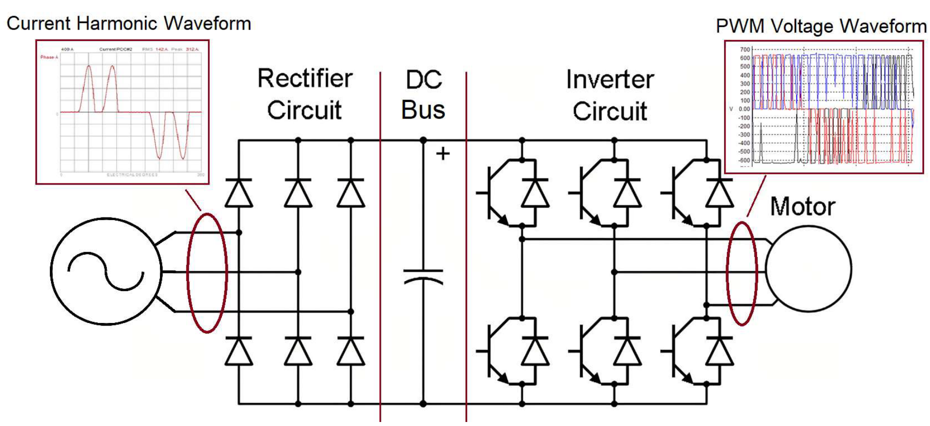
Comparative of VFD Drive, Harmonic Mitigation Methodology, and Output PQ Options
A Practical Discussion and Concept Overview

Section 1: Introduction/Objective
Section 2: Common VFD Topologies
Section 3: Typical VFD Input Harmonic Mitigation & Power Conditioning Configurations /Topologies
Section 4: DC Bus Construction Notes:
Section 5: Typical VFD Output Options and Waveform Conditioning
Section 6: VFD Topology with Line-side Options/Harmonic Mitigation Comparative Schedule
Section 7: VFD Topology and Costing Comparative Schedule and Notes
Section 8: Technical References and Referral White Papers

Section 1: Introduction/Objective:

Unfortunately, for engineers and end users, manufacturers seem to highlight all the advantages of their products and technology, but little is discussed about the limitations or circuit challenges that can result due to the application of the product. I have often highlighted in my discussions and training sessions; there is no such thing as a perfect solution. The key is to isolate a "solution" where the Pros outweigh the Cons. This paper is a review of some of the factors you must consider when choosing a VFD topology and common options for your specification that could provide a credible solution to your operational, harmonic profile, and output circuit power quality that will provide dependable operation and fit within your project budgets.

Functionally, VFD/ASD's convert the AC source voltage to DC potential, which then acts as a source for the output inverter which converts the DC source to an AC Pulse Width Modulated voltage (PWM waveform) which approximates an RMS voltage to the load motor. The width of the output pulse regulates the approximate voltage value. The frequency of the output will dictate the speed of the motor. In the case of VFD/ASDs designed to run Permanent Magnet Motors, this output frequency can be significantly higher than a traditional 60 Hz—70 Hz output speed associated with more traditional designs. It is now common to see 200Hz through 400Hz Permanent Magnet Motor installations in many industrial applications.



Typical 6 Pulse VFD/ASD Output harmonic waveform illustration

Applicational challenges witnessed for VFD/ASD installations include:

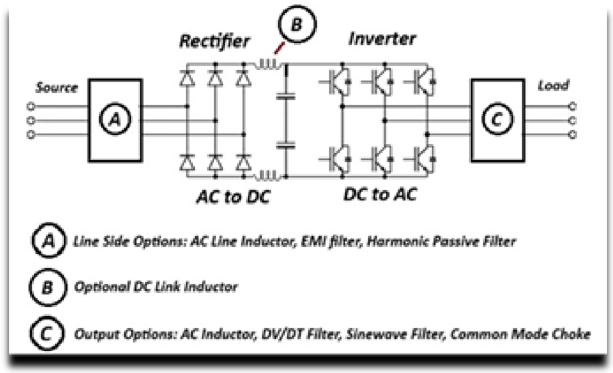
- Line-side/Sources Challenges
  - Source Background Voltage Distortion: The level of voltage distortion preexisting within a system prior to energizing the subject non-linear loads. This voltage distortion is being directly injected into the circuit from the Utility or created by pre-existing non-linear loads current harmonic injection into the system impedance. Verification by test is strongly suggested but if it is not possible for commercial loads you may want to assume 1% to 1-1/2% for modeling and reviews. For industrial applications 2% to 2-1/2% and O&G it is not unusual to see between 4% to 8% and higher. The presence of a pre-existing Source Vthd increases the level of current harmonic Ithd created by the VFD/ASD and leaves less headroom to meet Table 1 – IEEE-519 Voltage Distortion Limits at the PCC.
  - Source or System Voltage Imbalance: Existing system voltage imbalances are typically supplied by the Utility directly or are being created by imbalance single phase loads within the subject circuit. Typically ranges from 1% to 2% in most applications. The presence of an existing system voltage imbalance will increase the total current harmonic distortion created by the VFD/ASD which will create a higher level of voltage distortion (Vthd) at the PCC. Higher levels of errant current harmonics frequencies will be created, i.e. triplen harmonics (3^{rd}, 9^{th}, etc.), which can exceed harmonic frequency range limits as noted in Table 2 – IEEE-519.
  - Existing Systemic Resonance or a Source Low Resonance Frequency: Typically, if this condition exists it only presents only after you have injected a low frequency current harmonic into the source (2^{nd} through 50^{th} harmonic – 120Hz through 3kHz). The only way to predict the condition is via a Resonant Frequency analysis of the source during the design and engineering review. Should this present, this resonance can induce potentially damaging voltage transients for line side distribution components, cable insultation systems and the drive rectifier.

- Load-side/Secondary Circuit Challenges
  - Resonance/Reflective Wave Development w/ High Transient Voltage Evolution: As discussed above, the presence of resonance/reflective wave is a serious condition. The development is more likely to be present since the output inverter switching speed is within a higher range, typically above 3kHZ, which is closer to the most secondary circuit natural resonance frequency ranges.
  - High Dielectric Stress from the Pulse Width Modulated Inverter Voltage: dielectric stress on the load and secondary components is a function of the rate of change of voltage as it relates to time, i.e. dV/dT this will be discussed further later. This is not like a constant voltage pressure/stress on the insulation systems but dynamic in nature and repetitive at high frequency, functioning to amplify aging and degradation due to high net stress coefficients due to amplitude and frequency.
  - Phase to Ground Partial Discharge & Parasitic Capacitance from Common Mode Noise: This has now been recognized as a bigger challenge than previously recognized. Due to inverter inefficiencies relative to switching and timing, the instantaneous sums of the three voltages at any given point in time is not equal to zero. This creates instantaneous phase to ground noise (common mode noise), which can then induce parasitic capacitance discharge within secondary circuit insulation structures and partial discharge. Significantly degrading the insulation due to stress and create partial discharge across the motor and mechanical load bearing structures. This degradation leads to lower life cycles for the secondary components and increased repair and maintenance costs for the installations.

Section 2: Common VFD Topologies

The three most common topologies for VFD/ASD assemblies: 6 Pulse Rectification, Multi-pulse/Phase shift Rectification and Active Front End designs. As stated, these are the most common, but other variations do exist. Each of the three variations have advantages and disadvantages associated with their design and operating characteristics which will be detailed within the discussion.

Typical 6 Pulse Diode Bridge Rectifier VFD topology

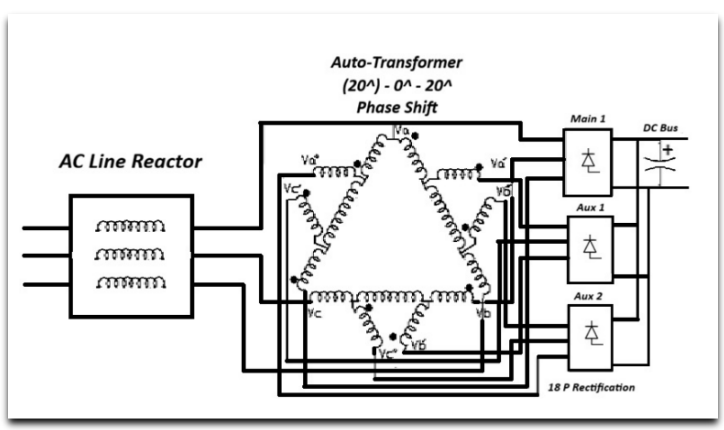


By far, the 6-pulse design is the most common and the mainstay of industry.

