Interpreting IEEE Std 519 and Meeting its Harmonic Limits in VFD Applications

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Abstract –

IEEE Std 519 was first introduced in 1981 to provide direction on dealing with harmonics introduced by static power converters and other nonlinear loads so that power quality problems could be averted. It is being applied by consulting engineers and enforced by Utilities more frequently in recent years as the use of Variable Frequency Drives and other non-linear loads has grown.

Two of the more difficult aspects of applying IEEE Std 519 are (i) determining an appropriate point of common coupling (PCC) and (ii) establishing a demand current at the design stage. This is because the standard does not provide a concise definition of the PCC and the recommended definition of demand current is a value that can only be determined by measurements taken after installation.

This paper represents the authors' best interpretation of IEEE Std 519. It attempts to provide clarity in the determination of the PCC and offers a means by which IEEE Std 519 can be applied at the design stage when the precise demand current is unknown.

Index Terms —

Point of Common Coupling (PCC): *(As found on p75 of IEEE Std 519-1992)* A point of metering, or any point as long as both the utility and the consumer can either access the point for direct measurement of the harmonic indices meaningful to both or can estimate the harmonic indices at point of interference (POI). Within an industrial plant, the PCC is the point between the nonlinear load and the other loads.[1]
(As presently defined by IEEE 519 Working Group) The Point of Common Coupling (PCC) with the consumer/utility interface is the closest point on the utility side of the customer's service where another utility customer is or could be supplied. The ownership of any apparatus such as a transformer that the utility might provide in the customer's system is immaterial to the definition of the PCC.[2]

Short Circuit Ratio (I_{SC}/I_L): The ratio of the short circuit current (I_{SC}) available at the point of common coupling (PCC) to the maximum fundamental load current (I_L).[1]

Maximum Load Current (I_L): Is recommended to be the average current of the maximum demand for the preceding 12 months.[1] *(Unfortunately, this value is inherently ambiguous making it difficult to derive at the design stage when measured load is not available)*.

Voltage THD: Total Harmonic Distortion of the voltage waveform. The ratio of the root-sum-square value of the harmonic content of the voltage to the root-mean-square value of the fundamental voltage.[1]

$$V_{THD} = \frac{\sqrt{V_2^2+V_3^2+V_4^2+V_5^2+....}}{V_1} \text{ x } 100\%$$

Current THD: Total Harmonic Distortion of the current waveform. The ratio of the root-sum-square value of the harmonic content of the current to the root-mean-square value of the fundamental current.[1]

$$I_{THD} = \frac{\sqrt{I_2^2+I_3^2+I_4^2+I_5^2+....}}{I_1} \text{ x } 100\%$$

Current TDD: Total Demand Distortion of the current waveform. The ratio of the root-sum-square value of the harmonic current to the maximum demand load current.[1]

$$I_{TDD} = \frac{\sqrt{I_2^2+I_3^2+I_4^2+I_5^2+....}}{I_L} \text{ x } 100\%$$

Variable Frequency Drive (VFD): A solid-state device that converts utility power to a variable voltage and frequency in order to control the speed of a three-phase induction motor. Drives typically use harmonic generating rectifiers on their front-end for AC-DC conversion.

I. INTRODUCTION

With their many benefits, Variable Frequency Drives (VFD's) have grown rapidly in their usage in recent years. This is particularly true in the Petrochemical Industry where their use in pumping and other applications has led to significant energy savings, improved process control, increased production and higher reliability.

An unfortunate side effect of their usage however, is the introduction of harmonic distortion in the power system. As a non-linear load, a VFD draws current in a non-sinusoidal manner, rich in harmonic components. These harmonics flow through the power system where they can distort the supply voltage, overload electrical distribution equipment (such as transformers) and resonate with power factor correction capacitors among other issues.

In order to prevent harmonics from negatively affecting the Utility supply, IEEE Std 519 has been established as the 'Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems'. This standard has been widely adopted, particularly in North America, but has often been misinterpreted and/or misapplied creating installations that have either been expensively overbuilt or critically under designed.

IEEE Std 519 in 1981 gave simple guidelines for limits on voltage distortion. In 1992, it more clearly established limits for both voltage and current distortion. Its 100 pages cover many aspects of harmonics in very technical detail making it difficult for the non-expert to decipher and isolate the important aspects of its implementation. This paper will attempt to simplify interpretation of the most applicable portions of the standard, allowing consulting and facility engineers to become more comfortable with applying the standard where necessary and appropriate.

