Solving Harmonics with SmartD's Clean Power VFD

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Summary

A brief overview of the issue of harmonics in VFDs.

Harmonics pose a significant challenge in electrical systems, particularly when using Variable Frequency Drives (VFDs). These harmonics can lead to inefficiencies, increase maintenance costs, and compliance issues.

SmartD Technologies' Clean Power VFD offers a groundbreaking solution that eliminates harmonics at the source. This white paper delves into the technical details, real-world evidence, and the advantages of SmartD's approach over traditional mitigation strategies.

1. IEEE 519

To understand this document's aim and the meaning of harmonics, a basic knowledge of IEEE 519-2022 is required.

IEEE 519 is a standard developed by the Institute of Electrical and Electronics Engineers (IEEE) to establish guidelines for controlling harmonics in electrical systems. The goal of IEEE 519 is to limit harmonic distortion in electrical networks, ensuring reliable operation of equipment and minimizing the adverse effects of harmonics on the electrical grid and connected devices.

Key Concepts and Vocabulary

- Harmonics: Frequencies that are integer multiples of the fundamental frequency (e.g., 60 Hz). Harmonics can distort voltage and current waveforms, leading to various operational issues.
- Total Harmonic Distortion (THD): A measure of the overall harmonic distortion in a voltage or current waveform, expressed as a percentage of the fundamental frequency.
- Total Demand Distortion (TDD): A measure of the harmonic distortion in current, expressed as a percentage of the maximum demand load (usually the peak current over a specified period).

Mathematical Explanation

IEEE 519 sets specific limits for both voltage and current distortion. These limits are expressed in terms of THD and TDD. The basic formulae involved are:

THD (Total Harmonic Distortion):

$$THD = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots + V_{n2}^2}}{V_1}$$

Where V_1 is the RMS value of the fundamental frequency, and V_2, V_3,..., and V_n are the RMS values of the harmonic frequencies.

TDD (Total Demand Distortion):

$$TDD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{n2}^2}}{I_L}$$

Where I_L is the maximum demand load current, and I_2, I_3, I_4, ...,and I_n are the RMS values of the harmonic currents.

Coverage of IEEE 519

IEEE 519 provides guidelines and limits for harmonic distortion at the point of common coupling (PCC), which is the point where the customer's electrical system connects to the utility's system. It's essentially the main connection point between the customer's power system and the utility's grid.

The standard specifies maximum allowable THD for voltage and TDD for current, based on the voltage level and the size of the load.

Even though IEEE 519 focuses on the PCC, it's also important to consider Total Harmonic Distortion and Total Demand Distortion for individual components, like VFDs. For a VFD, THD indicates how much the VFD's output deviates from a perfect sine wave, and TDD helps understand the impact of harmonic currents relative to the VFD's full load capacity.

Considering the cumulative effect of multiple VFDs and other nonlinear loads within the installation. While individual VFDs may comply with local harmonic limits, their combined impact can contribute to higher overall distortion levels at the PCC.
It's therefore essential to manage THD and TDD for individual VFDs within the customer's installation

For most systems, IEEE 519 sets a maximum allowable THD for voltage at 5%. This means the harmonic voltage should not exceed 5% of the fundamental voltage.

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \leq 1.0$ kV	5.0	8.0
1 kV $< V \leq$ 69 kV	3.0	5.0
69 kV $< V \leq$ 161 kV	1.5	2.5
161 kV $< V$	1.0	1.5[a]

IEEE519 - Table 1 - Voltage distortion limits

The allowable TDD for current varies depending on the size of the load and the short-circuit ratio at the PCC. The IEEE 519 standard sets limits on how much current distortion is allowed for each harmonic frequency, based on a percentage of the maximum load current. It also defines limits for Total Demand Distortion (TDD). Harmonics are grouped into categories, and each group has different limits depending on the system's voltage and the ratio of short-circuit current to maximum load current (I_{SC}/I_L).

