Mirus Series AUSF Inversine Sinewave Filter versus dV/dT Filter Discussion:

San Antonio Water Authority Case Review

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For long VFD/ASD secondary cable lead lengths, it has become common practice to use a dV/dT filter to avoid reflective wave phenomena and to attempt to control common mode noise issues with the motor being driven. No matter the circumstances of the application, manufacturers often claim that their dV/dT filter:

- Greatly extends the motor and cable life
- Provides 30% reduction in common mode current
- Is suitable for lead lengths up to 1,000 ft

Unfortunately, there is often not much technical information provided within the dV/dT literature and brochures to back their assertions. But, for some, dV/dT filtration is an accepted 'one size fits all solution' even though this may not always be the case.

dV/dT filters are typically of an LRC configuration, designed to detune the secondary circuit resonant frequency characteristics to avoid creating a reflective wave condition, or ringing with the secondary cable and motor. A reflective wave condition occurs from a mismatch in cable and motor impedance resulting in voltage reflecting back along the cable. Ringing occurs when the natural resonant frequency of the secondary cable and motor amplifies a harmonic present in the voltage waveform. Ringing and Reflective Wave are often used interchangeably but are actually two different conditions. Either one can result in overvoltages, usually on the leading edge of the PWM waveform which can be as high as 2x the equivalent DC bus voltage (i.e. a 480V AC system will have a 678V DC equivalent), which would mean on a 480V PWM output, the transient voltage can reach 1350V peak. This repetitive transient voltage then compromises the secondary cable insulation system, motor insulation systems, and even the inverter of the drive itself. The dV/dT filter is meant to reduce the overvoltage and thereby reduce this dielectric stress on the equipment. It does little to reduce the normal PWM differential stress associated with the waveform of the PWM voltage. So they are deployed to avoid a resonance condition, without treating the root cause of the resonance. The PWM waveform itself.

On the common mode front, there is little published material on how a dV/dT filter lowers the common mode noise segment of the secondary waveform. In a discussion contained within an Eaton Application guide on dV/dT filtration:

Applying dV/dT filters with AFDs, Application Paper AP043001EN Effective September 2014

"Common mode current is created mostly by capacitance due to oversized cables combined with increased lead length. One way to control this effect is to take care not to oversize the cables to the AFD. Depending on the lead length, a dV/dT filter may not be the best choice, and a sine wave filter may need to be used. An effect of lead length is that as the cable becomes longer, common mode current is bled off across the length of the wire, making the common mode current at the motor less than a shorter cable. Shorter cables will have less common mode current; however, the current at both ends of the cable will be very similar because less current is bled off, which will lead to higher common mode currents at the motor and increased current across the bearings. When the current across the bearings is high it can lead to premature bearing failure, which is why some motors are designed with insulated bearings."

This discussion is insightful and highlights that a sinewave filter may be a more appropriate solution for a common mode condition. The mentioning of the insulated bearing within the motor ignores that there are other paths to ground besides the motor bearing within the assembly, such as the mechanical pump bearings and other structures. If it is believed that common mode noise is the primary cause of concern, integrating a common mode choke into the sinewave filter would be your best option to assure control of both differential mode and common mode secondary noise conditions.

Ringing, resonance and common mode challenges are a function of the PWM output of the VFD inverter. If we change the PWM output to a sinusoidal waveform, the potential for these three conditions can be significantly reduced. A Case study may prove insightful to all the advantages that a sinewave filter presents to a VFD/ASD output circuit operation over a dV/dT filter deployment.

