Technical Paper

Harmonic Filters for High Background Voltage Distortion Applications

Written By:
Ian Wallace, Ashish Bendre, Neil Wood
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Introduction

High background voltage distortion can result in equipment malfunction and reduce the likelihood of meeting IEEE-519. Background distortion levels of 5% and higher are being seen at facilities from oil and gas pumping sites to industrial plants. It is critical to select the right harmonic mitigation approach under these harsh voltage conditions.

Harmonic filters help users meet IEEE-519 current harmonic standards on typical industrial and commercial electrical power systems. These filters were usually installed on variable frequency motor drives (VFDs) in sites where the power system had low background voltage distortion (<1%-2% vTHD). However, with the continued proliferation of non-linear and VFD loads, customers are experiencing higher background voltage distortion at the utility point of common coupling (PCC) [1]. This can create difficulty in meeting current total harmonic distortion (iTHD) requirements at the PCC and maintaining the total voltage harmonic distortion (vTHD) within a facility to safe levels.

In rural oil and gas pumping locations across the US and Canada for example; it is not uncommon to have more than 5% background voltage distortion at the PCC before any pumping begins. The loads at such sites are typically VFDs. To be compliant with IEEE-519 current harmonic standards and achieve low current distortion (iTHD) under these harsh background voltage conditions it is critical to select the right harmonic mitigation approach.

Not all harmonic mitigation approaches are designed to operate well with background voltage distortion, including some passive filters and multi-pulse rectifiers. Choosing the incorrect filter technology may increase the voltage distortion and make it all the more challenging to meet IEEE-519 current distortion levels.

This paper outlines the causes of voltage distortion and identifies harmonic filtering solutions that will perform well under challenging background voltage distortion conditions.

Cause of Background Voltage Distortion

Voltage distortion is caused by harmonic currents flowing through power system impedances, such as long distance cable's parasitic inductance or a distribution transformer's series impedance [2].

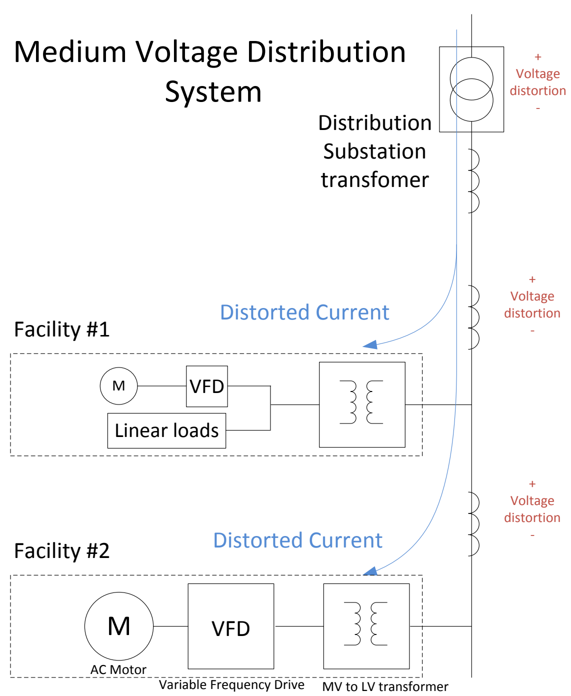

Figure 1: Effect of non-linear loads on nearby sites in a medium voltage distribution system [3]

The distortion, which can be present at the utility PCC before any load is drawn at a facility, is caused by harmonic currents produced by neighboring or distant facilities fed by the same power line. To illustrate this, a simplified MV radial power distribution system with multiple facilities is shown in *Figure 1.*

The system consists of a distribution transformer, multiple facilities with linear and non-linear loads connected via long cable lengths. Distorted, harmonic rich current drawn by Facility 2 creates background voltage distortion across the distribution cable inductance that will be seen by Facility 1.