In addition, a case study is presented which describes an application where a passive harmonic filter was used in an Electrical Submersible Pump application. The filter was applied to a standard AC PWM Variable Frequency Drive with a 6-pulse rectifier front-end to meet the limits proposed in IEEE Std 519 while maintaining optimum VFD performance.

II. IEEE STD 519

IEEE Std 519 was introduced in 1981 and was most recently revised in 1992. It was intended to provide direction on dealing with harmonics introduced by static power converters and other nonlinear loads. The list of static power converters is extensive. It includes power rectifiers, adjustable speed or variable frequency drives (both AC and DC), switch-mode power supplies, uninterruptible power supplies and other devices that convert ac to dc, dc to dc, dc to ac or ac to ac. The standard recognizes the responsibility of an electricity user to not degrade the voltage of the Utility by drawing heavy nonlinear or distorted currents. It also recognizes the responsibility of the Utility to provide users with a near sine wave voltage.

The standard was written to establish goals for the design of electrical systems with both linear and nonlinear loads. Distortion limits for both current and voltage are defined in order to minimize interference between electrical equipment. It is presented as a guideline for power system design when nonlinear loads are present and assumes steady-state operation.

Sections 4 through 9 of the standard provide quite extensive discussion on the generation of harmonics, typical system response to these harmonics, their effects, methods of reduction, methods of analysis and measurement techniques. This information can help in developing a better understanding of the problem and those interested should take some time to read these sections. This paper will make reference to these sections when appropriate but will not cover them in detail.

From an electrical users perspective, Section 10 is the most important section in the standard. It describes the 'Recommended Practices for Individual Consumers'. The primary focus of this paper will be on the items in this section and how they can be applied to VFD applications. Section 11, which describes 'Recommended Practices for Utilities', will not be discussed.

IEEE Std 519 was intended to be used as a system standard. The voltage and current harmonic limits presented in the standard were designed to be applied while taking the entire system into consideration, including all linear and non-linear loading. However, many consulting and facility engineers have found it difficult to apply IEEE Std 519 as a system standard because detailed information on the system and its loading is often not available at the design stage. It is therefore, difficult to accurately determine compliance at this stage. And even when the information is available, the resources required to do a proper analysis does not always exist. Further complicating matters is that the standard applies to the maximum load current which may be a poor estimate at the design stage.

Therefore, in order to ensure that some harmonic limits are applied, these engineers have often resorted to applying the standard on an individual equipment basis. By insisting that the current harmonic limits be met at the terminals of the non-linear equipment, compliance on a system basis can be ensured. Although this approach can be effective, it often requires very costly and sometimes unreliable treatment equipment that many VFD manufacturers have been reluctant to integrate into their product offerings.

III. IEEE STD 519 RECOMMENDED PRACTICES FOR INDIVIDUAL CONSUMERS

Section 10 of IEEE Std 519 defines the limits for various harmonic indices that the authors of the standard believe strongly correlate to harmonic effects. The defined indices are:

1. Depth of notches, total notch area, and distortion of the bus voltage by commutation notches
2. Individual and total voltage distortion
3. Individual and total current distortion

The philosophy adopted to develop the limits for these indices was to restrict harmonic current injection from individual customers so that they would not cause unacceptable voltage distortion levels when applied to normal power systems. Notches and voltage distortion are presented in a single table, Table 10.2, 'Low-Voltage System Classification and Distortion Limits'. Current distortion limits are found in 3 separate tables based on bus voltage levels. Table 10.3 is applied to distribution systems of 120 V to 69,000 V. Table 10.4 is 69,001 V to 161,000 V and Table 10.5 is > 161 kV. Since essentially all VFD applications fall into the 120 V to 69,000 V range, only Table 10.3 will be analyzed in this paper.

