 500th harmonic using an ION 7650 Power Quality Analyzer.

Current Total Harmonic Distortion (ITHD) is only 5.12% even when all harmonics up to the 500th are included. Clearly noticeable is that, unlike the AFE Drive, there are extremely low levels of harmonic currents past the 50th.

Voltage Total Harmonic Distortion (VTHD), including all harmonics up to the 500th, is only 2.54%. This is well below the maximums recommended by IEEE Std 519-1992 of 5% and -2014 of 8%. Again, the harmonics above the 50th are virtually non existent, while for the AFE Drive, these were the highest harmonics present.

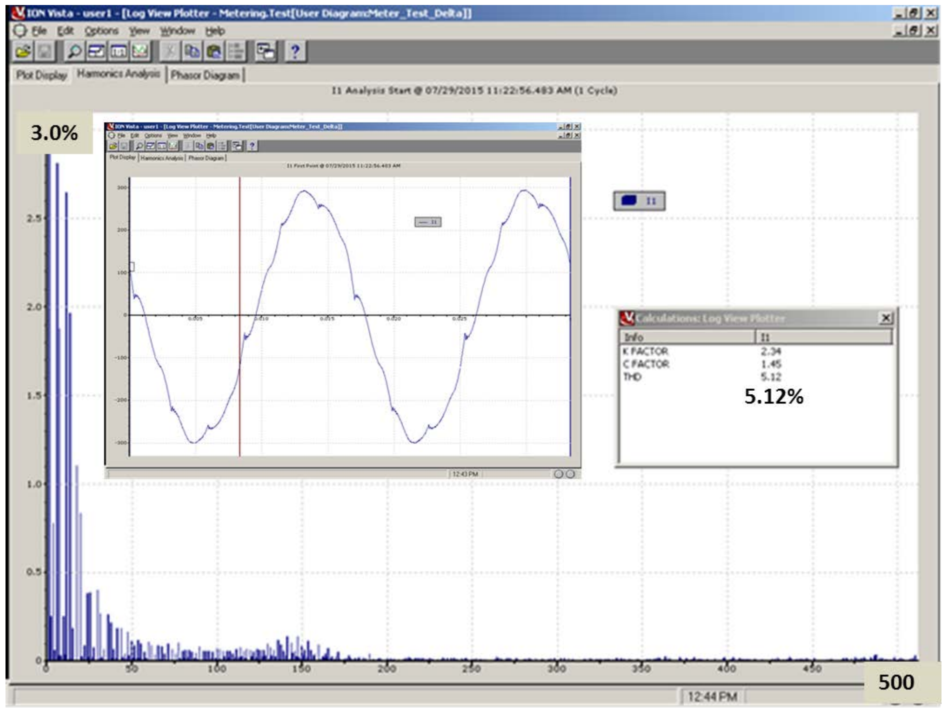


Fig. 6: Input Current Waveform and Spectrum for 200HP, 480V Lineator AUHF

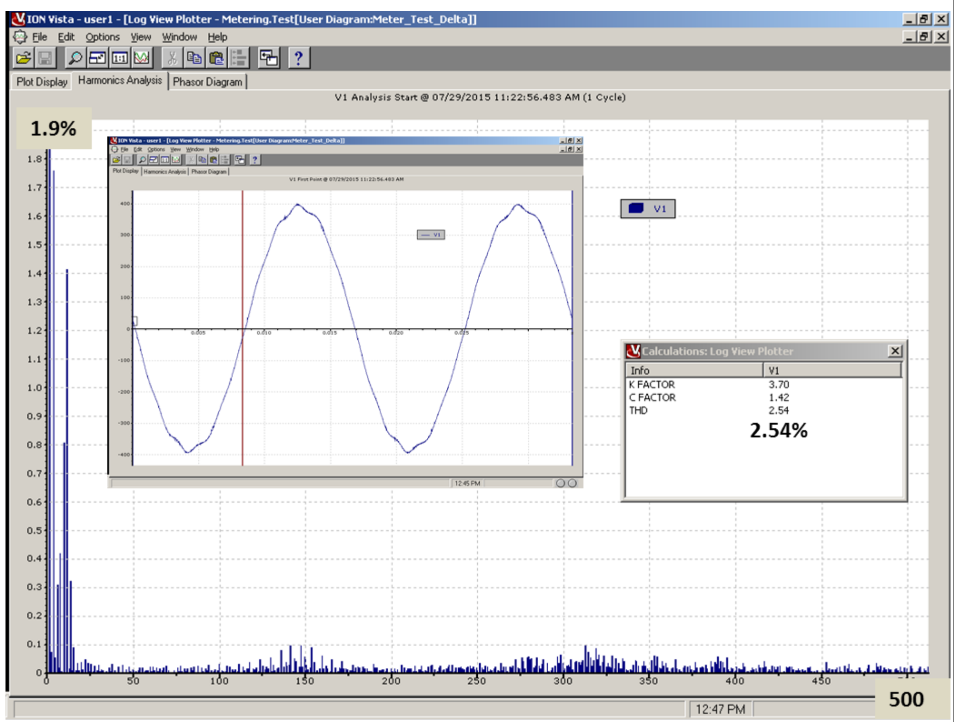


Fig. 7: Input Voltage Waveform and Spectrum for 200HP, 480V Lineator AUHF

Appendix C: Lineator AUHF's design protects against power system resonance:

As a series connected passive filter, the Lineator's combined inductance and capacitance presents a resonant frequency to the upstream power system. To prevent inadvertent resonance with the power system at a common characteristic harmonic frequency, the input resonant frequency is designed near the 4th harmonic to be comfortably below the 5th and other 6-Pulse rectifier harmonics.