Distorted current is drawn by standard 6-pulse variable frequency motor drives (VFDs), per *Figure 2*, and other non-linear loads. VFD input current contains a fundamental component (60Hz) and distortion current at odd, non-triplen integer harmonic multiples of the fundamental frequency (300Hz, 420Hz, etc.). *Figure 2* shows a 30% current distortion waveform (iTHD) producing a 1% voltage distortion (vTHD). *Figure 3* shows the impact of a more distorted current on longer distribution cables with larger cable inductance. A 40% iTHD line current produces a 5% vTHD that would be experienced by neighboring facilities as background voltage distortion.

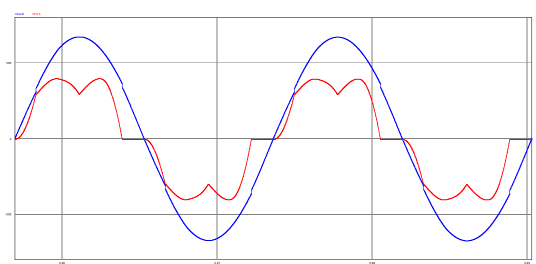

Figure 2: VFD line current waveform (red) with 30% iTHD and line voltage waveform (blue) with 1% vTHD

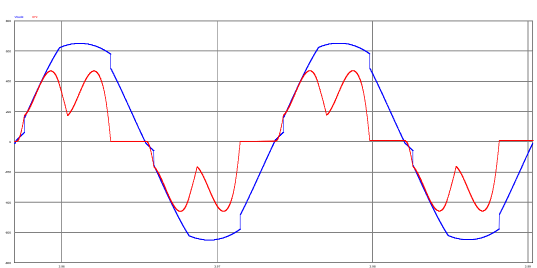

Figure 3: VFD line current waveform (red) with 40% iTHD and line voltage waveform (blue) with 5% vTHD

Impact of Background Voltage Distortion

The national harmonic standard, IEEE-519-1992, calls for voltage THD limits at typical, general facilities to be less than 5% vTHD. (IEEE-519-1992 Table 10-2, and duplicated in *Figure 4* below).

Harmonic voltage limits are necessary because typical industrial equipment can be sensitive to voltage harmonics. Usually, the manufacturers only guarantee performance when the background voltage contains no more than 5% vTHD. Higher levels can result in equipment malfunction and or erratic behavior [4].

Furthermore, IEEE-519 Table 10-3 prescribes current demand distortion limits (iTDD) at the PCC. These limits are based on the ratio of available short circuit current (I_{sc}) to load current (I_L) at a facility. The TDD limits range from

- a minimum of 5% iTDD for a heavily loaded power system (I_{sc}/I_L<20), to
- a maximum of 20% iTDD for a lightly loaded power system (I_{sc}/I_L >1000).

The presence of background voltage distortion causes two main issues that must be addressed to both meet IEEE-519 and ensure proper operation of equipment.

1. Background harmonic voltages drive higher levels of harmonic currents in both the linear and non-linear loads. This effect increases the voltage distortion created by facility loads, potentially exceeding the IEEE-519 vTHD limits and causing equipment reliability problems.

2. Many harmonic mitigation solutions do not work well in high background voltage distortion conditions. The current harmonic distortion can be above IEEE-519 levels and cause:
   - Motor, transformer and cable heating and insulation degradation.
   - Harmonic energy losses
   - Additional voltage distortion within a facility

	Special Applications: Hospitals, Airports	General System	Dedicated System (only converters)
Voltage THD	3%	5%	10%

Figure 4: Table10-2 of IEEE-519-1992 – Low Voltage System Classification and Distortion Limits

Effects of Voltage Distortion on Harmonic Mitigation Technologies

Background voltage distortion can significantly reduce the effectiveness of common harmonic mitigation equipment and filtering methods. Achieving 5% iTHD or even 8% iTHD levels with moderate 3%-5% background vTHD is not achievable in many cases without careful design.