I_{SC}/I_L	Individual harmonic limits. Harmonics values are in % of maximum demand load												TDD
	$2 \leq h < 6$		$6 \leq h < 11$		$11 \leq h < 17$		$17 \leq h < 23$		$23 \leq h < 35$		$35 \leq h \leq 50$		
	Odd	Even	Odd	Even	Odd	Even	Odd	Even	Odd	Even	Odd	Even	
<20[c]	4.0	2.0	4.0	4.0	2.0	2.0	1.5	1.5	0.6	0.6	0.3	0.3	5.0
20<50	7.0	3.5	7.0	7.0	3.5	3.5	2.5	2.5	1.0	1.0	0.5	0.5	8.0
50<100	10.0	5.0	10.0	10.0	4.5	4.5	4.0	4.0	1.5	1.5	0.7	0.7	12.0
100<1000	12.0	6.0	12.0	12.0	5.5	5.5	5.0	5.0	2.0	2.0	1.0	1.0	15.0
>1000	15.0	7.5	15.0	15.0	7.0	7.0	6.0	6.0	2.5	2.5	1.4	1.4	20.0

IEEE519 - Table 2 - Current Distortion Limits for Systems Rated 120 V – 69 KV

ISC stands for short-circuit current. It is the amount of current that would flow if there were a direct short-circuit at a specific point in the electrical system. This value is important because it indicates the potential maximum current that the system can experience during a fault condition.

To calculate IL (the maximum demand current), take the average of the highest monthly demand currents over the past 12 months. Ideally, you need data showing the monthly maximum demand current for the last year. If this data isn't available, use 15- or 30-minute interval kWh and/or kVA data from utility meters. If that's also not available, rely on the monthly power bills, which usually show the maximum demand in kVA. Convert these kVA values to current, sum up the last 12 months, and then divide by 12 to get the average, which you may use for IL.

2. How traditional VFDs generate harmonics.

Ordinary VFDs generate harmonics at both their input and output.
On the motor side, the VFD creates a PWM signal to emulate a sine wave. However, this PWM signal, characterized by a square-like voltage waveform, inevitably introduces harmonics due to the limited switching frequency of IGBTs. On the grid side, the diode bridge architecture draws current non-linearly at the voltage waveform peaks, resulting in a current waveform rich in harmonic content.

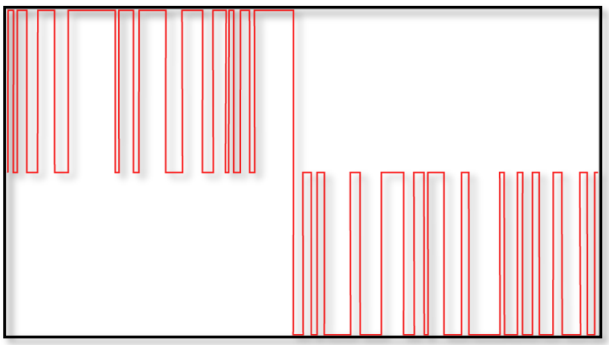
PWM signals, switching frequencies, and IGBT limitations.

PWM

Pulse Width Modulation (PWM) is a technique commonly used in VFDs to generate an approximation of a sinusoidal AC signal from a DC source. The basic principle involves switching the DC voltage on and off at high frequencies, modulating the width of the pulses to control the average voltage, and effectively creating a variable AC voltage output.

How does PWM work?

Switching:
The DC input is rapidly switched on and off by power transistors at a high frequency.
Modulation:
The width of each pulse is varied (modulated) to match the desired amplitude of the AC sine wave.



PWM signal

Smoothing:
Inductive and capacitive elements in the motor help smooth out the pulsed signal, resulting in an AC output that approximates a sine wave.

Impact on Harmonics:
the PWM signal inherently contains harmonic frequencies due to its square-like waveform characteristics. The sharp transitions between on and off states introduce high-frequency components into the signal, leading to harmonic distortion. The primary harmonics generated by PWM include:
Switching Frequency Harmonics:
These are multiples of the switching frequency used to modulate the signal.
Sideband Harmonics:
These occur around the switching frequency and its mutiples, influenced by the modulation process.

Switching Frequencies

Switching frequency refers to the rate at which the power transistors (IGBTs) in a VFD switch on and off to generate the PWM signal.
This frequency is a critical parameter affecting both the quality of the output waveform and the extent of harmonic distortion.

