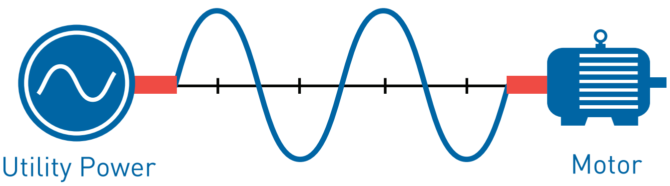
Variable Frequency Drive Effects on Power Quality.

A simplified approach to what you need to know.

"Across the Line" Motor Application... Why VFDs Are Needed

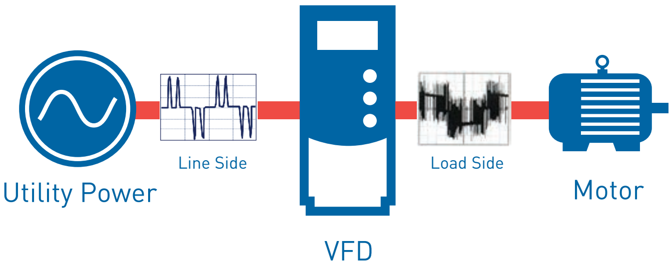
When a motor runs directly from the power source, it is said to be running "across the line". In this approach, there are uniform, sinusoidal current and voltage waveforms and relatively few power quality concerns.



Unfortunately, this method is significantly inefficient because the motor is continuously running at its top speed, regardless of the requirements placed on it by the load. The application uses the energy it needs, and the rest of the energy is wasted.

VFDs Add Efficiency... But Create Power Quality Issues

Adding a VFD to electrically control motor speed increases efficiency by limiting energy consumption and reducing equipment wear. However, VFDs inadvertently create power quality issues in the form of harmonics, which are changes or distortions in the waveforms. There are different types of harmonic distortions on the line and load side of a VFD.



On the line side, harmonics are created because the incoming side of a standard six-pulse VFD does not draw current linearly. Instead, it pulls in six distinct pulses that each use some of the current and send the unused portion back to the source as current harmonics. Since current and voltage are proportional, current harmonics ultimately affect voltage, which impacts connected equipment. This is not only a problem for equipment in the same facility as the offender, but for any consumer who shares a connection to the facility.

On the load side, the VFD does not feed the motor a true voltage waveform, but rather series of electrical pulses in a pattern that replicates an AC sinewave. This is called pulse-width modulation (PWM) and although it is effective at precisely controlling motor speed, it creates harmonics that can damage motors, cables and bearings. The problems are magnified if the physical distance between the VFD and motor is long.

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IEEE-519 STANDARD

The Institute of Electrical and Electronics Engineers (IEEE) provides some guidance about harmonic distortion. The IEEE-519 standard is a recommended practice for acceptable levels of harmonic distortion at a facility's "point of common coupling," or the electrical connecting point between the facility and the public power system. From a user viewpoint, it is a guideline for setting limits on how much harmonic distortion a facility's total system can pass back to the grid. The goal is to limit the harmonics from individual customers, so they do not cause unacceptable distortion for the neighboring population. In exchange, the utility promises to act to maintain prescribed levels of voltage distortion going to a facility.

Line Side Harmonics Problems

The two main line side harmonic concerns are the problems caused in the facility where they are being generated and the degree of harmonic infection passed to neighboring facilities. The degree of impact for either area depends on the number, size and frequency of use of all linear and non-linear loads (including VFDs).