Fig. 8a and 8b show a simple power system 1-Line and its equivalent diagram. Fig. 8c shows the reactance curves of the Lineator AUHF and the resonance point which occurs where these curves intersect. Since power systems are inherently inductive (unless installed Power Factor Correction capacitors are overcompensating which should always be avoided), the inductance curve will shift upwards moving the resonant frequency lower and further away from characteristic harmonics (Fig. 8d).

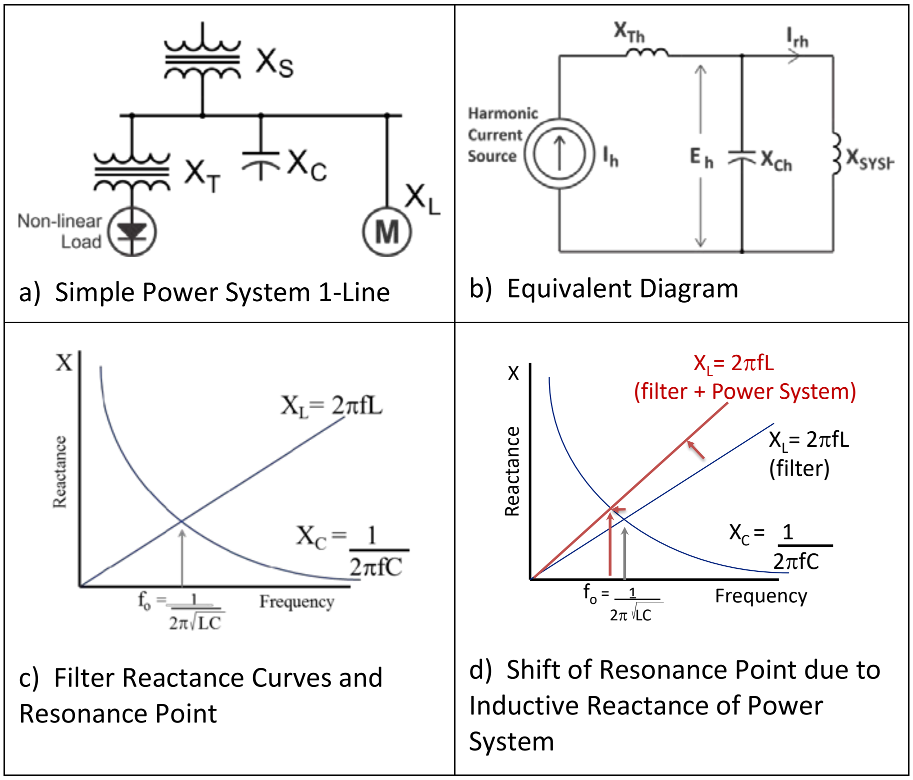


Fig 8: Lineator AUHF and Power System Resonance

The passive LCL and EMI/RFI filters required by AFE Drives, on the otherhand, are always tuned at a frequency above the 5th harmonic. The added inductive reactance of the power system will then lower the overall resonant frequency. When the resultant frequency matches a predominant harmonic on the power system, resonance will occur with its serious consequences. Therefore, the AFE Drive is much more susceptible to power system resonance than the Lineator AUHF.

Appendix D: AFE has higher losses resulting in lower efficiency:

Although the introduction of high frequency harmonics should in itself be enough justification to avoid the use of AFE Drives that do not have sufficient input passive filtering, there are many other reasons why the Lineator AUHF combined with a simple 6-Pulse VFD is a better solution. One significant one is the higher losses and lower efficiency resulting from the operation of the input IGBT rectifier of the AFE.

Tables 1 and 2 show a major electrical manufacturer's technical data for their AFE and 6-Pulse Drives, respectively. Table 3 provides a comparison of electrical losses and efficiency using the power loss statistics of a 75 kW (100 HP) and 400 kW (500 HP) Drive from these tables. With the losses of a Lineator AUHF added to the 6-Pulse VFD, that combination is still 1.7% more efficient than the AFE Drive. It is important to note that the stated AFE losses are for operation at the lowest IGBT switching frequencies. Losses increase with higher switching rates, further widening the efficiency gap.