- This design includes the greatest variations in input and output options for power conditioning, harmonic mitigation, and long lead/resonance control.
- Integration friendly, allowing for the greatest flexibility in deployment and application based on specific project requirements.
- Typically, the most cost effective VFD/ASD design for most applications.
- Easily serviceable by field and installation service personnel, due to its modular design and componentized construction.
- Primarily used on 690V or less with HP rating now through 1200HP being readily available.
- Usually configured for single load applications but can be integrated into larger capacity/multiple load configurations utilizing multiple rectifiers feeding a large capacity DC bus and multiple inverters to meet numerous individual load structures or an integrated process system application.
- When 6-Pulse VSDs and AFE Drives are on the same switchboard, voltage ripple from the AFE Drive can raise the DC bus voltage in the 6-Pulse VSDs creating overvoltage conditions.

From a component/chassis perspective, each manufacturer has their own technical nuisances and designs depending on their manufacturing and engineering processes. The VFD chassis assembly is the basis of any integrated solutions/assembly designs to meet applicational requirements. Environmental options have been standardized within industry allowing integration and deployment within all the conditions presently serviced with variable frequency technology.

Multi-pulse/Phase Shift VFD Topology



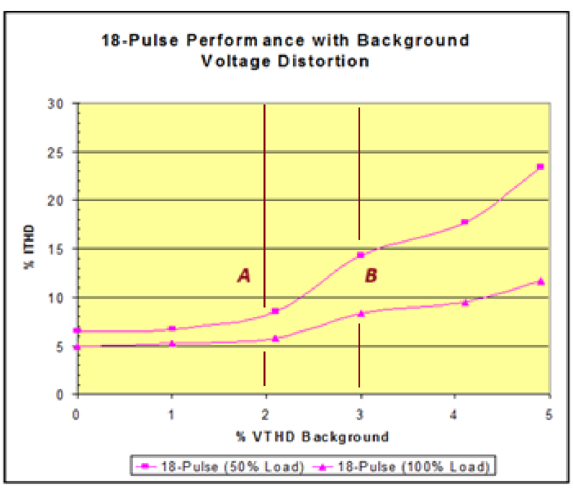
In Low-Voltage Drive applications, the original isolation transformer design phase shift/multi-pulse drive topology was replaced by an Auto-Transformer design over 20 years ago. Medium Voltage Multi-Pulse Drives still feature an isolation transformer within their design, typically a 4-winding design for current 18-P designs. The Low-Voltage design change obsoleted the 12-pulse drive within the market since a 12-pulse drive is inherently not IEEE-519 compliant. Most Multi-Pulse LV VFD's are now 18-pulse, see referenced schematic to the right. The design change to an Autotransformer configuration was initiated to lower the capital cost of the drive, making them more economical for deployment. But harmonic compliance with IEEE-519 was compromised because of the economically driven engineering.

Unfortunately, the design change compromised the suitability of the drive to meet IEEE-519 requirements within many “Real World” applications due to its inability to maintain harmonic performance and operating integrity when deployed into circuits which exhibit ***either Source/Background Voltage Distortion over 2% or Source Voltage Distortion over 2%.*** Notice the qualification of OR. The 18-Pulse Phase shift topology will also integrate a line reactor which will lower the overall full load efficiency of the drive to 96% or less in typical installations.

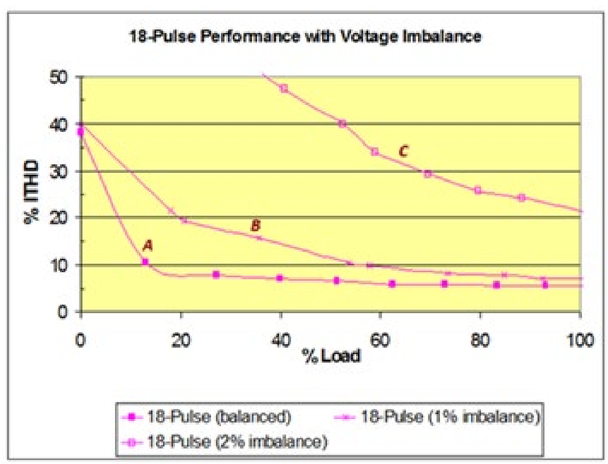
IEEE-519 allows up to 8% Vthd which means that deploying an Auto-18 Pulse VFD into an existing IEEE519 compliant can and will compromise the harmonic compliance and potential integrity of the VFD itself. For installations where the potential source is greater than 2% Vthd, thermal challenges can be created in the autotransformer and higher Ithd can result. Efficiency is also lower than typical specifications for the devices.

- The original multi-pulse drive design utilizing isolation transformers versus autotransformers was a qualified offering to the industrial market, with extended life cycles. Isolation transformer Multipulse Installations that still meet IEEE519 compliance are still commonly seen within many industrial applications with over 20 years life cycles.
- More expensive than 6-Pulse Rectifier VFD’s equipped with qualified harmonic passive filters.
- Lower operational efficiency than 6-Pulse Rectifier VFD’s equipped with qualified harmonic passive filters, due to higher harmonic reactive power consumption under real world conditions.
- Many manufacturers are discontinuing the 18-P Auto design in favor of other technology solutions, and they now acknowledge that design has applicational challenges in real world industrial environments.

Below is a graphic detail based on testing a typical 18-Pulse LV drive with source voltage distortion and source voltage imbalance. In “Real World” applications, every electrical circuit and installations will have systemic voltage distortion and imbalance. There are no perfect systems within modern grid systems due to the substantial load imbalances and high harmonic loads within today’s modern distribution systems. So, in most of the applications an Autotransformer based Phase-shift 18-P VFD will not meet the objectives of your harmonic strategy.



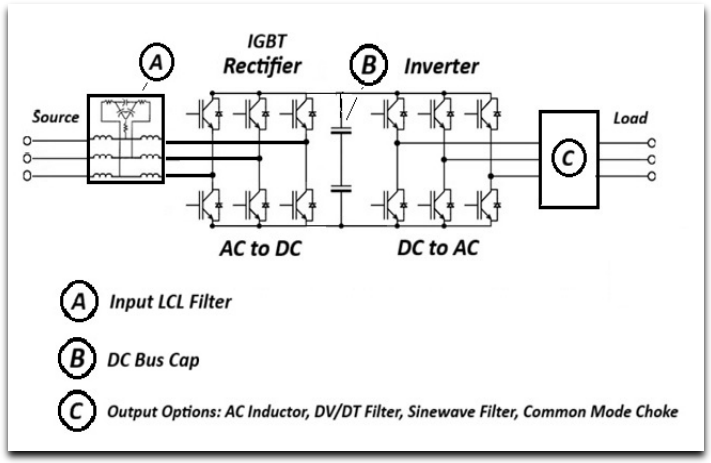
Note @ 2% Vthd with no source Voltage imbalance an inflection point of performance begins to present, by 3% Ithd limits are reached.
IEEE 519-2022allows for up to 8% Vthd.



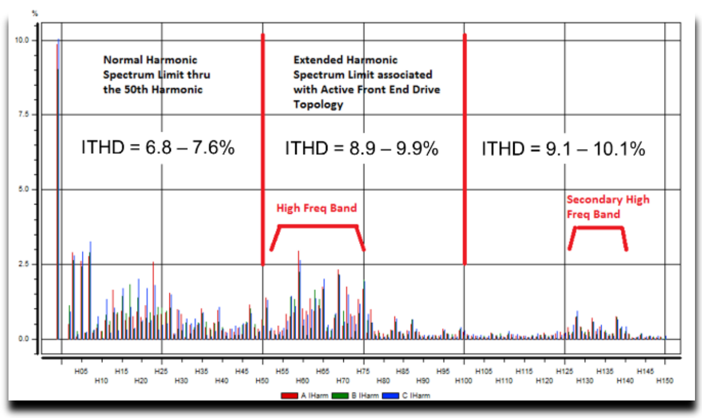
A: Based on a balance source voltage, Ithd performance is excellent through the majority of the load range.
B: At a 1% source voltage imbalance, Ithd must be around 75% load to meet Ithd levels.
C: At 2% source voltage imbalance, under no load circumstance can IEEE 519 limits be meet.