Within the facility

Within a facility, the ultimate expense of line side harmonics are the costs of frequent downtime or errors, premature equipment replacement and utility expenses. Some of the specific problems a facility may experience include:

- Inadvertent "nuisance" tripping of breakers, fuses and relays are caused by harmonic current peaks that are higher than standard waveforms.
- Logic faults in digital devices, malfunctions of automatic control systems and inaccuracy of instrument measurement are possible because harmonics can alter the parameters these devices are designed to run on.
- Current harmonics create inefficiencies that cause overheating in the supply transformer and cables feeding the VFD.
- High harmonics require oversizing, where equipment is sized larger to accommodate harmonics. This adds additional cost and may make it difficult, or impossible, to expand facilities.
- Higher utility bills caused by increased total power consumption. Additional current harmonics represent reactive power (power not actually used to complete work). Since utilities typically bill for total power (active + reactive power), they are both still included in a facility's utility bill.

Neighboring facilities

Since line side harmonics are being pushed from the VFD back to the source power, most of the problems seen in the offender's connected equipment can eventually be seen by neighboring facilities connected to the same utility distribution system. To avoid this overabundance of dirty power, many utilities require compliance to the IEEE-519 standard. Utilities also investigate individual facility harmonics when connected customers complain or if the utility experiences voltage distortion over its system. Offending facilities can be fined and have their power limited or cut off if they are not able to improve their harmonic output.

Load Side Harmonics Problems

Load side harmonic issues are related to differential mode or common mode. In addition to individual problems related to each mode, excess heat generation and audible noise are shared concerns.

Differential mode

Differential mode is associated with the voltage used to power the motor. Elevated differential mode voltages create premature cable and motor failure. The effects worsen as the distance between the VFD and motor increases. As the distance grows, the increasing cable resistance and electricity flow to and from the motor cause the peak voltage and rise time to increase and multiply. This is referred to as creating a reflective wave.

Common mode

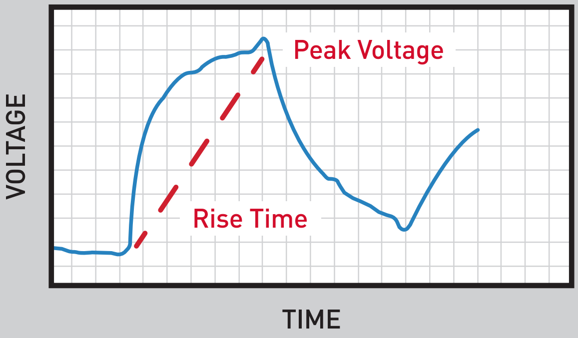
Common mode problems are associated with the flow from line to ground. Utility power produces three smooth waveforms that at any point average a sum of zero. This is an ideal scenario with no common mode effect. VFDs give power through pulses that on average achieve a sinewave. The sum at any point is never zero, which results in damaging common mode voltage and current that travel through the cabling and motor. Over time, common mode voltages can cause pitting to motor bearings and premature motor insulation failure. Common mode ground currents can cause unexpected ground fault trips and erratic behavior on VFD or PLC controller boards.

Differential mode explained

Peak Voltage; the highest voltage point on the waveform. Each pulse going from the VFD to the motor begins with a spike of voltage. High peak voltages can cause pinholes in the motor's insulation, allowing access to the motor windings and causing premature failure.

Rise Time; the time it takes voltage to rise from its minimum to its maximum value. Due to the on/off switching that creates the VFD's PWM output, the growth of a voltage wave takes place too fast. The faster the pulse grows, the higher the levels of voltage between turns of the motor coil, causing the insulation system to wear away more quickly and shortening the motor's life.

dV/dt; the rate the voltage changes over time, or the slope of voltage rise time. dV/dt can be approximated as 80% of the peak voltage divided by the rise time. High dV/dt rates produce a reflection of the incoming voltage pulses at the motor terminals.