Low vs. High Switching Frequencies:
Low Switching Frequency:
Traditional VFDs using IGBTs typically operate at switching frequencies ranging from 2 kHz to 20 kHz. Lower frequencies result in a more pronounced square-like PWM signal, leading to higher harmonic content.
High Switching Frequency:
Modern VFDs utilizing wide-bandgap (WBG) semiconductors, like SiC and GaN, can operate at much higher frequencies, often exceeding 50 kHz. Higher switching frequencies result in a closer approximation to a sine wave, significantly reducing harmonic distortion.

Impact on Harmonics
Higher switching frequencies produce a smoother output waveform with less harmonic content. This reduction in harmonics translates to lower Total Harmonic Distortion (THD) and fewer negative impacts on the motor and electrical grid.

Integrated Gate Bipolar Transistors (IGBT) Limitations:

IGBTs are the power transistors commonly used in traditional VFDs for their ability to handle high voltages and currents. However, they have inherent limitations that affect the performance and efficiency of VFDs.
Limitations of IGBTs

Switching Speed:
IGBTs have slower switching speeds compared to newer semiconductor technologies. This limitation restricts the achievable switching frequency, leading to higher harmonic distortion.

Switching Losses:
Each switching event introduces losses due to the energy dissipated during the transition between on and off states. These losses increase with switching frequency, limiting the efficiency gains from higher frequencies.

Thermal Management:
Higher switching frequencies generate more heat, necessitating robust thermal management systems. This adds complexity and cost to the VFD design.

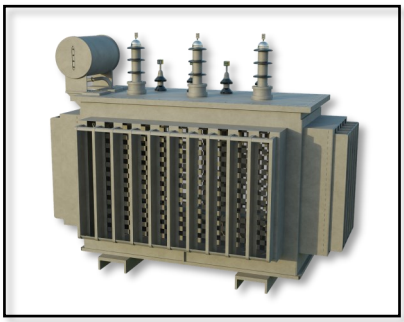
Impact on Harmonics:
The slower switching speeds of IGBTs contribute to the creation of more pronounced harmonic components in the PWM signal.
Harmonics can have several consequences that impact electrical systems and equipment. Let’s look at them

3. Impact of Harmonics

Effects on motors:

The presence of harmonics increases the total RMS current in motors, leading to higher copper and core losses. This excess current manifests as heat, which can cause thermal nuisance trips and degrade motor insulation over time, moreover it translates into a reduction of efficiency.
Additionally, harmonic-induced high dV/dt can cause arcing, damaging motor windings and bearings, further reducing motor lifespan and efficiency.
Harmonic currents also create torque pulsations within the motor. These pulsations are periodic variations in torque that can cause mechanical vibrations, noise, and additional wear on motor bearings and couplings. This mechanical stress can lead to premature failure of these components.

Effects on electrical systems:



Transformer.
Image by Achin bm from Pixabay

Oversized conductors, equipment wear, IEEE 519 compliance.
Harmonics in electrical distribution systems necessitate oversizing conductors, increasing capital costs, and limiting future scalability.
Equipment connected to the grid, such as transformers and lighting, can suffer from excessive heating, premature wear, and operational inefficiencies. Compliance with IEEE 519, which limits THDi to 5% at the point of common coupling, is essential to avoid penalties from utility providers.

Economic impact:

Maintenance costs, penalties, and efficiency losses.
The financial implications of harmonic distortion are significant. Facilities may incur increased costs for oversized conductors, additional cooling systems, and frequent equipment replacements. Non-compliance with IEEE 519 standards can result in penalties from utility companies, adding to the overall cost burden. Additionally, operational inefficiencies due to harmonics can lead to higher energy consumption and increased utility bills.

4. Common Harmonic Mitigation Strategies

Line Reactors and Passive Filters

Line reactors and passive filters installed between the VFD and the grid can reduce THDi. However, line reactors only reduce THDi to 40%, insufficient to meet IEEE 519 standards.
Passive filters can achieve the required limits but at the cost of efficiency, space, and maintenance complexity.