Active Front End Drives/IGBT Rectification

Active Front End (AFE) Drives function very similar as 6-Pulse Diode Bridge VFD's in their topology with the exception that the Diode Bridge has been replaced with a IGBT network for the rectification process with the addition of an input LCL filter for attenuation of high frequency EMI (Electromagnetic Interference) noise and TIF (Telephone Interference Factor) noise to comply with IEEE and EU harmonic standards. Functionally, the drive assembly has a built-in passive filter to comply with noise/harmonic standards. The normal frequency ranges for the input IGBT rectification are from 2kHz to 8kHz, but higher switching speeds are available.



- The drive cost indexed by HP is expensive and can be cost prohibitive.
- Not easily serviceable without factory service technical assistance.
- Requires Start-up and Programming assistance at time of installation, to ascertain the high frequency switching of the rectifier does not resonate with the source circuit design.
- Introduces high frequency harmonics above the 50th (3kHz) and does not compliant with IEEE519 when reviewed through 2.5x the rectifier switching frequency, i.e. >3kHz.



- Vulnerable to Source Background Voltage Distortion and Systemic Voltage Imbalance. *Consult the manufacturer for Vthd-source and Source Vimb performance warranty limits.*
- Higher losses and lower efficiencies than similarly rated 6 Pulse ASDs with passive harmonic filters.
- When 6-Pulse VSDs and AFE Drives are on the same switchboard, voltage ripple from the AFE Drive can raise the DC bus voltage in the 6-Pulse VSDs creating overvoltage conditions.

The advantage of the high-speed switching frequency of the input rectifier is that lower order harmonic frequencies are not significant. But higher order harmonics (Supraharmonics) will present in and around the set switching frequency of the IGBT rectifier and multiples of that frequency. The harmonic spectrum to the right illustrates this. In this case, the switching frequency is set to around 3.8 kHz, which creates a band of harmonics in and around the 57^{th} through the 75^{th} harmonic and a reflexive band at around double that frequency. As will be witnessed, the harmonics below the 50^{th}, which some may confuse as the IEEE519 compliance range, is below 8% which is the 20 < 50 ISC/IL TDD requirement, the total harmonic distortion through 2.5X the switching frequency is well above the limit.

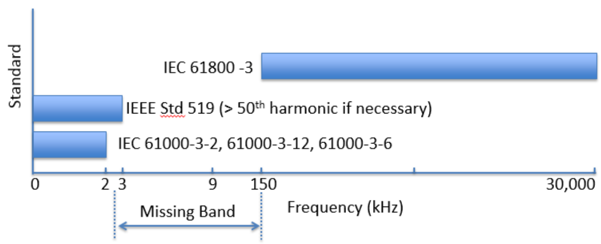
The IEEE-519 does not address this well for harmonic limitations, but the subject of Supraharmonics is addressed within the definitions if THD and TDD on page 15 of the IEEE-519-2022 publication:

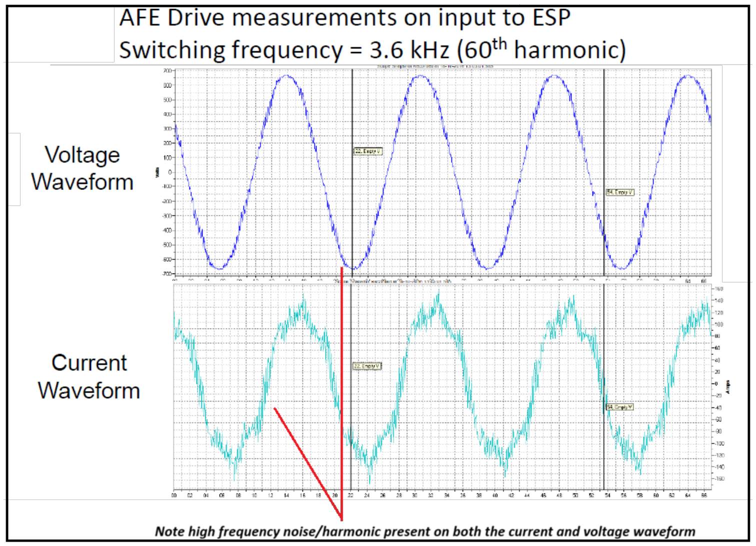
***total demand distortion (TDD):* The ratio of the root-mean-square of the harmonic content, considering harmonic components up to the 50th order and specifically excluding interharmonics, expressed as a percent of the maximum demand load current.**

Harmonic components of order greater than 50 may be included when necessary.

total harmonic distortion (THD): ***The ratio of the root-mean-square of the harmonic content, considering harmonic components up to the 50th order and specifically excluding interharmonics, expressed as a percent of the fundamental.***
Harmonic components of order greater than 50 may be included when necessary.

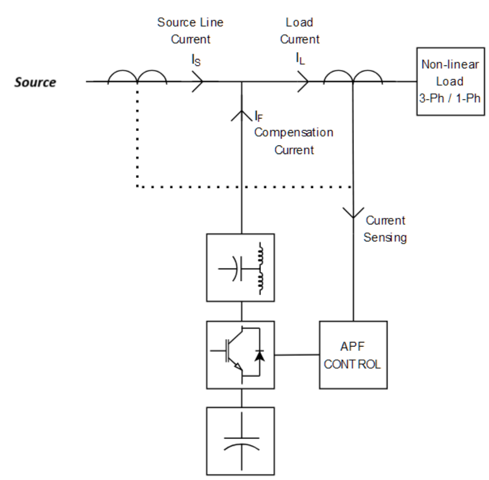
Within the definitions, it is acknowledged that harmonics above the 50th (3 kHz) may be included, and functionally can be of consequence, which is appropriate for AFE (Active Front End) drives when the switching frequency is set above the 3 kHz level.





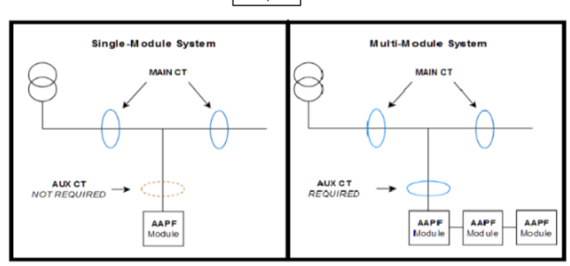
A common specification seen when qualifying harmonic performance requirement for ITDD references harmonic measurement and verification through 2.5X the switching frequency of the IGBT rectifier to determine compliance to the associated harmonic performance specification, whether IEEE 519 or IEC 61000-3-2, 61000-3-12, 61000-3-6 and 61800-3. The range between 2kHz for IEC and above 3kHZ for IEEE Std's is often referred to as the "Missing Bandwidth". An excellent discussion of high frequency harmonics can be found within, **ACTIVE HARMONIC MITIGATION – WHAT THE MANUFACTURERS DON'T TELL YOU, Copyright Material IEEE Paper No. PCIC 2018-43.**

Active Harmonic Filtration

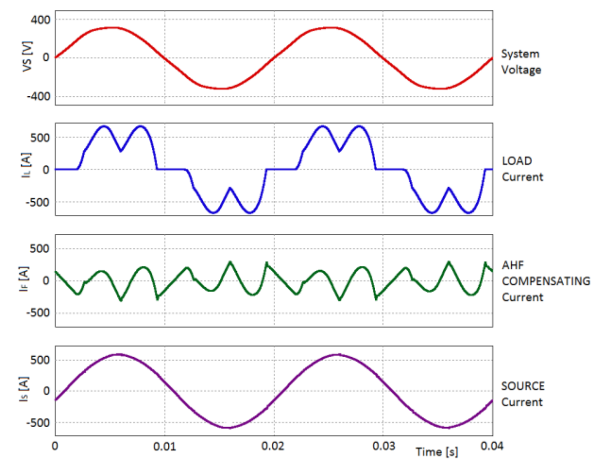


Typically, the use of active harmonic filtration is when a group of non-linear loads are incorporated into a larger MCC or branch circuit configuration with linear loads and a Systemic Harmonic Mitigation strategy is required. I have included this discussion within the VFD discussions versus the Section 3: Typical VFD Input Harmonic Mitigation & Power Conditioning Configurations /Topologies due to the load mix and displacement power factor correction capability of the device.