IV. IEEE STD 519 VOLTAGE HARMONIC LIMITS

Table 10.2 in IEEE Std 519 establishes harmonic limits on voltage as 5% for total harmonic distortion and 3% of the fundamental voltage for any single harmonic (see Figure 1). The justification for these limits is not fully explained but a reference in Section 6.6 states that:

"Computers and allied equipment, such as programmable controllers, frequently require ac sources that have no more than a 5% harmonic voltage distortion factor, with the largest single harmonic being no more than 3% of the fundamental voltage. Higher levels of harmonics result in erratic, sometimes subtle, malfunctions of the equipment that can, in some cases, have serious consequences. Instruments can be affected similarly, giving erroneous data or otherwise performing unpredictably. Perhaps the most serious of these are malfunctions in medical instruments."[1]

The reference to medical equipment sensitivity provides some indication as to why the limits are even more severe (less than 3% V_{THD}) for special applications such as hospitals and airports (see note 1 in Figure 1). In contrast, the limits are relaxed (V_{THD} < 10%) for dedicated systems. A dedicated system is defined as one that is exclusively dedicated to converter loads assuming the equipment manufacturer will allow for operation at these higher distortion levels.

For applications in the petrochemical industry, the general system limits are most appropriate. This means that we must design our systems for < 5% V_{THD} and with no single harmonic greater than 3%. These generally will be met at the PCC provided the current harmonic limits are met.

It should be noted that even if the voltage distortion limits are met at the PCC, they could very easily be exceeded downstream where connected equipment could be affected. Since voltage distortion is the result of harmonic currents passing through the impedance of the power system, voltage distortion will always be higher downstream where the harmonic currents are generated and where system impedance is highest.[3]

V. IEEE STD 519 CURRENT HARMONIC LIMITS

The level of harmonic voltage distortion on a system that can be attributed to an electricity consumer will be the function of the harmonic current drawn by that consumer and the impedance of the system at the various harmonic frequencies. A system's impedance can be represented by the short circuit capacity of that system since the impedance will limit current that will be fed into a short circuit. Therefore, the short circuit capacity can be used to define the size and influence of a particular consumer on a power system. It can be used to reflect the level of voltage distortion that current harmonics produced by that consumer would contribute to the overall distortion of the power system to which it is connected.

To define current distortion limits, IEEE Std 519 uses a short circuit ratio to establish a customers size and potential influence on the voltage distortion of the system. The short circuit ratio (I_{SC}/I_L) is the ratio of short circuit current (I_{SC}) at the point of common coupling with the utility, to the customer's maximum load or demand current (I_L). Lower ratios or higher impedance systems have lower current distortion limits to keep voltage distortion at reasonable levels.

For power systems with voltage levels between 120 V and 69,000 V, the limits can be found in Table 10.3 of the standard (see Figure 2). The table defines Total Demand Distortion (current) limits as well as individual harmonic current limits. The limits are most severe for short circuit ratios of less than 20 because this lower ratio indicates a high impedance power system or a large customer or both. Voltage distortion is more likely to develop from current harmonics consumed at a PCC where the short circuit ratio is low, thereby justifying the more severe limits.

VI. DETERMINING AN APPROPRIATE POINT OF COMMON COUPLING (PCC)

Table 10.2, p77
Low-Voltage System Classification and Distortion Limits

	Special Applications[1]	General System	Dedicated System[2]
Notch Depth	10%	20%	50%
THD (voltage)	**3%**	**5%**	10%
Notch Area (A_N)[3]	16 400	22 800	36 500

NOTE: The Value A_N for other than 480 V systems should be multiplied by V/480

[1] **Special applications include hospitals and airports**
[2] A dedicated system is exclusively dedicated to the converter load
[3] In volt-microseconds at rated voltage and current

Figure 1: Table of voltage distortion limits in IEEE Std 519

Table 10.3, p78
Current Distortion Limits for General Distribution Systems
(120 V Through 69,000 V)

Maximum Harmonic Current Distortion in Percent of I_L						
Individual Harmonic Order (Odd Harmonics)						
I_{SC}/I_L	<11	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h$	TDD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Where:
I_{SC} = maximum short-circuit current at PCC.
I_L = maximum demand load current (fundamental frequency component) at PCC.

Figure 2: Table of current distortion limits in IEEE Std 519

One of the most difficult aspects to applying IEEE Std 519 is determining the location of the Point of Common Coupling or PCC. Since the original objective of IEEE Std 519 was to prevent the proliferation of non-linear loads from creating power system problems and in particular voltage distortion, the limits were intended to be applied at the point where a high level of harmonics generated by one customer could distort the power system to a level that might affect other customers on the power grid.

The concept of PCC has been used to define this point but unfortunately, the existing standard has not provided a clear definition. Two definitions are provided in the earlier 'Index Terms' section. The first is as found in Section 10 of IEEE Std 519. It has been found to be too ambiguous to be effectively applied on a consistent basis therefore, the 519 Working Group has provided a second definition which can be found on their website.