Passive Harmonic Filter

Active Harmonic Filters

Active harmonic filters dynamically inject currents to cancel out harmonics, providing a more effective solution than passive filters. However, they are expensive, require substantial maintenance, and increase the complexity of the system.

Challenges and limitations of these mitigation strategies.

Harmonic mitigation strategies, while essential, come with their own set of challenges and limitations. Installing sinusoidal filters, line reactors, and passive harmonic filters between a VFD and its connected systems can reduce harmonic distortion, but these solutions often fall short of complete elimination.
Sinusoidal filters help smooth the output waveform but can be costly and require regular maintenance to ensure optimal performance.
Line reactors, although effective in reducing harmonic currents, only decrease THDi to around 40%, which is insufficient to meet the stringent IEEE 519 standards.
Passive harmonic filters can achieve the necessary THDi levels, but they are complex, and bulky, and demand precise tuning and ongoing upkeep to remain effective.

These mitigation measures also introduce additional losses, reducing overall system efficiency and increasing operational costs over time.

Comparison of mitigation effectiveness and costs.

When comparing the effectiveness and costs of various harmonic mitigation strategies, it becomes evident that traditional methods, while beneficial, are not always the most economical or efficient.
Active and passive harmonic filters can meet compliance standards, but their high initial costs, space requirements, and maintenance needs can outweigh their benefits.
Line reactors offer a lower-cost alternative but fall short of achieving the required harmonic reduction levels. Active harmonic filters, although highly effective, represent a significant investment and add complexity to the system.
In contrast, SmartD Technologies' Clean Power VFD eliminates the need for these auxiliary devices by addressing harmonics at the source. This innovative approach not only meets and exceeds IEEE 519 standards but also offers long-term cost savings by reducing the need for maintenance and enhancing overall system efficiency. The higher initial cost of a Clean Power VFD is offset by the reduced operational expenses and extended lifespan of connected equipment, making it a superior and more cost-effective solution in the long run.

SineWave Filter

What about the motor side

While much of the focus on harmonics is often placed on the grid side of VFDs, it is equally important to consider the impact of harmonics on the motor side. As described in a previous section, harmonics on the motor side can lead to several operational and maintenance challenges that can significantly affect the performance and longevity of motors.

Sinusoidal filters

Installing sinusoidal filters between a VFD and a motor can reduce harmonics on the motor side but not eliminate them. These filters require significant investment and maintenance.

5. Advanced VFD Technologies: Active Front End (AFE) and Matrix VFDs for Harmonic Mitigation

Advanced VFD technologies such as Active Front End (AFE) VFDs and Matrix VFDs are technologies that offer innovative solutions to reduce harmonic distortion.

Active Front End (AFE) VFDs

AFE VFDs incorporate an additional power conversion stage that actively controls the input current waveform, significantly reducing harmonic distortion.

By using Insulated Gate Bipolar Transistors (IGBTs) or other fast-switching devices, AFE VFDs shape the input current to be nearly sinusoidal, generally achieving THD levels below the 5% target. However, AFE VFDs come with higher initial costs, increased complexity, and potential electromagnetic interference (EMI) issues that require careful consideration.

Matrix VFDs

Matrix VFDs offer a direct AC-to-AC conversion without the intermediate DC bus, utilizing a matrix of bidirectional semiconductor switches.

This design reduces harmonic content at both the input and output. Despite their advantages, Matrix VFDs are characterized by higher costs, complex control algorithms, limited power ratings, and the need for advanced thermal management and EMI mitigation.

6. The SmartD Approach: Don't create, Don't Mitigate

SmartD Technologies has pioneered a revolutionary approach with the Clean Power VFD, fundamentally transforming how harmonics are managed.
Rather than relying on complex mitigation strategies, the Clean Power VFD addresses harmonics at their source, leveraging cutting-edge wide-bandgap (WBG) semiconductor technology, silicon carbide (SiC) transistors MOSFET. This innovative approach offers a host of benefits that extend beyond compliance with industry standards.

Elimination of Harmonics at the Source

The Clean Power VFD's advanced design effectively eliminates harmonics at both the input and output, ensuring Total Harmonic Distortion (THDi) levels are well within the stringent limits set by IEEE 519.
This proactive approach negates the need for external filters and reactors, simplifying installation and reducing overall system complexity.