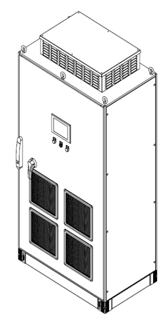
- Parallel Active Harmonic filters require additional circuit protective equipment feeding their installations, typically priced at over $ 25K per 200A module plus ancillary equipment requirements.
- Requires CT installation and coordination for retrofit switchboard applications.
- Requires a qualified harmonic study to assure proper sizing to the non-linear load structure. If the AHF will be treating displacement power factor, an engineering review to determine the necessary capability is required.
- Higher order harmonic injection is possible.



- Advantage: Can be programmed to treat displacement power factor challenges within the circuit but will take away capacity from harmonic current control capacity.
- Advantage: Can treat multiple VFD loads (systemic harmonic mitigation) effectively without having to size the filter for the linear load component of the secondary load structure.
- Caution: If the secondary circuit contains AFE VFD's deployment of an Active Harmonic Filter upstream of the AFE drive may create a resonance condition which can catastrophically affect the AHF and all secondary circuit components.



The benefit of an Active Harmonic Filter (AHF/AAPF) is that you can treat not just the harmonic condition of the load structure but also isolate a portion of the filter capacity for displacement power factor correction at the same time. Also, over-excitation is not an issue since the AHF/AAPF controller will self-regulate the reactive power injection to avoid leading power factor and voltage boost. Making the deployment easier without more traditional capacitance reactance applicational concerns.



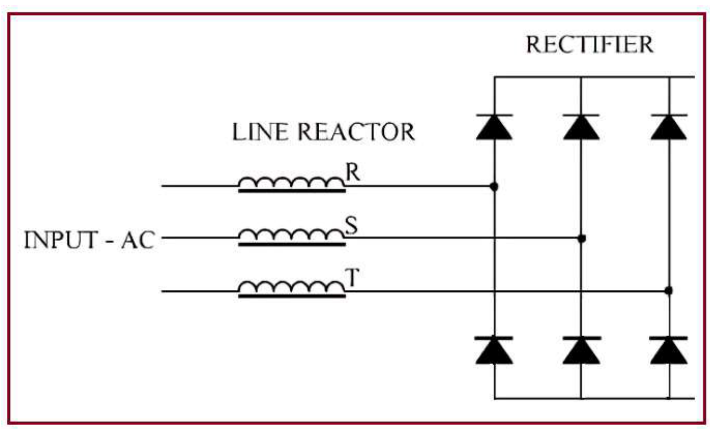
The modules and assemblies can be easily paralleled for high-capacity installation requirements.

Modules: 100, 150* Factory Enclosures: 100, 150, 200, 250*, 300*, 350*, 400*, 450* (*Higher current ratings are possible when connected in parallel.)

Section3: Typical VFD Input Harmonic Mitigation & Power Conditioning Configurations /Topologies

Ⓐ Typical Line-side/Primary options for power conditioning and harmonic integrations include:

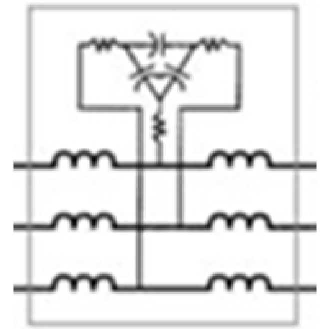
- AC Line Reactors: Adding a line reactor increases the source impedance lowering current harmonics which lowers current based stress on the rectifier. Typically, a line reactor will lower the Ithd of the assembly around 35% to 50% Ithd depending on overall system impedance.



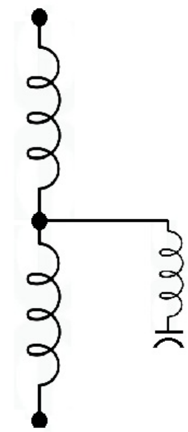
  Line reactors do not comply with IEEE-519 harmonic limits at the input of the assembly to required Table 2 Itdd limits. Additionally, the reactor through impedance lowers the assembly efficiency by about the percentage of the reactor impedance. The capital cost to add line reactors is relatively low, but the additional losses associated with the harmonic kVAR, incremental inductor losses and demand distortion losses increase the operational expense of the assembly.

  For small frame HP VFD's (20HP and under), the utilization of line reactors/inductors is a valuable tool to lower small harmonic contribution assemblies within a larger non-linear harmonic circuit and mitigation strategy.

- EMI (Electro-Magnetic Interference) Filters: Within the EU markets, EMI filters are standard equipment, whereas in the US ANSI markets it is not commonly deployed. Many VFD manufacturers are bringing their European designs into the US markets due to competitive circumstances. EMI filters are a combination of high frequency inductors and capacitors to reduce noise in the 150KHz to 30MHz frequency range. There is an additional through impedance associated with this device when utilized on the line side of the rectifier. Consult the VFD Instruction Booklet should you decide to de-activate the filter, via an isolation provision provided within the assembly. Active Front End VFD's (AFE drives) automatically include a passive design EMI due to high frequency harmonics created by the IGBT rectifier. The schematic shown is just one variation of commercially available units.

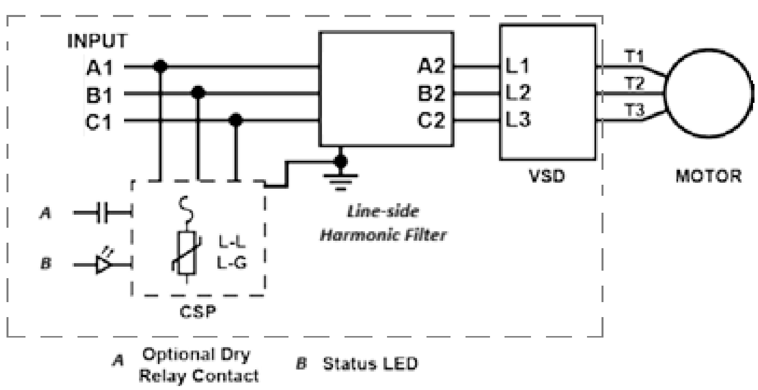


- Passive Harmonic Filters: Passive filters (LCL design harmonic filters) are the primary means of IEEE-519 compliance for 6-Pulse Diode Bridge VFD/ASD's and very competitive as compared to other VFD topology strategies. There is additional through impedance added to the assembly which increases the assembly losses, but this is greatly offset by the additional energy efficiency due to reduction of systemic eddy current losses by mitigation of the current harmonics from the VFD and lower induced linear load harmonic losses from the associated voltage distortion.



  Filter No-Load and Low-Load voltage boost can be an issue with most commercial Passive Filter brands on the market. In many cases, the manufacturer of the filter or integrator of the drive will recommend a capacitor contactor which adds additional capital and installation costs as well as increase the complexity of the VFD and operating systems. Low Capacitance Reactance filters, i.e. 15% kVAR to kW ratio designs are available from most manufacturers and significantly lower potential voltage boost as well as, assure compatibility with most Backup Generator Source installations without special engineering or integration.

  - Manufacturer integration of a coordinated surge protection MOV assembly into the passive filter component will provide additional surge and transient protection for the integrated VFD assembly including an extended 5-year warranty by some manufacturers of VFD and passive filter component assemblies.



    CSP –Coordinated Surge Protection: Potentially damaging voltage transients, spikes and surges in heavy industrial environments and remote location installations can commonly occur due to lightning, source capacitive switching, upstream large system load changes and circuit equipment inrush events; potentially compromising the drive branch circuit and its components. The CSP option consists of an integrated surge protection device (SPD) designed to augment the harmonic filter's natural surge suppressive characteristics. The combination of a harmonic filter and CSP device further reduces the transient let through voltage, ensuring optimal protection to the power/electronic components of the VFD/VSD loads. Factory integrated with harmonic filters, Sinewave filters and other VFD option assemblies to provide a coordinated Low impedance internal circuitry designed with very low let through voltage levels to enhance protection of the component and entire VFD assembly.