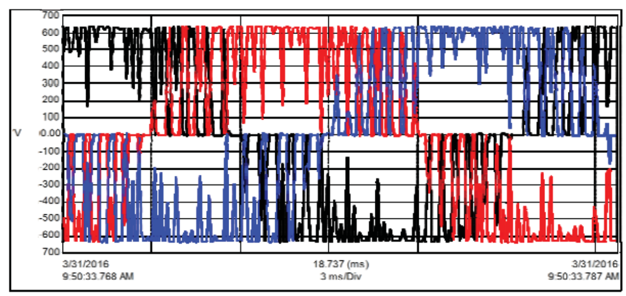
San Antonio Water Lift Stations Project
Comparative dV/dT filtration versus Mirus Inversine AUSF Sinewave Filter
Evaluation and Testing: March 31st, 2016

For this installation and test protocol, I was not employed by Mirus at the time but instead was an independent contractor providing services to Five Star Electric through my company NSOEM, Inc. The goal was to compare a ‘standard’ dV/dT installation where repeatedly the motors had been failing on a down hole water pumping application. This same failure had been experienced on multiple sites, so the site which was experiencing the highest failure rate was chosen for the test. The depth of the motors was approximately 800’, and the meantime between failures was reported to be between 6 months and 1 year on average. Testing was conducted on one of six installations for determination of suitability. The dV/dT filters were of an LRC configuration and the new Mirus Inversine Sinewave filters were being tested in a comparative mode to determine waveform and harmonic condition of the secondary circuit. It was assumed at the time of test that a differential noise condition was leading to the motor/pump failures, and the manufacturer of the pump assemblies had expressed concern over the use of the dV/dT filter and the stress it placed on the motor. It should also be understood that previous inspections of failed motor/pump equipment had shown winding flashovers as the primary failure condition but fluting of the bearings had also been observed. No bearing failures had been reported as the primary failure mode.

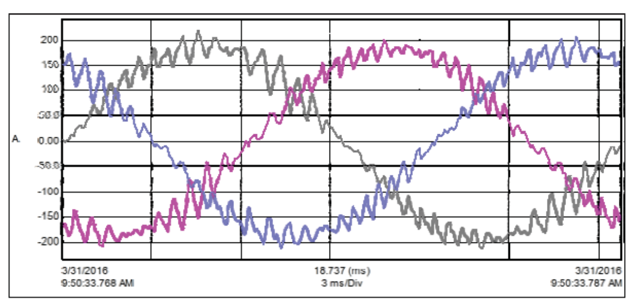
Voltage, Current Wave Trace and Harmonic Spectrum Analysis of the VFD Output Upstream of the Existing dV/dT filter

To establish whether there was an issue with the drive output itself, a waveform trace and harmonic spectrum of the drive output for voltage and current was taken. The output switching frequency of the VFD/ASD was 2 kHz, so an AEMC 8335 PQ Meter was used since it can measure accurately up through 3kHz (50th harmonic). The analysis of the waveform, current and voltage, as well as the harmonic spectrum would indicate if there were any issues with the VFD/ASD operation.

Voltage Wave Trace



Current Wave Trace



RMS Measurements with Harmonic Value

Phase	Ithd	Vthd
A	11.36% (136A)	37.91% (467V)
B	10.63% (132A)	38.74% (470V)
C	10.46% (131A)	37.94% (467V)

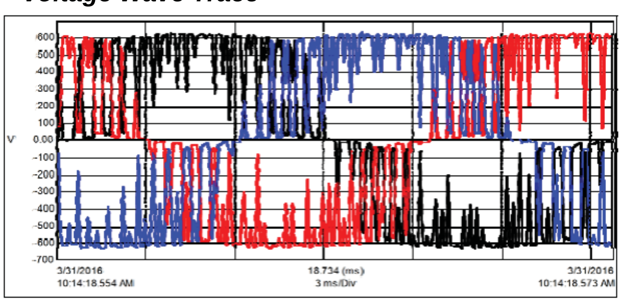
The voltage wave trace, sawtooth current waveform pattern and the output current and voltage balance, as well as, current and voltage harmonic values are all typical of a properly operating inverter/drive package. No resonance, phase imbalances or other conditions were witnessed. It was determined the VFD/ASD was operating properly.