Enhanced System Efficiency

By utilizing WBG semiconductors, SmartD's Clean Power VFD achieves significantly higher switching frequencies compared to traditional IGBT-based drives.
This results in a more accurate emulation of a sine wave, reducing losses and improving overall system efficiency. The enhanced efficiency translates to lower energy consumption and reduced operational costs.

Smaller Installation Footprint

The compact design of the Clean Power VFD, facilitated by the high-performance WBG technology, requires less space for installation. This smaller footprint is particularly advantageous in applications where space is at a premium, offering greater flexibility in system design and layout.

Extended Motor Lifespan

The Clean Power VFD's near-true sine wave output significantly reduces stress on motor windings and bearings, leading to lower operating temperatures and reduced wear and tear. This not only minimizes the risk of thermal nuisance trips but also extends the operational lifespan of motors, enhancing reliability and reducing long-term maintenance costs.

Ease of Scaling and Integration

The modular design of SmartD's Clean Power VFD facilitates easy scaling and integration into existing systems. This adaptability makes it an ideal solution for a wide range of applications, from small industrial setups to large-scale manufacturing operations.

Reduced Maintenance and Downtime

With fewer external components required for harmonic mitigation, the Clean Power VFD reduces the need for ongoing maintenance. This results in less downtime and lower maintenance costs, further improving the total cost of ownership for end-users.

Compliance with Industry Standards

SmartD's Clean Power VFD ensures full compliance with IEEE 519 standards, eliminating the risk of penalties from utility providers and ensuring a smoother operation within regulated environments. This compliance also provides peace of mind to facility operators and managers, knowing their systems meet or exceed industry benchmarks

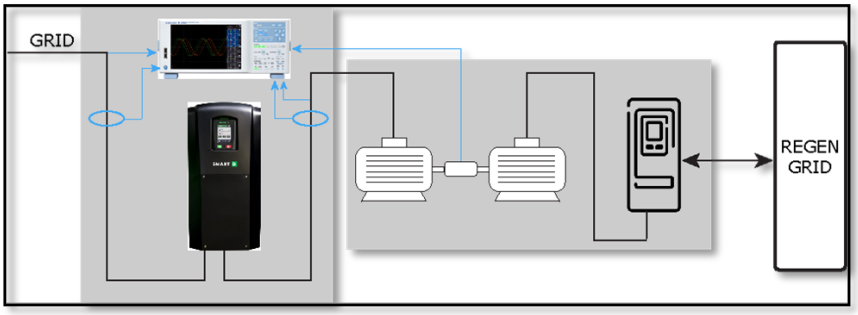
7. Real-World Harmonic Measurements: Comparing VFD Performance

A test bench is set to provide empirical evidence of the harmonic performance of SmartD's Clean Power VFD compared to a traditional VFD.
Two motors are connected in the test bench, driven by VFDs. One set motor+VFD is emulation load behavior at various speeds and torques. The second VFD is the equipment under test (EUT)

The test bench is connected to the electrical grid, which provides the input power to the VFDs being tested. This connection is crucial for evaluating how each VFD interacts with the grid and affects harmonic distortion.

A power quality analyzer is connected to monitor the voltage and current waveforms. This device measures the harmonic content and overall power quality, providing a visual representation of the harmonics generated by the VFD on grid size and on motor size.

A dynamometer measures the torque and rotational speed (RPM) of the motor so its instantaneous power may be calculated, and torque/speed conditions can be accurately monitored during tests.



Harmonics test bench

This system allows for the recycling of energy from the motors back into the grid, providing a controlled envi-

Understanding and Interpreting a Harmonics Bar Chart

A harmonics bar chart is a graphical representation of the harmonic content present in an electrical signal. It provides a clear visual way to understand the magnitude of various harmonic frequencies relative to the fundamental frequency. Here’s a detailed explanation of how to read and interpret a harmonics bar chart:

Components of a Harmonics Bar Chart

Horizontal Axis (X-Axis:
the horizontal axis represents the harmonic order, which is the integer multiple of the fundamental frequency. The fundamental frequency (1st harmonic) is typically at 60 Hz (in many regions), and harmonics are displayed as 2nd (120 Hz), 3rd (180 Hz), 4th (240 Hz), etc.