The second definition is more precise in that it stipulates that the PCC is 'the closest point on the utility side of the customer's service where another utility customer is or could be supplied'. It also points out that the ownership of any supply transformer is irrelevant. That is, if a supply transformer connected to the public power grid supplies only one customer, the PCC will be located at the primary of that transformer, rather than the secondary, regardless of whether the transformer is owned by that customer or the utility. This is an important distinction because the transformer's impedance will decrease the short circuit ratio and consequently increase the harmonic current limits. Also, voltage distortion will be higher on the secondary side of the transformer making it more difficult to meet the voltage distortion limits.

Although applying IEEE Std 519 limits at the transformer primary is allowed, good engineering practice should include consideration of the secondary side voltage distortion. Voltage distortion will always be higher downstream near the harmonic generating loads and therefore, meeting IEEE Std 519 limits at the PCC will not necessarily ensure that voltage distortion is less than 5% throughout the power distribution system.

VII. HOW TO ESTABLISH A DEMAND CURRENT DURING THE DESIGN STAGE

Maximum load current (or demand current), as used in the short circuit ratio (I_{SC}/I_L) and Total Demand Distortion (TDD) calculations, is given a recommended, rather than firm, definition in IEEE Std 519. It is recommended to be the average current of the maximum demand for the preceding 12 months. Unfortunately since this definition is a measured value, it is totally dependent upon the operating mode of the application, which makes determination at the design stage extremely difficult, if not impossible. Also, since the performance of many treatment methods will vary significantly with loading, designing an installation that will meet the limits under any and all operating conditions is very challenging when this definition is used.

What then should be used? It seems more practical to use the full load rated current of the non-linear load and apply a treatment method whose performance level does not degrade too severely under lighter loading conditions. This strategy is effective because, in general, a loads maximum contribution to harmonic distortion (both current and voltage) occurs when operating at full load. If percent current total harmonic distortion (I_{THD}) was the same at all load levels, a non-linear load running at rated current would draw more harmonic current than it would while running at a lighter load. And although I_{THD} normally increases as loading decreases, a non-linear load will draw less harmonic current at lighter loads even when the I_{THD} is higher provided the increase is proportionately less than the load decrease.

Figure 3 shows measurements taken on a 150HP, 6-pulse VFD that has had no harmonic treatment. As percent loading decreases, I_{THD} increases but the magnitude of the individual harmonic currents decreases. Since both voltage distortion and harmonic overheating are the result of the ampere level of the harmonic currents, they will be worse at full load operation even though the I_{THD} is higher at the lighter loads. Therefore if treatment applied to the VFD resulted in IEEE Std 519 limits being met at full load operation, then both voltage distortion and overheating would be satisfied at all load levels.

	Current (amps)		**Current Harmonics (amps)**					
Load	**RMS**	**60 Hz**	**5th**	**7th**	**11th**	**13th**	I_{THD}	I_{TDD}
Full	233	182	118	80	12	12	79%	79%
75%	187	142	96	70	15	7	86%	65%
50%	134	96	69	54	17	5	96%	48%
25%	67	43	33	29	14	9	120%	30%

Figure 3: Current measurements on a 150HP, 6-pulse VFD with no harmonic treatment

If we accept the premise that maximum load current should be the full rated current of the non-linear load, then we can determine current total demand distortion (I_{TDD}) and apply the limits found in Table 10.3 of the standard at the design stage. Total demand distortion is defined as 'the ratio of the root-sum-square value of the harmonic current to the maximum demand load current' (see 'Index Terms'). Therefore at rated load, I_{TDD} and I_{THD} are the same value. As load drops, the value of I_{TDD} relative to I_{THD} will drop proportionately with the load. For example, if I_{THD} is 96% at 50% loading, then I_{TDD} at that load would be ½ that value or 48% (see Figure 3).

VIII. CASE STUDY

Location: Amerada Hess Corporation, Tioga, ND
Application: Down Hole Electrical Submersible Pump (ESP)
VFD: 200HP, 480V AC PWM VFD
Harmonic Filter: 200HP, 480V series connected passive
LC filter

The VFD was operating as part of an Electrical Submersible Pump (ESP) installation in a remote area of North Dakota. It was equipped with a built-in DC link reactor which reduced the harmonic currents reflected back into the power system by approximately 2 times. However, even at this reduced level, the harmonic currents generated by the VFD exceeded the limits as defined by IEEE Std 519, Table 10.3.