Start Date	3/31/2016
Start Time	9:50:33.000 AM
var	100.4k W
Power Factor	0.575
Displacement Power Factor (DPF)	0.785

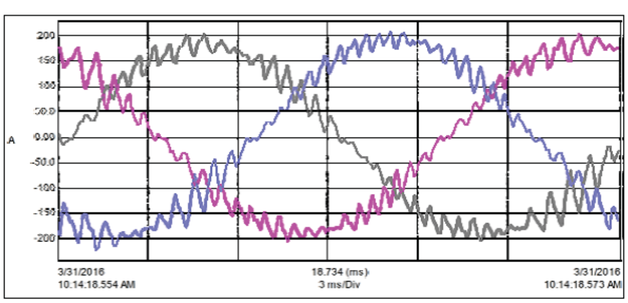
When we measured the output power of the inverter, it was observed that the capacitive reactive power being consumed was higher than the real power consumption (i.e. kVAR of 100.4). The displacement power factor was close to the motor power factor, 0.785 versus a motor nameplate value of 0.80, but the True Power Factor (TPF) was low at 0.575, due to the high harmonic kVAR component. These values were also typical for the output of a drive, and not an indication of any errant equipment operation. Since the dV/dT filter was downstream of the measurement point the device capacitive reactance factored into the values measured.

Voltage and Current Wave Trace and Harmonic Spectrum Analysis of the dV/dT filter Output

Voltage Wave Trace



Current Wave Trace

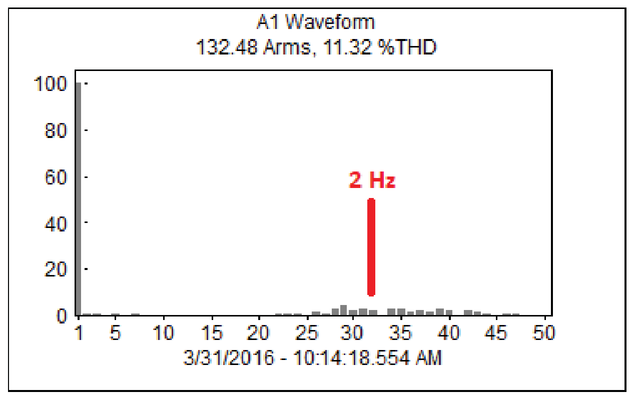


RMS Measurements with Harmonic Value

Phase	Ithd	Vthd
A	11.32% (132A)	34.10% (451V)
B	10.61% (131A)	34.71% (450V)
C	10.68% (137A)	34.56% (450V)

Start Date	3/31/2016
Start Time	10:14:18.000 AM
var	96.39k W
Power Factor	0.597
Displacement Power Factor (DPF)	0.794

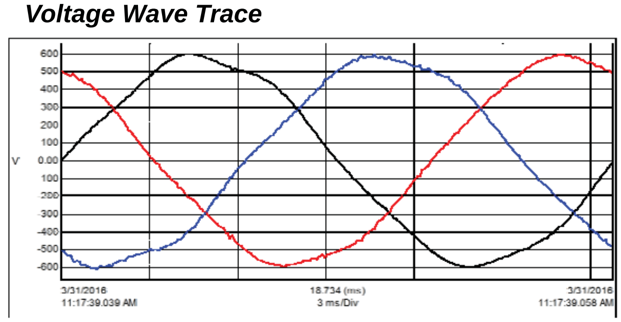
There was only a minor change in the Voltage waveform and an associated lowering of the measured Vd to around 34% from 39%. The current waveform is still exhibiting a sawtooth pattern, which means the high frequency current harmonic is still present due to the PWM output waveform. The current harmonic band is around the noted switching frequency of the inverter.



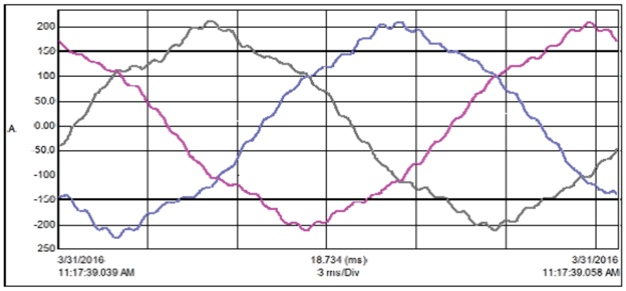
Voltage and Current Wave Trace and Harmonic Spectrum Analysis of the Mirus Inversine AUSF filter Output

After replacing the dV/dT filter within the circuit with a Mirus AUSF Series Inversine Sinewave filter, we then proceeded to rerun the filter output tests at the same operating speed and recorded the following.