Multi-Pulse Drives

Multi-pulse rectifiers are one of the available solutions to help meet IEEE-519 at a facility power system (e.g. 12-pulse and 18-pulse rectifiers). A schematic of an 18-pulse VFD and the input current waveform are shown in *Figure 5*. Under ideal voltage conditions the rectifiers' low order current harmonics (5^{th}, 7^{th}, etc.) circulate in the secondary side of the multi-pulse transformer and cancel before reaching the primary side. With a high quality, low vTHD primary voltage, a multi-pulse rectifier will have much lower current harmonics than a 6-pulse VFD. With no background voltage distortion and a balanced 3-phase voltage source, the 18-pulse rectifier can achieve 5% input current iTHD at full load [2].

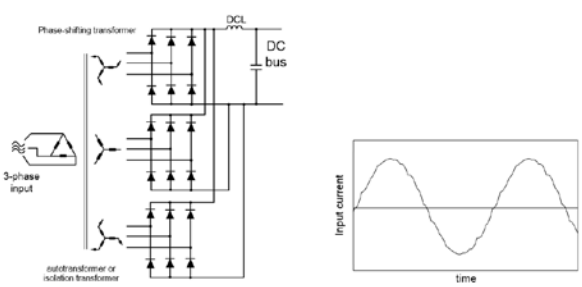

Figure 5: Schematic of an 18-Pulse Rectifier design and resulting low iTHD current waveform [5]

However, as the background vTHD increases, so does the current iTHD. Current iTHD can increase to 12% with 5% background vTHD (*Figure 6*), making the rectifier ineffective in meeting IEEE-519. The higher current distortion increases the voltage distortion further and may cause the vTHD to reach undesirable levels, affecting other equipment on the power system.

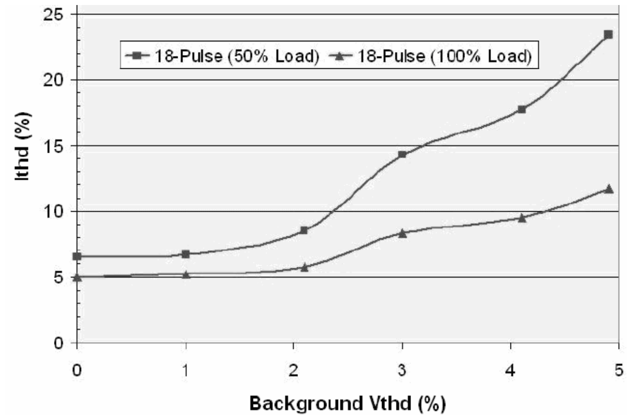

Figure 6: Effect of background voltage distortion on 18 pulse drive input harmonics [2].

Passive Filters

Passive filters are a common and cost effective means of mitigating harmonics from non-linear loads such as 6-pulse variable frequency motor drives and dc drives with SCR front ends. Passive filters are applied to the input of individual VFDs.

They are typically made up of (*Figure 7*):

i) A shunt connected LC circuit consisting of the tuning reactor and the capacitor bank. This circuit provides a low impedance path for the VFD harmonics to circulate so they do not reach the source.
ii) A line reactor that further blocks load harmonics from flowing in the source. It also blocks source voltage from driving harmonic currents into the LC circuit and load.

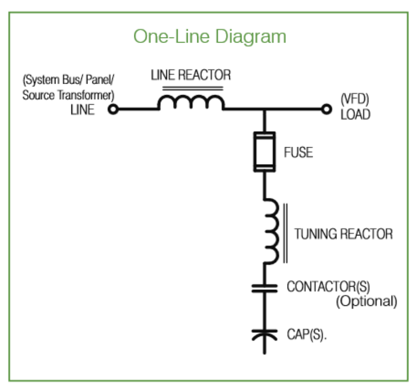

Figure 7: One-line diagram of a typical passive filter for a 6-pulse VFD [6]

Passive filters typically perform well under normal voltage conditions. They are commercially available from multiple vendors and when sized correctly can achieve current distortion levels less than 5% iTHD across the load range. TCI's HarmonicGuard Passive (HGP) filters can achieve less than 5% iTHD down to less than 40% drive load at typical installations. To verify the partial load performance and provide an equal platform for comparison, 75HP