The Utility provided three 100 kVA, 12.5kV-480V 1-ph transformers with an impedance of 2.6% to supply the 200HP VFD. Fault current, Isc, on the primary side was 900A and 8,700A on the secondary side. The Utility was not specific as to the location of the PCC so both primary and secondary locations were considered.

Even without the installation of harmonic treatment, voltage distortion (V_{THD}) was comfortably below IEEE std 519 limits. V_{THD} on the secondary side of the transformer was measured at 3.4% (< 5% limit) with the largest harmonic being the 5th at 2.3% (< 3% limit). Even though measurements could not be taken on the primary side because the measuring instrumentation was not suitably rated for the higher voltage, meeting the limits on the secondary side ensured that they were being met on the primary side. This is because the transformers impedance always results in higher voltage distortion on its secondary side than on its primary side.

To determine whether current distortion limits were met, the short circuit ratio was calculated.

For PCC at primary:
I_{SC} = 900A
I_L = 7A (full load 60 Hz current)
I_{SC}/I_L = 128
From Table 10.3, I_{TDD} <15%

For PCC at secondary:
I_{SC} = 8,700A
I_L = 180A (full load 60 Hz current)
I_{SC}/I_L = 48
From Table 10.3, I_{TDD} <8%

Current THD (I_{THD}) at the secondary of the transformer before installation of the Lineator filter was measured to be 35% when operating at 60% load which was the maximum operating load attainable at the time. Since the load current contained no zero sequence harmonic currents, the primary side I_{THD} could be assumed to be essentially the same as the secondary side. Using full load current rating as the peak demand, I_{TDD} was calculated to be 21% (35% x .6) which exceeded the IEEE 519 maximum limits on both the primary (15%) and the secondary (8%).

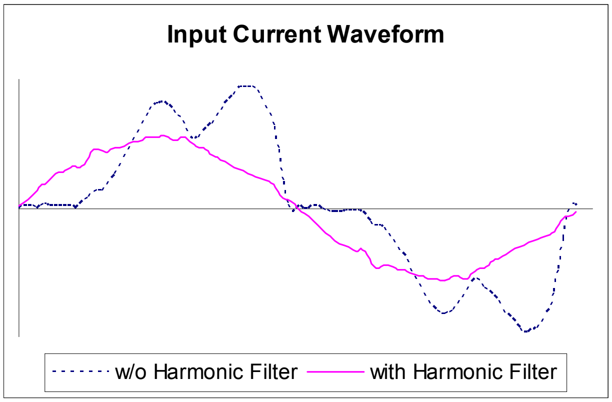

Figure 4: Input Current Waveform with and without harmonic filter

With the harmonic filter installed, I_{THD} dropped to 5.4% which was comfortably below the IEEE Std 519 limit at both the primary and secondary even without calculating I_{TDD} based on full load rating. Figure 4 shows the input current waveforms both with and without the harmonic filter. With the filter, current is virtually sinusoidal with a much lower peak level than without the filter.

One other benefit of the filter installation was a reduction in Radio Frequency Interference (RFI) which eliminated an AM reception problem experienced by a neighboring farmer.

IX. CONCLUSIONS

Applying the harmonic limits as defined in IEEE Std 519 to VFD applications is a useful exercise but often a challenging one. Most VFD suppliers and filter manufacturers can help by running a power system harmonic analysis for a specific application to determine THD levels at the point of common coupling. This analysis can be developed considering various harmonic attenuation methods while comparing hardware requirements, performance and cost.

It is also important to keep in mind that the entire power system comes into play when analyzing performance and reliability. For example, a ‘weak’ power system using onsite generation may not have the voltage and frequency stability to work in conjunction with an active filter or some passive filters with high capacitive reactance. Experience has also shown that drive performance can sometimes be impacted as the system architecture is modified in an attempt to lower THD levels. For critical systems, on-site performance testing may be helpful.

Overall, it is important to understand how the various system components interact with each other and with the power system. It is essential that a coordinated solution be provided which meets THD levels, system performance demands and power system requirements. Fixing a harmonic distortion problem in the field after installation can be difficult, time consuming and expensive.

V. ACKNOWLEDGEMENTS

Alan Hartwell, Amerada Hess Corporation, Williston, ND

VI. REFERENCES

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VIII. VITA

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