Vertical Axis (Y-Axis):
The vertical axis indicates the magnitude of each harmonic, usually expressed as a percentage of the fundamental frequency's magnitude or in absolute units such as amperes or volts.

Bars:
Each bar on the chart represents the magnitude of a specific harmonic frequency. The height of the bar correlates with the strength of that particular harmonic component.

How to Read a Harmonics Bar Chart

1. Identify the Fundamental Frequency:
 The first bar typically represents the fundamental frequency. This is the primary component of your signal and should have the highest magnitude.

2. Examine Harmonic Orders:
 Subsequent bars represent higher-order harmonics. For example, the 2nd bar is the 2nd harmonic (120 Hz if the fundamental is 60 Hz), the 3rd bar is the 3rd harmonic (180 Hz), and so on.

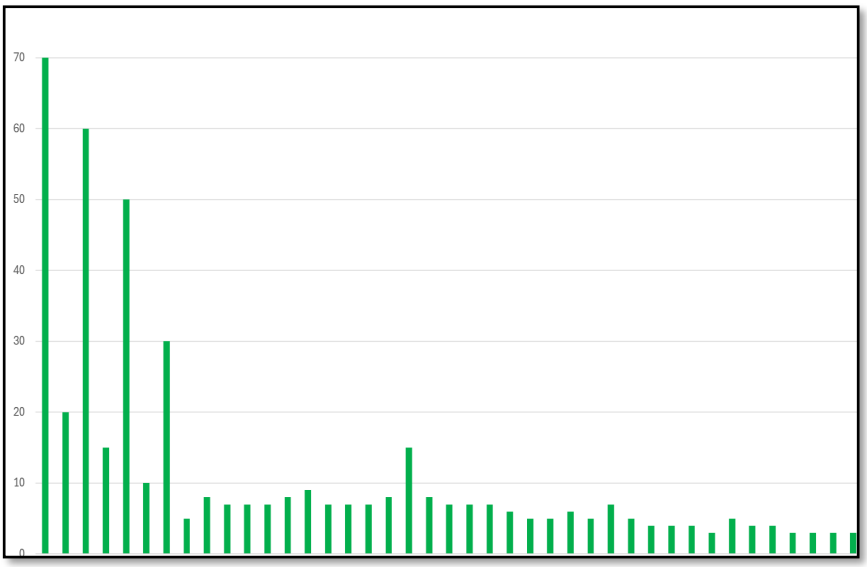
3. Magnitude Comparison:
Compare the heights of the bars to understand the relative magnitude of each harmonic. Higher bars indicate higher harmonic distortion at that particular frequency.

4. Total Harmonic Distortion (THD):
THD can be interpreted from the chart as the overall distortion level, which is the sum of the magnitudes of all harmonics. A higher THD percentage indicates more distortion. It is expressed as a percent of the fundamental frequency.

Interpreting the Chart

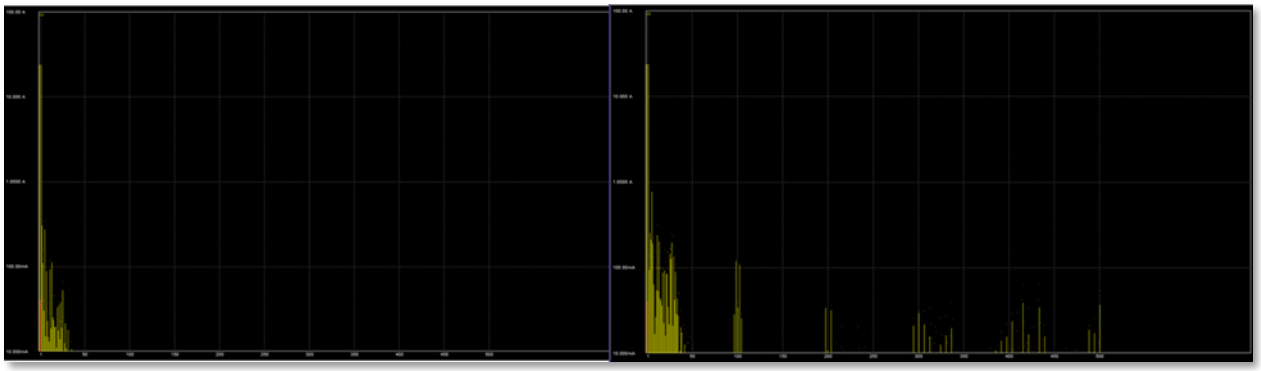
1. Low Harmonic Content:
If the bars for higher-order harmonics (2nd, 3rd, 4th, etc.) are short or nonexistent, this indicates low harmonic distortion. This is desirable as it means the signal is closer to a pure sinusoidal waveform.