Voltage Wave Trace



Current Wave Trace



Start Date	3/31/2016
Start Time	11:17:39.000 AM
var	28.73k W
Power Factor	0.660
Displacement Power Factor (DPF)	0.797

As can be witnessed, there is no trace of a PWM Voltage waveform being fed to the load circuit… the associated Voltage Distortion has been reduced to a high leg phase value of 4.2% versus the dV/dT measurement values of 34%+ level. The current draw stayed about the same at approximately 134A, but the measured voltage was 413V versus the previous measured 451V level. The 413V level was more appropriate based on the operating speed of the VFD which was between 52 Hz to 55 Hz controlled by the current loop. The reactive power consumption was reduced from 96.39 kVAR to approximately 29 kVAR, which helped to improve the True Power Factor (pf) from 0.597 to 0.66. The Displacement Power Factor (dPF) stayed unchanged at just under .80 the nameplate value of the downhole motor. Although not measured at the time, dPF upstream of the sinewave filter would have been improved to near unity since the capacitive reactance of the filter is designed to supply most of the inductive reactive power being drawn by the motor.

The elimination of the PWM waveform through the use of the Mirus AUSF Inversine Sinewave Filter was intended to eliminate the differential mode noise dielectric stress on the secondary circuit, and provide some mitigation of the common mode noise typical from a VFD/ASD driver associated with the long cable lead length and capacitive current evolution. We did not test for common mode noise however, since the primary failure analysis indicated a differential mode failure pattern. As of the writing of this article, December 2020, on the 6 original sites where the Inversine filters were deployed in 2016, there have been no further motor/pump package failures recorded.

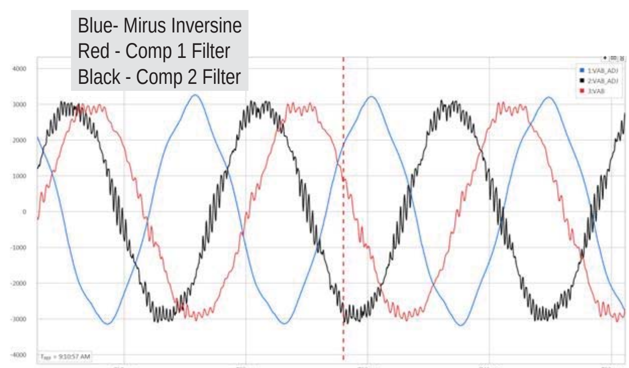
Spreadsheet Summary of Measurement Data with Notes

Measurement Criteria	Inverter Output Upstream of Existing dV/dT filter	Output of Existing dV/dT filter	Output of New Mirus Inversine Sine Wave Filter	Performance Improvement % Inversine versus dV/dT	Notes
Ithd	10.46% - 11.36%	10.61% - 11.32%	7.24% - 8.6%	31.7% - 24.1% Reduction	The amount of current harmonic improvement was dramatic due to the elimination of the injected high frequency voltage harmonic and reduction of the harmonic capacitive reactance.
I RMS	131A - 136A	131A - 137A	134A - 139A	1.4% - 2.3% Increase	There was a slight increase in the current draw of the load, but not of a material magnitude.
Vthd	37.91% - 38.74%	34.1% - 34.71%	3.08% - 4.17%	87.9% - 90.9% Reduction	The conversion of the PWM waveform to a sinusoidal waveform accounts for the dramatic improvement in the voltage distortion. Elimination of the high frequency harmonic voltages typical of a traditional Sinewave Filter tuning was key to its performance.
V RMS	467V - 470V	450V - 451V	412V - 413V	8.4% Reduction	By eliminating the PWM waveform, the RMS voltage is now more in line with the established Volts/Hz ratio of the operating speed of the VFD.
kVAR	100.4 kVAR	96.39 kVAR	28.73 kVAR	70.1% Reduction	By reducing the Voltage distortion and associated current harmonic levels, the amount of reactive power being consumed by the load is drastically reduced.
Comments	The test was performed to determine if there were any functional issues with the VFD/ASD being used for the test. The VFD/ASD was performing within specification.	This was the base line measurement of the dV/dT performance for the comparative to the Mirus Inversine filter to be installed.	The Sinewave is smooth and does not show any typical high frequency noise or any indication of a PWM differential noise condition.		