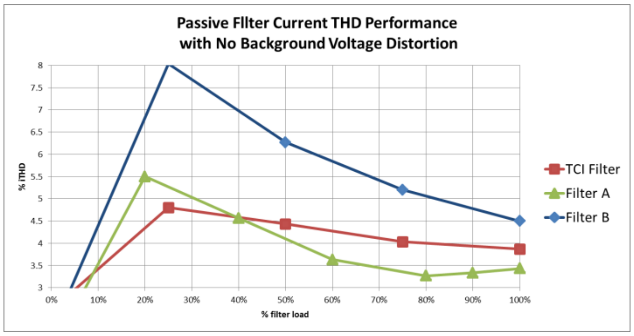

Figure 8: Passive filter current THD performance with no background vTHD

filters from TCI and other manufacturers were tested side by side. A common lab setup using a standard industrial VFD with 5% ac line reactance on a 250 kVA, 480V 3-phase power system was used to evaluate all three passive filters. The performance results are shown in *Figure 8*.

The performance curves clearly show the TCI filter can maintain less than 5% iTHD at full load, along with Filter A and Filter B. TCI's filter can also maintain less than 5% iTHD at lighter loads, unlike Filter B where the iTHD increased to 8%. This is extremely important in applications where a 5% iTHD target is specified and the VFDs operate at partial load.

Passive Filters with Background Voltage Distortion

Selection of the right passive filter under high background voltage distortion conditions is critical to meeting iTHD requirements and maintaining voltage THD to safe levels. Not all commercially available filters perform well under harsh voltage conditions.

A high background voltage configuration (H.B.V) of the TCI HGP filter maintains low iTHD with moderate to high vTHD. Filter performance under high background distortion was evaluated in side by side laboratory testing with other manufacturers. Current THD results are shown in *Figure 9*.

At full load the TCI filter is capable of a current iTHD below 5% with up to 5% background voltage distortion. This is a significant milestone, as the filter allows users to meet the most stringent IEEE-519 current THD limits with up to 5% background vTHD.

However, with Filter A, the current iTHD increases monotonically with vTHD as shown in *Figure 9*, which is undesirable. With 5% vTHD the filter lets through current with 9% iTHD, well above the first and second IEEE-519 performance tier of 5% and 8% iTHD respectively. Filter B performance is similar to the TCI filter with high vTHD.

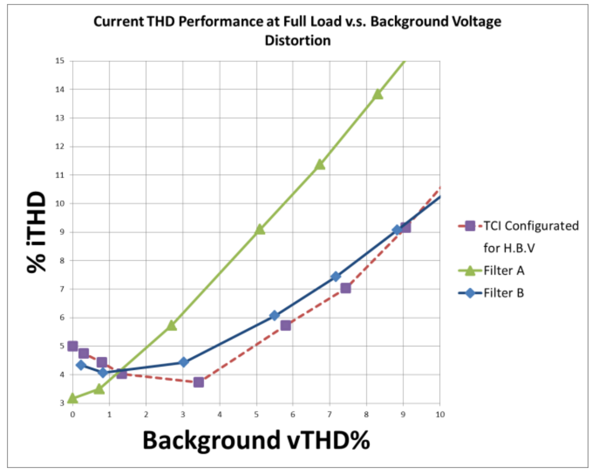

Figure 9: Passive filter current iTHD performance at 100% load with background voltage distortion present

Active Filters

Active filters monitor harmonics on the line or load and inject a counter current to cancel these out. They are also capable of correcting the power factor to unity. Active filters are commonly applied at the bus level to compensate for a single large drive or multiple smaller drives (*Figure 10*). An active filter with standard 6 pulse drives can be a cost effective alternative to 18 pulse VFDs or use of multiple passive, drive-applied filters [7].Active filters are known in the industry to be high performing even under varying load conditions and voltage quality. Active filters can reduce the source current iTDD to less than 5% with 10%-100% load on the VFD.