Key specificational points for high efficiency and low voltage boost passive filter qualification are listed below:

- Harmonic mitigation shall be by passive inductor/capacitor network. To prevent possibility of switching frequency resonance, active electronic components shall not be used.
- To ensure compatibility with engine generators, the harmonic mitigation equipment must never introduce a capacitive reactive power (kVAR) which is greater than 15% of its kW rating for sizes ≥ 100HP and 20% for sizes ≤ 75HP.
- Maximum voltage boost at no load must be < 3% of nominal line voltage without the need for a capacitor contactor assembly or other capacitor isolation strategy.
- Current Total Demand Distortion (ITDD) at the input terminals of the harmonic mitigation equipment shall meet the limits as defined in IEEE Std. 519 (Table 10.3 in 1992 and Table 2 in 2014 & 2022) but shall not exceed 8%. ITDD to include harmonics up to 100th. The full load efficiency of the harmonic mitigation equipment / VFD combination shall be greater than 96%. The harmonic mitigation equipment itself shall have efficiency of no less than 99%.
- Performance Guarantee: ITDD must be <8% with background voltage distortion up to 5% and voltage imbalance up to 3%. Must be capable of operating in voltage distortion environments up to 8% without derating.
- Provide coordinated surge protection factory integrated into the harmonic filter to provide additional protection against voltage transients, spikes and surges. The coordinated surge protection must extend the warranty of the harmonic filter to 5 years. Surge protection must include:
  - Low impedance internal circuitry with very low let through levels coordinated below most harmonic filtered drive circuit withstand limits.
  - LED status lights installed on the filter 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).
  - Compatibility with systems with SCCR rating up to [120kAIC] or [200kAIC].

Section 4: DC Bus Construction Notes:

(B) DC Link Inductors & DC Bus Capacitance:

- DC Link Inductors are used to help mitigate DC bus ripple by adding impedance to the DC bus. By lowering the amount of ripple, you will lower the Ithd created by the rectifier and injected back into the source. DC link inductors were originally an option and not part of the standard VFD package. But "Pump Duty" variations of VFD construction, which involve downsizing the DC bus cap has necessitated many manufacturers to add this into their standard topology to avoid disruptive DC bus ripple and to help avoid resonance with upstream capacitance reactance and higher systemic impedances.

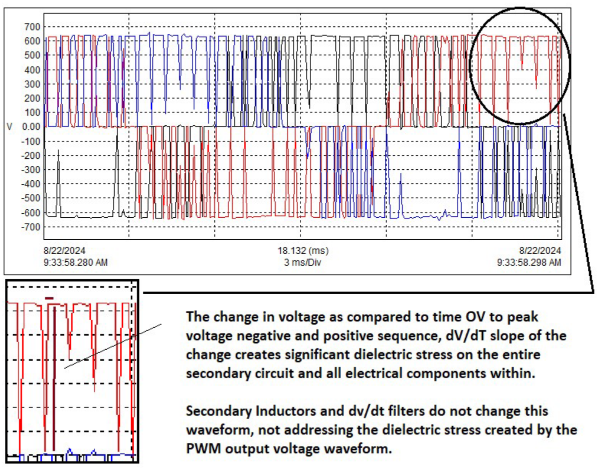
- DC Bus Capacitance: DC Bus capacitors are present to be the primary control technology for limiting DC bus ripple. As discussed above, new "Pump Duty" and other "Definite Purpose" VFD designs which feature smaller footprints and more economical pricing typically have downsized the DC bus cap to achieve the "improvements". Unfortunately, this design change has also made VFD's more prone to resonance with upstream capacitive sources and high impedance source conditions. Adding a line reactor or even a passive filter to these drives can trigger nuisance tripping and potential damage to the VFD itself. Most manufacturers now incorporate a programmed option to help avoid nuisance tripping that must be set up at time of start-up. The name varies by manufacturer for the algorithm change. Consult the manufacturer and the instruction booklet for setting up the VFD for a high impedance source such as a generator application and if you plan to harmonically mitigate the drive with any device that requires adding impedance to the system.

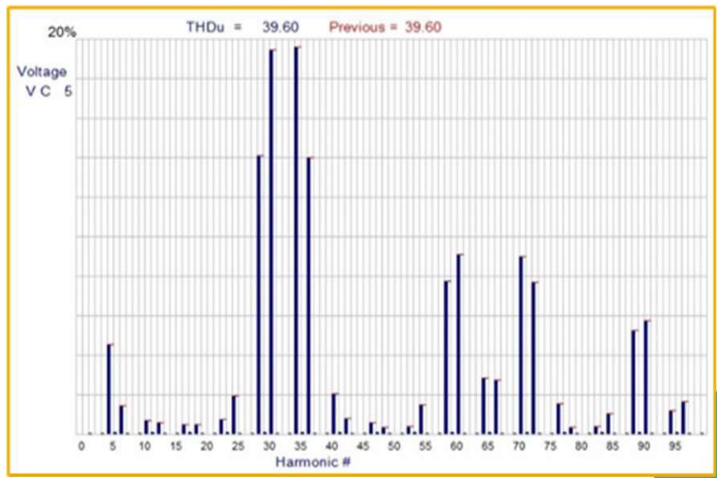
Section 5: Typical VFD Output Options and Waveform Conditioning

The typical Inverter Output Voltage Waveform is a PWM (Pulse Width Modulated) waveform which due to the pulse widths approximates a variable RMS voltage to drive the motor.

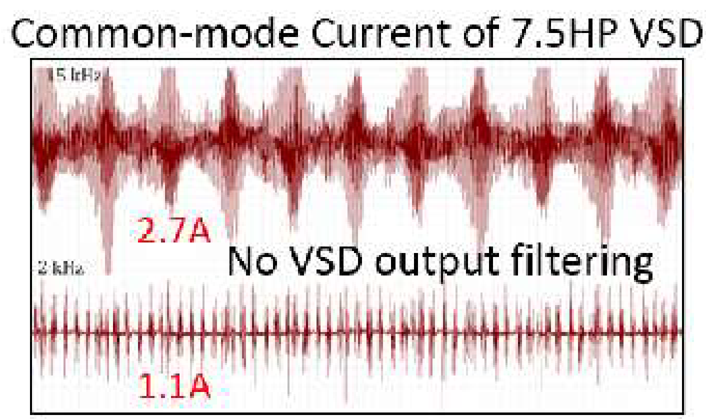
The dV/dT sequences, 0V to peak, create significant repetitive di-electric stress on the secondary circuit, cable and load motor, which can lead to premature failure due to compromise of the phase to phase and phase to ground insulation materials. It can also trigger additional losses within the secondary circuit due to the creation of high levels of eddy current losses within all components of the secondary circuit, cables & load motor.

Below is a typical PWM wave trace and voltage distortion harmonic spectrum.





Another issue with utilizing an IGBT Inverter assembly is the creation of common-mode noise. 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 and partial discharge in the motor and motor feeder cable. High frequency capacitive coupling exists across the motor bearings and between the feeder conductor or motor winding and ground, and can lead to premature motor bearing failure, mechanical load bearing failure and cable insulation breakdown.

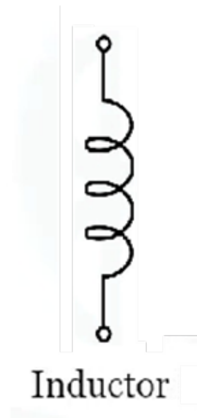


The discussion of Inverter Output Options below will discuss both differential mode and common mode noise challenges within the secondary circuit.

© Inverter Output Options:

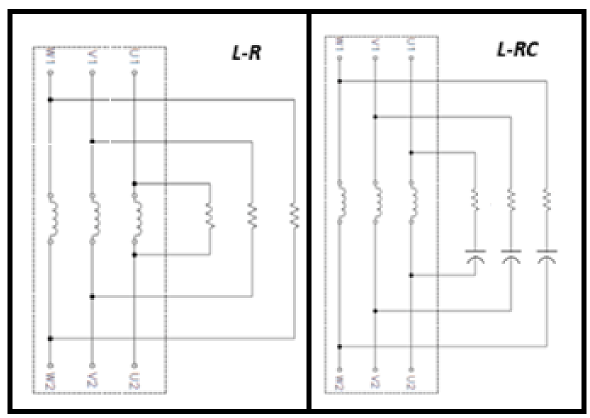
The most common inverter output options are added typically to either detune or add impedance to the output circuit to avoid resonance/reflective wave due to the switching frequency of the inverter be in and about the natural resonance frequency range of the secondary circuit. Common Mode noise attenuation can be achieved by the utilization of Common Mode Chokes within the secondary circuit. These options include Output Inductors/Reactors, dV/dT filters, Sinewave Filters, and Common Mode Attenuation via Common Mode Chokes with the Sinewave Filter.