2. High Harmonic Content:
Tall bars at higher-order harmonics signify significant harmonic distortion. This can lead to various issues such as overheating in motors, additional losses, and potential interference with other electrical equipment

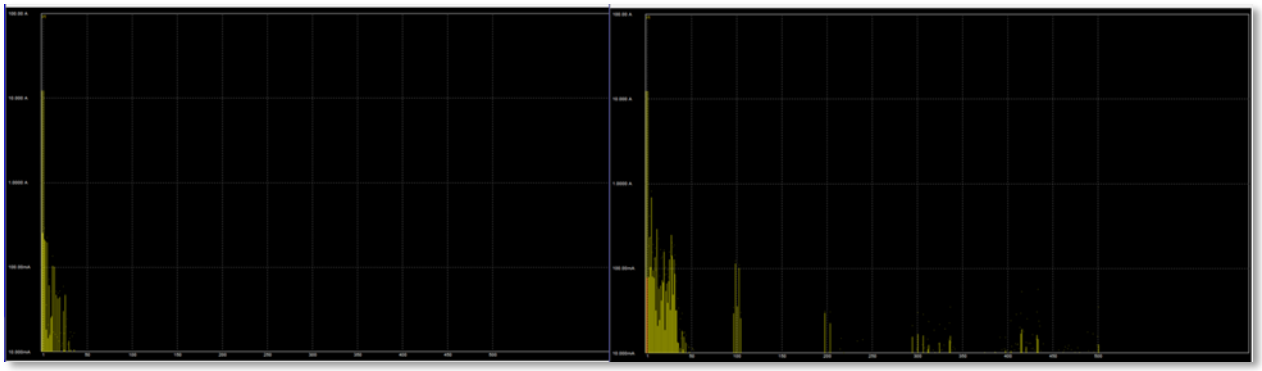


Harmonics bar chart

Measures VFD Power Inputs



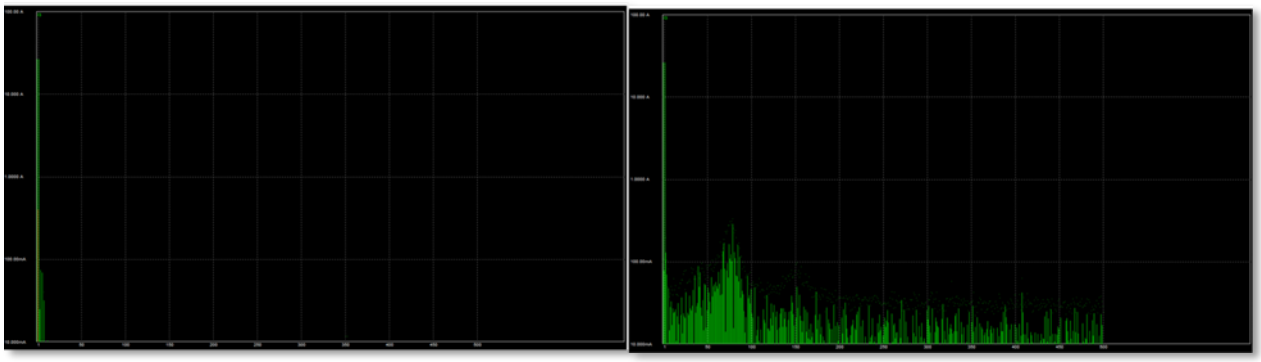
Harmonics contents of VFDs input side, at rated speed and load