Type output kW	Rated output current A	Base load current A	short-time current A	Rated input current *) A	AFE-Converter Order-No.	Power loss (3 kHz) kW	Cabinet dimensions W x H x D mm	Weight approx. kg
Line supply voltage, 3-ph. 380 V to 460 V AC								
400 V								
45	92	84	126	92	6SE7131-0EC61-5BA0	2,8	900 x 2000 x 600	400
55	124	113	169	124	6SE7131-2EE61-5BA0	3,5	1500 x 2000 x 600	600
75	146	133	199	146	6SE7131-5EE61-5BA0	4,1	1500 x 2000 x 600	600
90	186	169	254	186	6SE7131-8EE61-5BA0	4,4	1500 x 2000 x 600	620
110	210	191	287	210	6SE7132-1EF61-5BA0	5,7	1800 x 2000 x 600	900
132	260	237	355	260	6SE7132-6EF61-5BA0	7,1	1800 x 2000 x 600	920
160	315	287	430	315	6SE7133-2EF61-5BA0	8,7	1800 x 2000 x 600	940
200	370	337	503	370	6SE7133-7EF61-5BA0	10,3	1800 x 2000 x 600	950
250	510	464	694	510	6SE7135-1EH62-5BA0	14,3	2400 x 2000 x 600	1500
315	590	537	802	560	6SE7136-0EK62-5BA0	16,0	3000 x 2000 x 600	1600
400	690	628	938	655	6SE7137-0EK62-5BA0	20,0	3000 x 2000 x 600	1700

Table 1: Technical Data for AFE Drives of a Major Drive Manufacturer [7]

Order No. - with filter, Class A	6SL3223-...	...0DE35-5AA0	...0DE37-5AA0	...0DE38-8AA0
Order No. - with filter Class B	6SL3223-...	...0DE35-5BA0	...0DE37-5BA0	...0DE38-8BA0
LO base load power		55 kW	75 kW	90 kW
LO base load input current		102 A	135 A	166 A
LO base load output current		110 A	145 A	178 A
HO base load power		45 kW	55 kW	75 kW
HO base load input current		84 A	102 A	135 A
HO base load output current		90 A	110 A	145 A
Fuse according to IEC		3NA3836	3NA3140	3NA3144
Fuse according to UL		160 A, Class J	200 A, Class J	250 A, Class J
Power loss		1.4 kW	1.9 kW	2.3 kW

Line voltage 380 ... 480 V 3 AC		Power Modules 6SL3310-1GE36-1AA3	6SL3310-1GE37-5AA3	6SL3310-1GE38-4AA3	6SL3310-1GE41-0AA3
Type rating					
• at I_L at 50 Hz 400 V 1)	kW	**315**	**400**	**450**	**560**
• at I_H at 50 Hz 400 V 1)	kW	250	315	400	450
• at I_L at 60 Hz 460 V 2)	hp	500	600	700	800
• at I_H at 60 Hz 460 V 2)	hp	350	450	600	700
Output current					
• Rated current I_{rated}	A	605	745	840	985
• Base load current I_L 3)	A	590	725	820	960
• Base load current I_H 4)	A	460	570	700	860
Input current					
• Rated input current	A	629	775	873	1024
• Input current, max.	A	967	1188	1344	1573
• Current requirement, 24 V DC auxiliary power supply 5)	A	1.0	1.0	1.0	1.25
Power loss	kW	7.8	9.1	9.6	13.8

Table 2: Technical Data for 6-Pulse VFDs of the same Drive Manufacturer [8][9]

	VFD Rating (kW)	VFD Losses kW	AUHF Losses (kW)	Total Losses (kW)	Efficiency	Difference
AFE Drive	75	4.1		4.1	94.8%	
6-P with Lineator	75	1.9	0.8	2.7	96.5%	1.7%
AFE Drive	400	20		20	95.2%	
6-P with Lineator	400	9.1	3.6	12.7	96.9%	1.7%

Table 3: Efficiency Comparison – AFE vs 6-P VFD with Lineator

This difference in efficiency can result in very substantial savings in energy and operating costs. For example:

Cost Savings/yr = (kW x Avg%load x hrs/yr) x ($/kWh) x Eff%gain

Where, kW = 400 (motor rating)

Avg%load = 0.7 (assumes 70% loading on average)

hrs/yr = 8760 (assumes 24/7 operation)

$/kWh = 0.12

Eff%gain = 0.017 (from Table 3)

Cost Savings/yr = 400 x 0.7 x 8760 x 0.12 x 0.017 = $5,004

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[1] Luis Moran, Jose Espinoza, Mauricio Ortiz, Jose Rodriguez, Juan Dixon, *"Practical Problems Associated with the Operation of ASDs Based on Active Front End Converters in Power Distribution Systems"*, IEEE Transactions on Industrial Applications, 2004

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[5] Ian C Evans, *"AFEs: Not the Only Answer for Tackling Harmonics"*, Letter to the Editor, Drives & Controls magazine, Nov/Dec 2007

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[8] SINAMICS G120P, *SINAMICS DRIVES Answers for industry*, Siemens Automation & Drives, A5E35319202B AA

[9] SINAMICS G130 Drive Converter Chassis Units, *SINAMICS DRIVES Answers for industry*, Siemens Automation & Drives, E86060-D4001-A510-C9-7600