- Output Inductors/Reactors: For short or medium length secondary cable runs, many times engineers will specify an output inductor/reactor with an impedance of 1-1/2% to 5% to shift the secondary resonance characteristic of the circuit. The introduction of this secondary impedance can and will lower the overall efficiency of the VFD operation, resulting in higher energy costs and lower production due to the higher current at the lower supply voltage to maintain real power. Physically the PWM waveform on the output of the inverter is still present, with a high dielectric stress value from the significant zero to peak rate of change of voltage on the secondary cables and load motor.



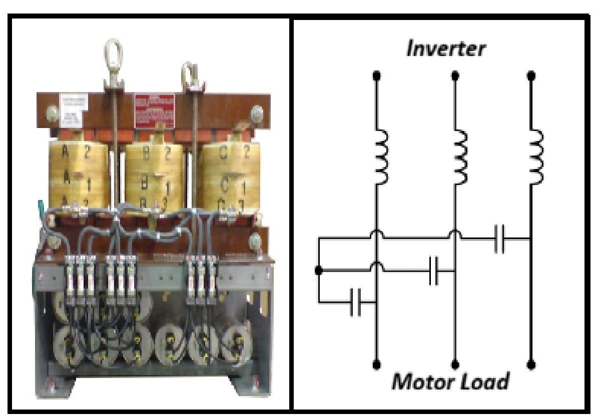
Typically, the manufacturer may advocate for an Output Reactor feeding motor leads of 100-300 feet.

- DV/DT Filters: A DV/DT filter is a variation of a standard inductor networked with a resistive element. It can be configured as a parallel L-R circuit or even may even include a capacitive element. These devices are advertised for medium to long cable lengths to prevent resonance/reflective- wave during inverter operation. ***<u>The advent of adding a dv/dt filter will not eliminate the dielectric stress of the PWM waveform on the secondary cabling and load motor, but can add up to 7% secondary impedance with some designs lowering the operating efficiency of the VFD/Load circuit.</u>*** The DV/DT filter functions to detune the secondary circuit in an effort to avoid resonance/reflective wave between the Inverter and load circuit structures.



Typically, the manufacturer may advocate for a dV/dT for motor leads from 300 feet to 1000 feet.

- Sinewave Filters: A Sinewave filter is designed to convert the PWM Inverter output voltage waveform to a sinusoidal waveform, functionally eliminating the possibility of secondary circuit resonance/reflective wave and the associated surges and transients that can develop. Most commercial Sinewave filters are tuned to 600 Hz, which will allow a high level of 5th and 7th harmonic voltage distortion to be injected into the load circuit. Tuning at 180Hz is available from suppliers, which will lower secondary cable and load eddy currents and further improve the secondary circuit efficiency. In addition, a Common Mode Choke can be integrated into the Sinewave assembly to attenuate common mode noise, parasitic capacitance discharge within the cable run, and controlling partial discharge across motor



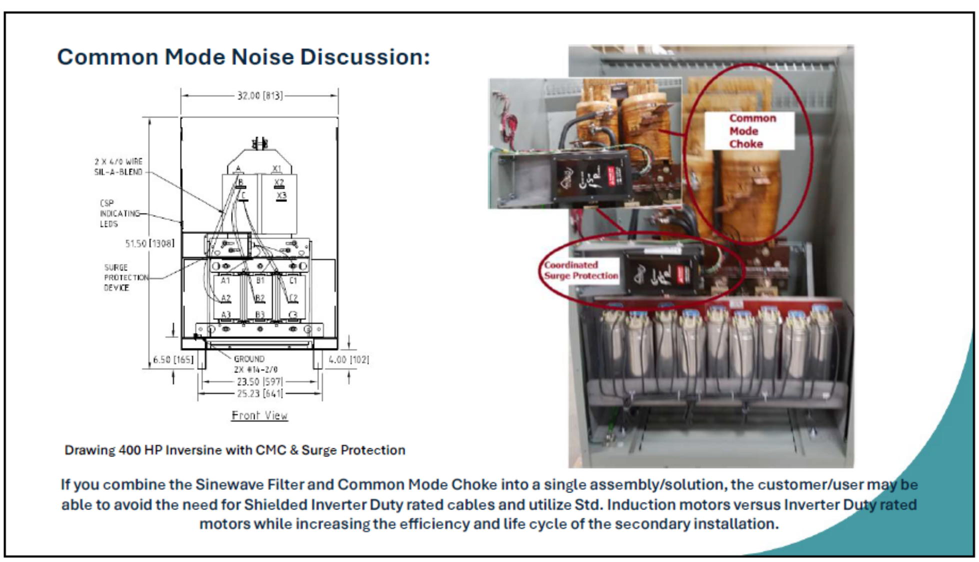
bearing assemblies to increase the life cycle of the load assembly. See Common Mode Choke section for further information. A Sinewave filter is the best solution to secondary circuit cable length and resonance/reflective wave concerns. It will also increase the overall efficiency of the VFD circuit through the significant lowering of Eddy current losses within the entire secondary circuit.

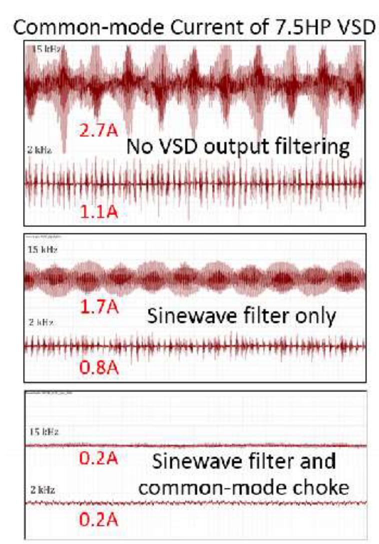
Typically, the manufacturer may advocate for a Sinewave filter feeding motor leads from 500 feet to 15000 feet.

Key specificational points for high efficiency and low voltage boost passive filter qualification are listed below:

- **The general Sinewave Filter topology shall be LC low pass circuit.**
- **The Sinewave Filter shall be designed to attenuate the carrier component, and its harmonics present in the output waveform of a typical PWM frequency converter (inverter) and produce sinusoidal output voltage waveform that has less than 5% THD(V) (voltage total harmonic distortion) measured to the 100th harmonic.**
- **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 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 shall also be eliminated when common-mode option is included.**
- **The Sinewave Filter shall have efficiency of no less than 99%.**
- **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. This shall lower overall filter insertion loss (ie. voltage drop) to < 3%.**
- **The Sinewave Filter 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.**

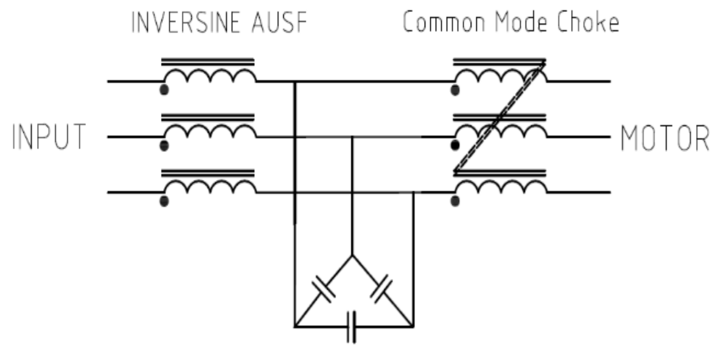
- Common Mode Chokes: A Common Mode Choke can be deployed within a secondary circuit to attenuate common mode noise within secondary circuits. A Common Mode Choke is different than a Common Mode Filter. Common Mode Chokes cancel/attenuate the common mode noise, where a Common Mode Filter functionally shunts the common mode noise to the





