

An 'Intuitive Understanding' of Electrical Harmonics: A Conversation

Mike McGraw

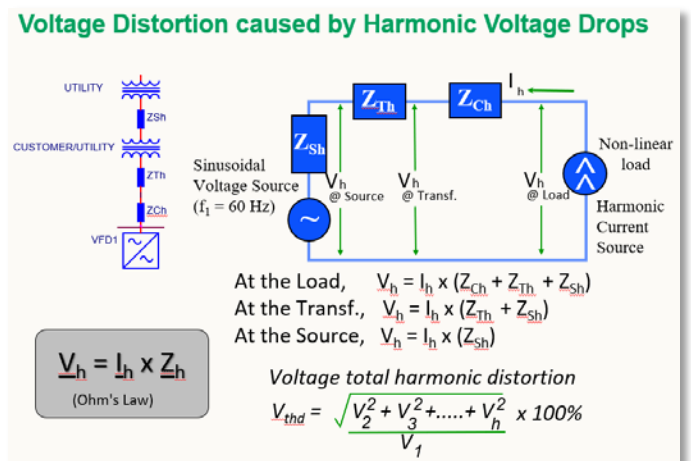
USA National Sales Manager, Mirus International Inc.

Most often in previous writings, I've focused on a particular technical topic relative to the subject of electrical harmonics... I center my discussions about the relationships between the major electrical components that create the harmonic conditions or specific strategies to mitigate the harmonics present; without discussing the fundamental relationships. However, understanding the harmonic condition is impossible without a basic knowledge of the relationships associated with the topic. The following is meant as a conversation to begin the process of developing this 'Intuitive Understanding'.

Often, it is assumed that the relationship between Ohm's Law and Harmonics is understood, but that is a poor assumption. Ohm's law is a basic and fundamental principal, beautifully simple and easy to understand. The best definition and the easiest to understand for me was published in Wikipedia: "Ohm's law states that the current through a conductor between two points is directly proportional to the voltage across the two points. Introducing impedance as the constant of proportionality, one arrives at the usual mathematical equation that describes this relationship: $I=V/Z$, where I is the current through the conductor in units of amperes, V is the voltage measured across the conductor in units of volts, and Z is the impedance of the electrical circuit in units of ohms."

Now taking that principal and modifying it a bit from a harmonic context... try this: Harmonic currents, when injected into or drawn through a system impedance, will create voltage distortion. The level of voltage distortion created, and the harmonic frequencies of that distortion is a function of the harmonic spectrum and magnitude of the current harmonic and the level of system impedance within the circuit at the

various harmonic frequencies. The total voltage distortion is the combined effect of voltage drops due to Ohm's Law at each harmonic frequency. That is, $V_h = I_h \times Z_h$, where V_h is the voltage at a specific harmonic, I_h is the current at that harmonic and Z_h is the system impedance also at that harmonic.



The Ohm's law interpretation when it comes to harmonics and an intuitive understanding of harmonics should start to take shape. From this, a few qualified basic relationships will start to develop.

System Impedance, Short circuit Ratio, and Current Harmonic Limits:

System Impedance is the cumulative total of all the impedances between the load, and the Source, including the Source impedance. The system impedance will include all the impedances of the cables, secondary series mounted devices, such as transformers and inductors. If the system is Utility supplied, this includes the Utility impedance and if Generator supplied, the unsaturated sub-transient reactance of the

Generator (X"d). In essence, just like when trying to calculate short circuit... these impedances must be known and understood in order to understand the relative strength or weakness of a source.

From a harmonic perspective, the relative strength or weakness of a source is expressed as the Short Circuit Ratio of the circuit, and defined as the ratio of the short circuit current at the designated point where the analysis is being done, divided by all the load currents fed from that point. So, based on the circuit, the Short Circuit ratio can change within the circuit, based on all the cumulative impedances up to that point, and all the current loads being fed from that point. Here is an example:

Available SC at the point where the system is being evaluated... 20kA, Total Connected Load secondary of that point: 1000A, Short Circuit Ratio: 20,000A/1000A = 20. If the available short circuit is 20 kA, but the Total Connected Load secondary of that point: 100A, Short Circuit Ratio: 20,000A/100A = 200.