TCI HarmonicGuard Active filters (HGA) are capable of meeting IEEE-519's 5% iTHD facility requirement in low and high voltage distortion conditions. The filter monitors the source current and provides the harmonic current needed by the load(s) – resulting in a source iTHD less than 5%.

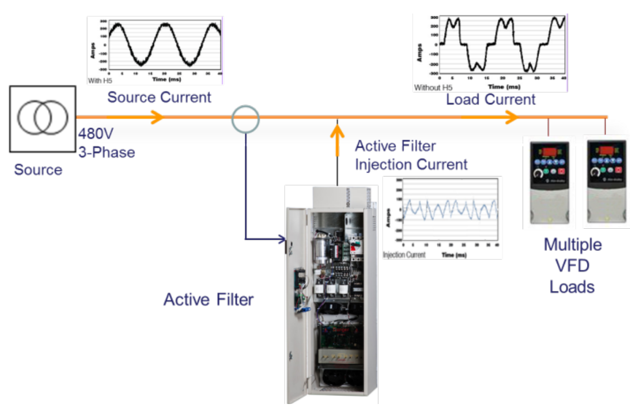

Figure 10: Active filter in an industrial power system

Active Filters with Background Voltage Distortion

TCI HGA active filters are immune to most power system disturbances and their performance is mostly independent of the voltage distortion present at the source. TCI HGA active filters monitor both the source current and source voltage. They use this information to control the amplitude and phase of the injection current, independent of the voltage distortion present on the source. Laboratory experiments have verified this performance and show the active filter capable of maintaining the source current to < 5% iTDD for a voltage distortion of 8% (*Figure 12*) and beyond.

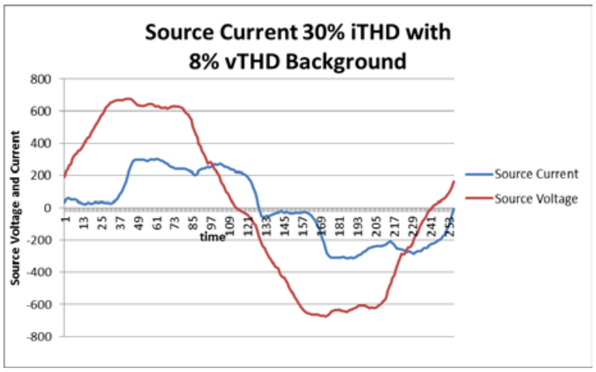

Figure 11: Baseline VFD current and voltage with 8% vTHD background (without Active Filter)

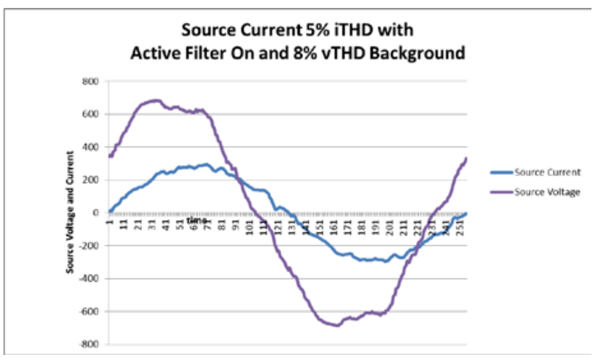

Figure 12: Source Current iTHD reduce to 5% in the presence of 8% vTHD background (with Active Filter on)

Conclusions

Background voltage distortion is a growing issue due to the increasing proportion of non-linear loads in industrial plants and the application of large VFDs in remote locations. Even moderate levels of voltage distortion (<5%) can drive high harmonic currents in a low voltage power system, leading to higher voltage distortion and possible equipment malfunction.

Multi-pulse rectifiers and some passive harmonic filters can be ineffective in reducing iTHD when background voltage is present, and should be avoided.

TCI passive filters and active filters are designed to meet low iTHD standards in the presence of medium (2-5%) and high (5-10%) background distortion.

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TCI, LLC
W132 N10611 Grant Drive
Germantown, WI 53022
(414) 357-4480
FAX (414) 357-4484
PQ Helpline (800) TCI-8282
www.transcoil.com