Line Side Industry Solutions

OPTION	COST	PROTECTION LEVEL	SIZE	COMPLEXITY	AVAILABILITY	USAGE NOTE
NO MITIGATION DEVICE	NONE INITIALLY; ULTIMATELY HIGH	>85% THID	N/A	START LOW; END HIGH	N/A	RISK OF FREQUENT DOWNTIME
LINE REACTOR	LOW	30-40% THID	SMALL	LOW	READILY AVAILABLE	MTE'S RL IS LINE/LOAD COMPATIBLE
PASSIVE HARMONIC FILTER	MODERATE	<5-12% THID	SMALL - MODERATE	LOW	READILY AVAILABLE	MTE'S ADAPTS TO VARYING LOADS
MULTI-PULSE DRIVE	HIGH	10-15% THID (12p) 5-8% THID (18p)	LARGE	HIGH	CAN BE LENGTHY	POPULARITY IS DIMINISHING
ACTIVE HARMONIC FILTER	HIGH	3-5% THID	MODERATE	HIGH	CAN BE LENGTHY	APPLIED AT THE SYSTEMLEVEL
ACTIVE FRONT END DRIVE	HIGH	3-5% THID	MODERATE - LARGE	HIGH	CAN BE LENGTHY	CAN REGENERATE POWER

NOTE: Chart data is an aggregate of general industry conditions and is not specific to any one manufacturer.

Load Side Industry Solutions

OPTION	COST	PROTECTION FROM	PROTECTION LEVEL	CABLE LENGTH	USAGE NOTE
NO PROTECTION	NONE INITIALLY; ULTIMATELY HIGH	NO PROTECTION	NONE	ANY	RISK OF SYSTEM FAILURE
SHAFT GROUNDING RING OR BRUSH	LOW TO MODERATE	COMMON MODE	MINIMAL	ANY	NEED FREQUENT REPLACEMENT & ARE NOT USABLE IN EXPLOSIVE AREAS
COMMON MODE INDUCTOR/CHOKE	LOW	COMMON MODE	MINIMAL	ANY	CAN NEED MULTIPLE PER MOTOR
LOAD REACTOR	LOW	DIFFERENTIAL MODE	STANDARD	UP TO 300'	REDUCES MOTOR NOISE & HEAT
dV/dt FILTER	LOW TO MODERATE	DIFFERENTIAL MODE	STANDARD	UP TO 1,000'	MTE'S SOLUTION ALSO HELPS WITH COMMON MODE
SINEWAVE FILTER	MODERATE	DIFFERENTIAL MODE	STANDARD	UP TO 15,000'	MTE HAS SOLUTIONS FOR COMMON MODE AND HIGH FREQUENCY APPLICATIONS
ISOLATION TRANSFORMER + SINEWAVE FILTER	HIGH	DIFFERENTIAL AND COMMON MODE	COMPLETE	UP TO 15,000'	TYPICALLY USED IN STEP-UP APPLICATIONS (IE. MEDIUM VOLTAGE)

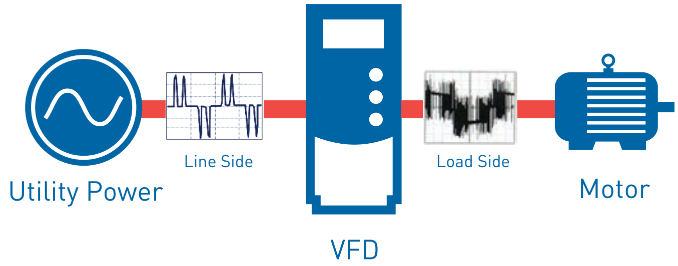
NOTE: Chart data is an aggregate of general industry conditions and is not specific to any one manufacturer.

NEMA MG-1, Parts 30 & 31

The National Electrical Manufacturers Association (NEMA) created NEMA MG-1 to define manufacturing standards for motors. Parts 30 & 31 of MG-1 are related to performance and have details about harmonic protection.

Part 30 of MG-1: States that standard, or non-inverter duty, motors should manage peak voltage of 1,000V, rise time of ≥2 microseconds (μs) and a dV/dt rate of 500V/μs. Non-inverter motors need more motor protection because they are not designed to protect against VFD harmonics.