The Inversine Difference

Not all Sinewave Filters are built the same, the key factor to the suitability of the Mirus AUSF Inversine Sinewave Filter is within its tuning and construction. Of significant importance is tuning of the filter to mitigate the higher switching frequency harmonics and reduce the voltage harmonics to approximately 5% or less which helps control high frequency current harmonics creation. This approach will lower the operating temperature of the down hole motor, increasing the expected life of the pump assembly. A typical Sinewave filter output tuned to 600Hz on a 60Hz system (10x fundamental), which is the standard for most Sinewave filters, often still has a high frequency component which can present dielectric and thermal challenges for the circuit. This can compromise the motor winding insulation, but is eliminated with the Mirus AUSF Inversine which is tuned to around 3x of the fundamental frequency to more effectively eliminate the high frequency harmonics.

A comparison of two competitive Sinewave filters to the Mirus Inversine highlights our engineering advantage. The elimination of the high frequency voltage noise with the Mirus Inversine is evident.



Other advantages of the Mirus Inversine versus competitive Sinewave Filters are as follows:

- Other filters have voltage drop (insertion loss) of 5-12%, limiting the motor power capability vs the Inversine™ filter which has voltage drop below 3%
- Other filters target VTHD performance of 5% although they rarely meet this especially when measured above the 50th harmonic. MIRUS Inversine™ filters target <3% and will be <5% even when measured up to the 100th harmonic.
- MIRUS Inversine™ filters correct for low motor power factor, improving it to near unity. This helps with the efficiency and power output of the drive. Other filters are not designed to correct for power factor, so motor pf remains low.
- MIRUS Inversine™ is typically 1.5% to 2% more efficient than other filters, with lower power losses and heat rejection.
- Other filters often require fan cooling vs natural convection cooling for the MIRUS Inversine™ filters
- Other filters may require damping resistors with the capacitor banks. By designing to a lower 'knee' frequency, the Mirus Inversine™ does not require resistors to eliminate resonance conditions, making it more efficient and resonant-free than other filters.

Conclusion

The most effective treatment of differential mode conditions and potential challenges within a VFD/ASD secondary circuit is the deployment of a Mirus Inversine Sinewave Filter (AUSF) and placing limits on the measured secondary circuit harmonic condition of 5% or less Vthd and 8% or less Ithd under full load conditions. By a complete conversion of the output PWM voltage waveform to a sinusoidal condition without the presence of higher order voltage noise/harmonics the advantages are:

- Reduction of dielectric stress associated with a normal PWM waveform on the secondary circuit and differential mode harmonic conditions.
- Some reduction of common mode current but, it should be noted, for common mode related issues such as motor bearing failures, consideration should be given to the addition of a common mode choke option.
- Lowering of the operating temperature of the drive and increasing the life expectancy of the motor.

To learn more about the Mirus Inversine AUSF please visit mirusinternational.com/inversine

About Mirus International

Mirus designs and develops world class power quality improvement products for mission critical operations. Their uniquely specialized product line includes highly efficient harmonic filters, transformers, autotransformers and Data Center power distribution equipment. Comprised of a leading team of power quality experts, Mirus' solutions minimize disruption to the power supply, improve reliability and adhere to the strictest of regulatory requirements while also saving energy. Proven to perform, Mirus products are available globally and are real-world tested in its own Harmonics & Energy (H&E) Lab.