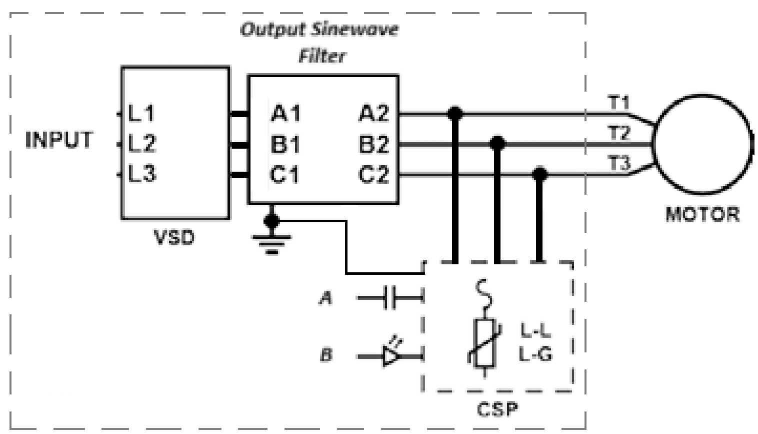
ground adding high frequency currents to the ground grid and inducing voltage and voltage distortion within the systemic single-phase distribution. It is preferred to combine the Common Mode Choke with a Sinewave filter for better attenuation of the common mode element due to the coordination of the two assemblies.

- **If you combine the Sinewave Filter and Common Mode Choke into a single assembly/solution, the customer/user may be able to 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. This can save significant installation costs for the cable and motor load. See Appendix A for example study.**



- **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 add additional saving on top of the initial installation cost saving discussed. Typically, depending on the secondary circuit physical characteristics, a 2% - 5% energy saving can be realized.**

- A CSP can provide voltage surge and transient attenuation like when deployed within the line-side circuit. The transients/surges in this case are typically created by secondary circuit resonance/reflected wave conditions and secondary circuit exposure to lighting strikes and other induced voltage events from either load or installation conditions. Functionally, the CSP is intended to protect the VFD assembly from over-excitation and dielectric stress by shunting the transient to ground. It should be noted, the advent of adding a CSP to a secondary circuit can create a "backdoor" for ground based transient events into the secondary circuit through the Ground MOV conduction. The CSP can be integrated into the Sinewave filter or be separately mounted within the VFD assembly as required. Utilization within industrial applications is not common, but a growing number of installations are utilizing this feature if secondary reflective wave or load circuit-based transients have been previously experienced.



Section 5: Schedule/Matrix

Mitigation Device/Topology	IEEE-519 Compliance & Harmonic Notes	Cost Profile	Notes
VFD Topology with Line-side Options/Harmonic Mitigation			
6-Pulse Drives **Line Reactors**	**No**	**Inexpensive**	• Will not lower the Ithd of the non-linear load to IEEE519 levels. • Adds a high voltage drop into the circuit which can impact energy efficiency. • May be utilized for small frame VFD applications where the demand distortion is not significant. • It is not recommended to add a line reactor to a VFD chassis that already has a DC link inductor due to cascading inductor impedances the potential for over-current conditions and triggering overcurrent trips due to that excessive voltage drop. • Advantage: A very practical mixed harmonic mitigation strategy for small chassis loads to control overall cost and budget limits. • Advantage: Easily serviceable without factory service assistance
6-Pulse Drives **DC Chokes**	**No**	**Inexpensive**	• Will not lower the iTHD of the non-linear load/VFD to IEEE519 requirements. • Typically reduces iTHD to around 25% to 35%. • DC chokes can be easily utilized in conjunction with other harmonic treatments dramatically improving harmonic performance. • It is not recommended to add a line reactor to a VFD chassis that already has a DC link inductor due to cascading inductor impedances the potential for over-current conditions and triggering overcurrent trips due to that excessive voltage drop. • Advantage: Since the DC choke is typically integrated by the manufacturer, there is no concern over proper VFD sizing and coordination and preferrable to AC Line Reactors integrated by third party contractors or integrators. • Advantage: A very practical mixed harmonic mitigation strategy for small chassis loads to control overall cost and budget limits.
6-Pulse Drives **Passive Filters**	**Yes**	**Moderate Expense**	• Will comply with IEEE519 Ithd requirements, increases net efficiency of the load drive by significantly reducing reactive power consumption and systemic harmonic eddy current losses. • **<u>Specification of a Reactive Power to filter power ratio (kVAR/kW) of 15% or less is important to avoid over-</u>**

6-Pulse Drives **Passive Filters** **Continued**			**excitation, voltage boost, and to avoid potential resonance conditions**. • By specifying a low capacitance reactance profile for the passive filter, you can avoid having to add capacitor contactors to reduce no-load and low-load voltage boost to the VFD, reduce the potential of over-excitation of alternate source back-up generation, reduce control circuit complexity and lower installation costs.
12/18 **Multi-pulse /Phases Shift Drives**	**No**	**Expensive**	• More expensive than 6P-Diode Bridge VFD's even when the 6-P VFD is equipped with an IEEE compliant harmonic filter. • 12P VFD designs are not IEEE519 compliant. • 18P VFD's which utilize Auto Zig Zag transformer for the phase shift cannot withstand either 2% Vthd-bg or 2% V-Imb and effectively mitigate Ithd. • Many manufacturers are discontinuing these designs since they now recognize they were vulnerable to performance compromise based on real world conditions. • The original multi-pulse drive design utilizing isolation transformers versus autotransformers was a qualified offering to the industrial market, with extended life cycles. Isolation transformer 19-P Multipulse Installations that still meet IEEE519 compliance are still commonly seen within many industrial applications with over 20 years life cycles. • Lower operational efficiency than 6-Pulse Rectifier VFD's equipped with qualified harmonic passive filters, due to higher harmonic reactive power consumption under real world conditions. • Can be coupled with Typical VFD Output Options and Waveform Conditioning – See Section 5
AFE Drives (Active Front-End Drives)	**Yes, through the 50th harmonic only**	**Very Expensive**	• The drive cost indexed by HP is very expensive and cost prohibitive. • Not easily serviceable without factory service technical assistance. • Introduces high frequency harmonics above the 50th (3kHz) and not compliant with IEEE519 when reviewed through 2.5x the rectifier switching frequency, i.e. >3kHz – 8 kHz. • Vulnerable to Source Background Voltage Distortion and systemic voltage imbalance. *Consult the manufacturer for Vthd-source and Source Vimb performance warranty limits.* • Higher losses and lower efficiencies than similarly rated 6 Pulse ASDs with passive harmonic filters

AFE Drives (Active Front-End Drives) Continued			• When 6-Pulse VSDs and AFE Drives are on the same switchboard, voltage ripple from the AFE Drive can raise the DC bus voltage in the 6-Pulse VSDs creating overvoltage conditions.
AHF Filters (Active Harmonic Filters)	**Yes, through the 50th, and if properly sized to the non-linear loads**	**Very Expensive**	• Parallel Active Harmonic filters require additional circuit protective equipment feeding their installations, typically priced at over $ 25K per 200A module plus ancillary equipment requirements. • Requires CT installation and coordination for retrofit switchboard applications. • Requires a qualified harmonic study to assure proper sizing to the non-linear load structure. • Higher order harmonic injection is possible. • Disadvantage: Complexity of design requires factory trained personnel for commissioning and servicing. • Advantage: Can be programmed to treat displacement power factor challenges within the circuit but will take away capacity from harmonic current control capacity. • Advantage: Can treat multiple VFD loads (systemic harmonic mitigation) effectively without having to size the filter for the linear load component of the secondary load structure.
VFD Output Options & Notes			
Output Reactors/Inductors	**High harmonic voltage will be injected into the output circuit due to PWM output waveform,** **No assurance of limitation of potential for control of resonance/reflecting wave creation.** **No limitation for potential transients and surges effecting secondary cable runs and load motor.**	Low Component Cost	• The concept of adding the reactor/inductor is to change the natural resonance point of the secondary circuit to avoid resonance/reflective wave/ringing of the secondary circuit. But, <u>without a resonance analysis of the secondary circuit there is no warranty for meeting that intent.</u> • Adds a high through impedance to the secondary circuit lowers voltage seen at motor by the impedance value of the inductor at full load. Typical secondary reactor/inductor impedances can range from 1-1/2% to 5% which can lower the overall efficiency of the VFD installation. Can prevent motor from achieving full speed and reducing maximum capacity of the load. • There is no attenuation of the PWM waveform meaning there is a high dielectric stress still present on the secondary cable insulation and motor winding assembly. • Typical voltage distortion within the secondary circuit will range from 35% to over 50%, triggering high levels of eddy current losses within the cable run and motor windings. • No attenuation of Common Mode Noise • Minor attenuation of differential mode noise.