Part 31 of MG-1: States that motors designed to work with VFDs, or inverter duty motors, should manage peak voltage up to 1,600V, rise time of ≥0.1μs and a dV/dt rate of 14,260V/μs (460V motors) or 17,825V/μs (575V motors). While inverter duty motors provide some protection from differential mode, protection may still be needed. Long cable lengths cause ringing, plus there is no common mode protection mentioned.



Line Side Harmonic Solutions

There are several line side harmonic mitigation solutions and there is no one size fits all. Factors like the size and types of loads, IEEE-519 compliance targets, timelines and project/maintenance budgets help determine which solution or combination of solutions are appropriate. Some common types of mitigation solutions are:

- **Line Reactors** are simple inductors made up of coil wire wrapped around a magnetic core. Passing current creates a magnetic field, increasing the impedance (degree of resistance) of the line and reducing the harmonic content returning to the system. They also offer some protection to the VFD from surges and other transients.
- **Passive Harmonic Filters** are a combination of reactors and capacitors that are tuned to eliminate some frequencies while passing others through. They lower harmonic effects inside a facility and often meet IEEE-519 requirements. They have VFD protection characteristics, guaranteed stability and little to no power consumption.
- **Active Harmonic Filters** monitor harmonic distortion levels and inject cancellation harmonic current into the line. They are more complex, using active components like transistors or amplifiers in addition to passive resistors and capacitors. They are usually designed for an entire system and are placed near the facility's power entrance. They will typically ensure IEEE-519 compliance, but do not always ensure that clean power is distributed throughout the facility and can be sensitive to the environment.
- **Multi-pulse & Active Front End (AFE) Drives** are types of VFDs that reduce the harmonics generated by using alternative technologies on the incoming side. Multi-pulse drives use phase shifting transformers and multiple diode bridges, while AFEs use an IGBT/diode-based converter. Since an AFE uses a power section on the incoming and outgoing portion of the drive, it can regenerate, or feed electricity back to the grid. Both types of drives can meet IEEE-519 standards, but are typically larger in size, require more maintenance and are more complex than a standard 6-pulse VFD.

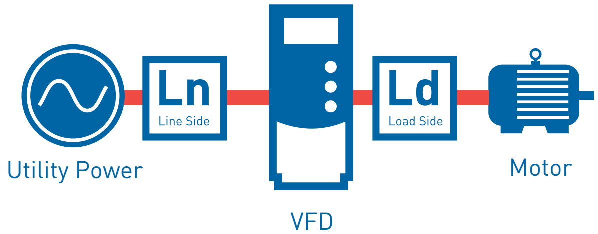
Load Side Harmonic Solutions

Load side protection means protecting the drive, motor and cabling. VFD manufacturers often suggest minimizing the distance to the motor and using inverter duty motors and VFD cables. These solutions are not always practical. In many cases, the application will not allow for close motor installation. Inverter duty motors and VFD cables can also be more expensive than using standard solutions with protection. Some common types of motor protection are:

- **Shaft Grounding Rings and Brushes** are mechanical devices that mount to the motor shaft. They reduce common mode effects at the bearings by providing an alternate path to ground, but may increase total ground current. Larger sized units can be costly and higher ratings require expensive insulated bearings.
- **Common Mode Inductor or Chokes** are mounted on the motor shaft and absorb common mode. Although they help with common mode, they do not have system damping resistance and may amplify current ring.
- **Load Reactors** are simple inductors like those used on the line side. They reduce dV/dt and audible noise and provide protection from voltage spikes. They also offer the VFD some short circuit protection.
- **dV/dt Filters** combine the current limiting ability of a reactor with a resistive capacitance circuit. They slow the rate of voltage increase and minimize the peak voltage that occur with long lead lengths so that they do not reach levels that can damage VFDs, cables and motors.
- **Sinewave Filters & Isolation Transformers with Sinewave Filters** offer the most complete protection. A sinewave filter cleans the PWM to provide a near clean sinewave output. It eliminates differential mode problems and significantly reduces audible noise. An isolation transformer is often combined with the filter. In this case, the system is at its ultimate protection because the transformer removes most of the common mode voltage. This solution can be used on any application but is not always cost effective if a change in voltage is not needed.