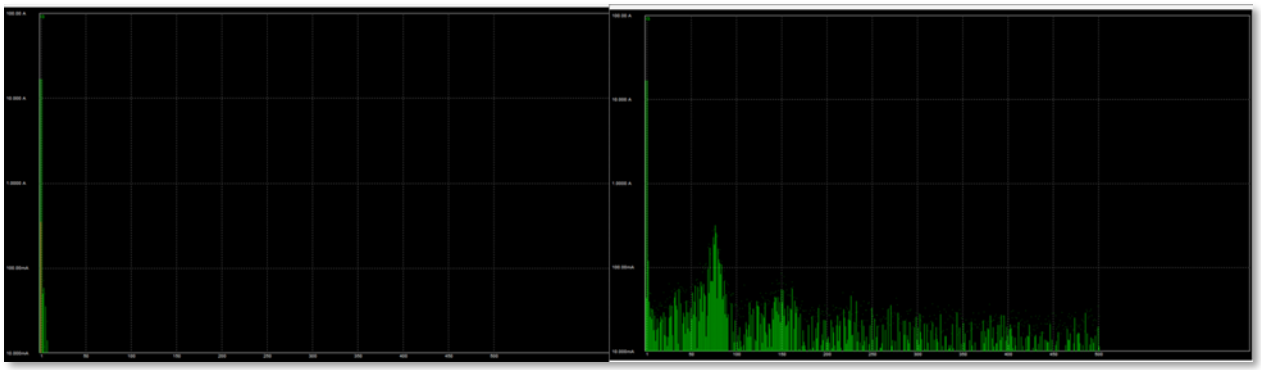
Harmonics contents of VFDs input side, at rated speed and half load

These bar charts are the harmonics content for the input side of two VFDs. The left charts are the measured spectrum of a SmartD's Clean Power VFD, and the right charts are the measured spectrum of a leading active-front-end VFD.

Measures VFD Power Outputs



Harmonics contents of VFDs output side, at rated speed and load



Harmonics contents of VFDs output side, at rated speed and half load

Those images display two harmonic bar charts representing the harmonic content at the output of two different VFDs. The left charts are the measured spectrum of a SmartD's Clean Power VFD, and the right charts are the measured spectrum of a leading active-front-end VFD.

Here’s how to read and interpret these charts to understand the performance differences:

On the left charts, the fundamental harmonic (1st harmonic) is the tallest bar, indicating it has the highest magnitude.
The subsequent harmonics (2nd, 3rd, 4th, etc.) are present but with significantly lower magnitudes.
The overall harmonic content diminishes rapidly, indicating lower levels of higher-order harmonics.
This rapid decrease in harmonic magnitudes with increasing harmonic order implies effective harmonic suppression.

On the right chart, the fundamental harmonic is the tallest bar.
However, the subsequent harmonics (2nd, 3rd, 4th, etc.) show higher magnitudes compared to the left chart.
There is a notable presence of higher-order harmonics, suggesting this VFD generates more harmonic distortion.
A more distributed harmonic presence across multiple frequencies reflects less effective harmonic control.

8. Conclusion

From the analysis of these two harmonic bar charts for VFD outputs, it is evident that the VFD represented by the left chart performs significantly better in minimizing harmonic distortion at the output compared to the VFD shown in the right chart.

The left VFD likely incorporates advanced output filtering and high-frequency switching technologies, resulting in lower Total Harmonic Distortion (THD) and a cleaner output signal. In contrast, the right VFD exhibits higher harmonic levels, indicating less effective harmonic management at the output.

SmartD Clean Power VFD

Not only do these measurements demonstrate compliance with IEEE 519 standards, but this comparison highlights the superior performance of SmartD Technologies' Clean Power VFD (represented by the left chart) in reducing harmonics and improving overall power quality at the output, making it a more reliable and efficient choice for minimizing harmonic-related issues in electrical systems.

Beyond harmonic elimination, SmartD's Clean Power VFD offers improved system efficiency, reduced installation size, and longer motor lifespan. The technology simplifies scaling, lowers overall installation costs, and reduces system complexity, making it a highly attractive solution for modern electrical systems.

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