Output dV/dT filters	**High harmonic voltage will be injected into the output circuit due to PWM output waveform,** **No assurance of limitation of potential for** **control of resonance/reflecting wave creation.** **No limitation for potential transients and surges effecting secondary cable runs and load motor.**	Low Component Cost	• The concept of adding the dV/dV filter is to change the natural resonance point of the secondary circuit to avoid resonance/reflective wave/ringing of the secondary circuit. But, without a resonance analysis of the secondary circuit there is no warranty of meeting that intent. • Adds a high through impedance to the secondary circuit lowers voltage seen at motor by the impedance value of the inductor at full load. Typical secondary dV/dT filter 2-1/2% to 5% which can lower the overall efficiency of the VFD installation. Can prevent motor from achieving full speed, reducing maximum capacity of the load. • Many dV/dT filters incorporate a resistive element, which makes the heat rejection higher than other std. inductor capacitor network designs and more prone to premature heat related component failures. • There is no attenuation of the PWM waveform meaning there is a high dielectric stress still present on the secondary cable insulation and motor winding assembly. • Typical voltage distortion within the secondary circuit will range from 35% to over 50%, triggering high levels of eddy current losses within the cable run and motor windings. • No attenuation of Common Mode Noise • Minor attenuation of differential mode noise. • Difficult to apply to high-speed Permanent Magnetic Moor applications • Integration of secondary surge protection is problematic.
Sinewave Filters	**Sinusoidal Output with less than 8% voltage distortion with low 5th and 7th harmonics when tuned to <3X fundamental frequency.** **Secondary circuit efficiency is significantly enhanced due to lower eddy current losses within the secondary circuit.**	Moderate Expense	• Converts the PWM waveform to a sinusoidal waveform • Typical tuning of the filter is 10X fundamental frequency (600 Hz), which will allow for high 5th and 7th voltage distortion to be injected into the secondary circuit. Increasing losses and resonance/reflective wave may still be present due to the higher harmonic frequency being present. • Specification of a 3X fundamental frequency tuning (<180 Hz) will provide optimum performance via lower voltage distortion being fed to the load structure and lower eddy current losses. In addition, attenuation of the carrier components at the rate of >40db per decade while minimizing the absorption of fundamental current by the filter will be possible. • Regardless of cable lead lengths by converting the PWM to a sinusoidal waveform will increase the secondary circuit overall efficiency due to the significant reduction

Sinewave Filters **Continued**			in cable and motor losses due to differential noise reduction. • Typically, the manufacturer may advocate for a Sinewave filter for motor lengths from 1000 feet to 15000 feet. • A key specificational point it to require no greater than 3% voltage drop across the Sinewave filter at full load, maximizing energy efficiency of the load and secondary circuit. • Partial attenuation of common mode noise. • Significant attenuation of differential mode noise due to a the PWM waveform being converted to a sinusoidal waveform.
Sinewave w/ Common Mode Choke **See Appendix A for Cost analysis of Cable Cost Saving Potential**	**Same benefits as the SWF above plus significant reduction in high frequency P-G noise (Common Mode Noise) which will reduce cable and motor parasitic capacitance and partial discharge through insultation systems and motor/mechanical device bearings**	Moderate Expense *Significant secondary circuit cost savings are available due to elimination of the need for inverter duty rated cables and motors.*	• Virtually eliminates common mode noise, significantly reducing parasitic capacitance discharge through the cable runs and increases the expected life cycle of the motor and cable leads. • When a Sinewave filter is paired with a Common Mode Choke Inverter rated cable and motors are no longer needed since both the differential mode and common mode noise is virtually eliminated .In many cases, the cable installation cost savings will more than offset the output SWF w/ CMC and in very long cable runs may even offset the drive assembly capital costs. • See Appendix A for cost saving discussion on inverter duty cable versus std. XHHW. The example is forwarded to highlight a real-world example.

Section 6: VFD Design Cost and Performance Matrix

VFD Topology Cost Comparative: All VFD's are Indoor single assembly enclosures, no load/output components or assemblies. (Based on Jan. 2026 pricing)				**Harmonic Perf.**	**Capital Cost Profile**	**Notes**
Topology	**100HP Assembly***	**400 HP Assembly***	**Equipment Spec**			
6 Pulse with AC Line Reactor	**$10,689/$106.00/HP**	**$26,818/$67.00/HP**	**NEMA 1 Enclosed with MCB & 120V Controls**			**Low Cost VFD design** **Poor harmonic performance.**
6 Pulse with DC Link Inductor	**$10,017/$100.00/HP**	**$25,269/$63.00/HP**	**NEMA 1 Enclosed with MCB & 120V Controls**			**Low Cost VFD design** **Poor harmonic performance.**

18P VFD with auto phase shift zig/zag transformer	$27,800/$278.00/HP	$58,000/$145.00/HP	NEMA 1 Enclosed with MCB & 120V Controls			High Equipment costs with poor harmonic performance under real world application conditions
6 Pulse VFD with low capacitance passive filter no capacitor contactor.	$22,380/$224.00/HP	$49,795/$125.00/HP	NEMA 1 Enclosed with MCB & 120V Controls			Moderate equipment cost, Qualified IEEE-519 harmonic requirements for total demand distortion.
Active Front End Drive which incorporates LCL EMI filter	$36,687/$367.00/HP	$89,556/$224.00/HP	NEMA 1 Enclosed with MCB & 120V Controls			Very expensive design, the least energy efficient operational design. Compliant with IEEE-519 through the 50th harmonic assuming less than 2% Vimb and Vthd-bg, not compliant when measured through 2.5X the rectifier switching frequency.
* Assembly Pricing does not include some common options and required coordination ancillary equipment. Cost per HP is rounded for convenience and meant generally as a rule of thumb. Costing does not include freight, installation labor, or start-up and testing.						

Section 7: Paper/Technical References

ACTIVE HARMONIC MITIGATION – WHAT THE MANUFACTURERS DON'T TELL YOU Copyright Material IEEE Paper No. PCIC 2018-43 Anthony Hoevenaars, P.Eng, Member, IEEE, Mirus International Inc., 31 Sun Pac Blvd., Brampton, ON L6S 5P6, Canada Marek Farbis, Member, IEEE, Mirus International Inc., 31 Sun Pac Blvd., Brampton, ON L6S 5P6, Canada Mike McGraw, Member, IEEE, NSOEM, 33427 Mayer Rd., Waller, TX 77484, USA	MIRUS International Inc. MIRUS-TP006-A [2020-05-12] A Practical Guide to Partial and Staged Harmonic Mitigation Strategies Michael A. McGraw Regional Manager: Southern USA
VFD's & Harmonic Mitigation in Modern Water/Wastewater Applications Michael McGraw – Five Star Electric, Kris Kotrla – McCreary Associates, & Austin Miller – Electromechanical Corp/Mirus International Venue: TXWATER 2025, Houston TX, March 20,2025 Presentation 2093	When is Enough - Enough or Maybe Too Much? Design Considerations for Harmonic Mitigation Strategies Michael A McGraw, Five Star Electric, Inc. FSE Document: FSE-MM-2025-11-08 Copyright © 2025-11-08
"An Ounce of Testing Can Save a Pound of Cure" A Discussion of Requirement for and Benefits of Specification of a New Installation and Retrofit Testing Protocol for LV VFD/ASD Projects FSE Document: FSE-MM-10202025 Copyright © 2025-10-20 Five Star Electric.	

Special thanks to:

Paul Hoevenaars – General Manager – Mirus International, Russ Brehm – Service Manager – Five Star Electric, and Mark Hajda – Director of Sales Five Star Electric for their review and contribution to the paper development.

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 immpact 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.