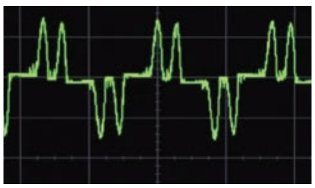
MTE's Power Quality Solutions:

The ins and outs of power quality are anything but simple. As the industry leader, MTE possess the know-how and experience to ease your power quality concerns. Our simple, robust solutions have a history of proven performance in nearly every industry. Their impact on the waveform distortion caused by VFDs can be seen below. To see a demonstration video of MTE products in action visit **mtecorp.com** and look for the "Product Demonstration Video" in our Video Resources section.

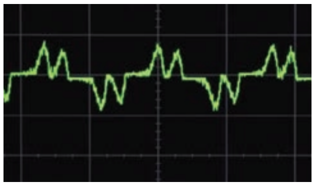


MTE's Line Side Harmonic Solutions

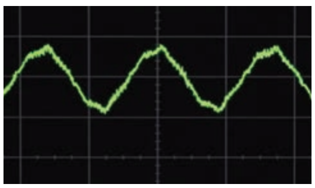
No Protection
Up to 85%+ current harmonics
Risk of failure & utility fines



RL Reactors
Reduces harmonics to 30-35%
150% continuous overload capability

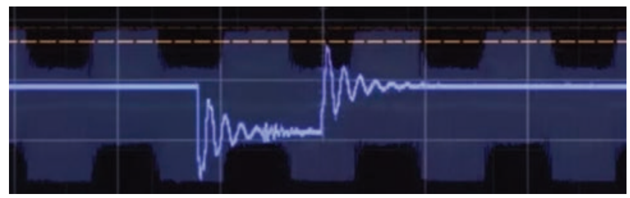


Matrix® AP Harmonic Filter
Reduces harmonics to 5%
Meets IEEE-519 standard

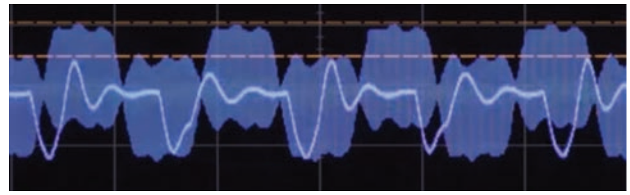


MTE's Load Side Solutions

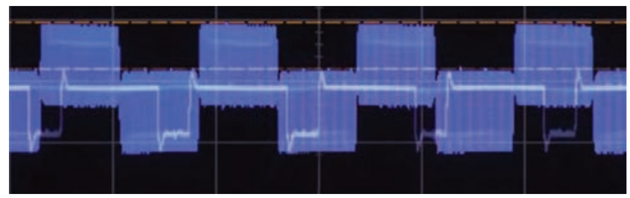
No Protection
Background: Distorted voltage waveform
Foreground: Reflected voltage wave (ringing)



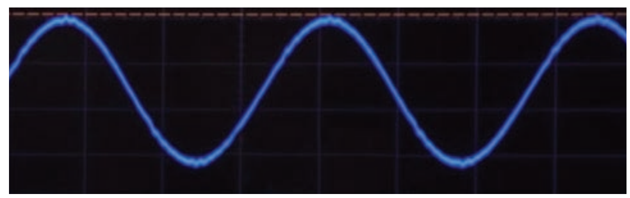
RL Reactors
For cable lengths to 300'
Line/load interchangeability without derating



dV Sentry™ Filter
For cable lengths to 1,000'
Triple defense: peak voltage, rise times, common mode



SineWave Guardian™ Filter
For cable lengths to 15,000'
Best protection, plus audible noise reduction



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