The harmonic standard IEEE Std 519 uses this ratio to set limits for current harmonics. From Table 2 of this standard, as the Short Circuit Ratio increases, the allowed TDD – Total Demand Distortion of current, increases. This is a result of the understanding that the ultimate Voltage Distortion created by the Current Harmonic injected into the system impedance will be lowered as the relative stiffness of the source increases. Within IEEE519, they also place individual current harmonic limits within specific frequency ranges. From the table, a SC ratio of 20 or less would require a limit of 5% TDD (or ITDD to be more specific) and as the short circuit ratio increases the ITDD limit also increases.

Table 2 – Current distortion limits for systems rated 120V through 69kV						
Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics) ^{a,b}						
I_{SC}/I_L	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h \leq 50$	TDD
< 20 ^c	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

^aEven harmonics are limited to 25% of the odd harmonic limits above

^bCurrent distortions that result in a dc offset, e.g., have-wave converters, are not allowed

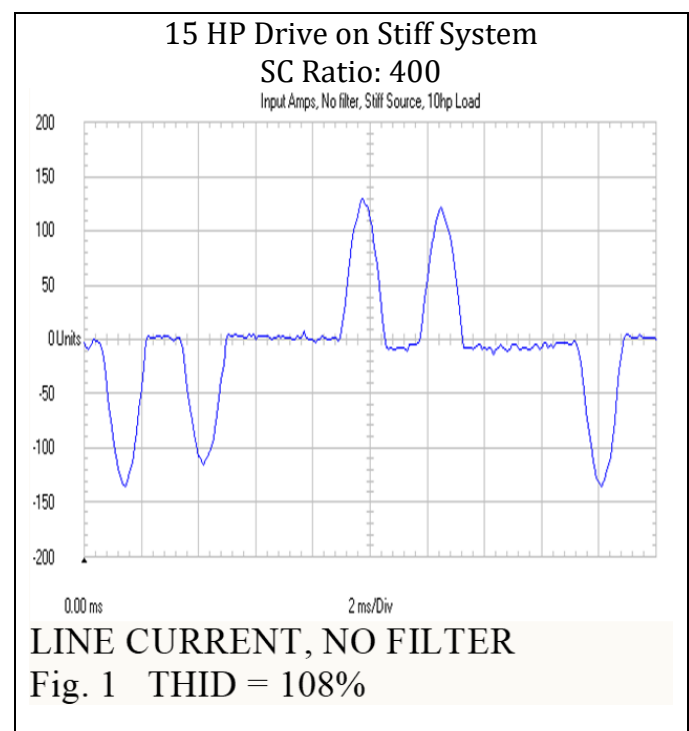
^cAll power generation equipment is limited to these values of current distortion, regardless of actual I_{SC}/I_L , where

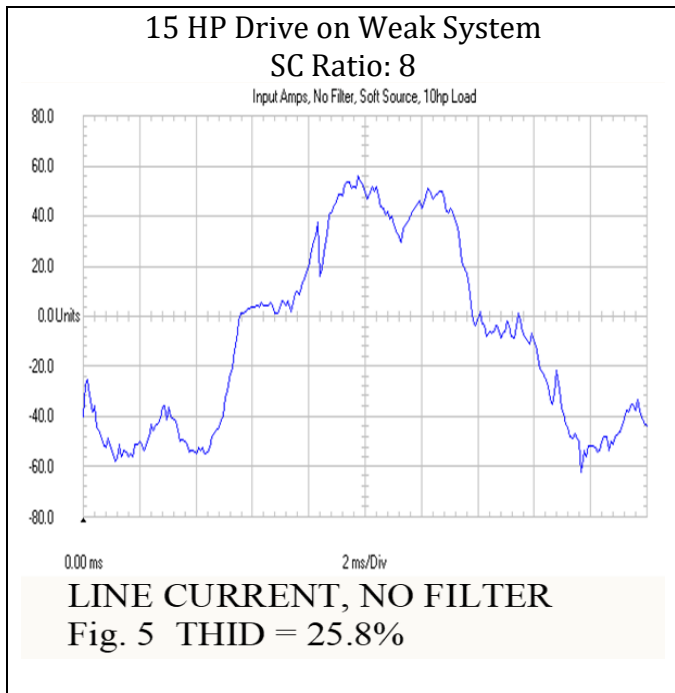
I_{SC} = maximum short-circuit current at PCC

I_L = maximum demand current (fundamental frequency component) at the PCC under normal load operating conditions

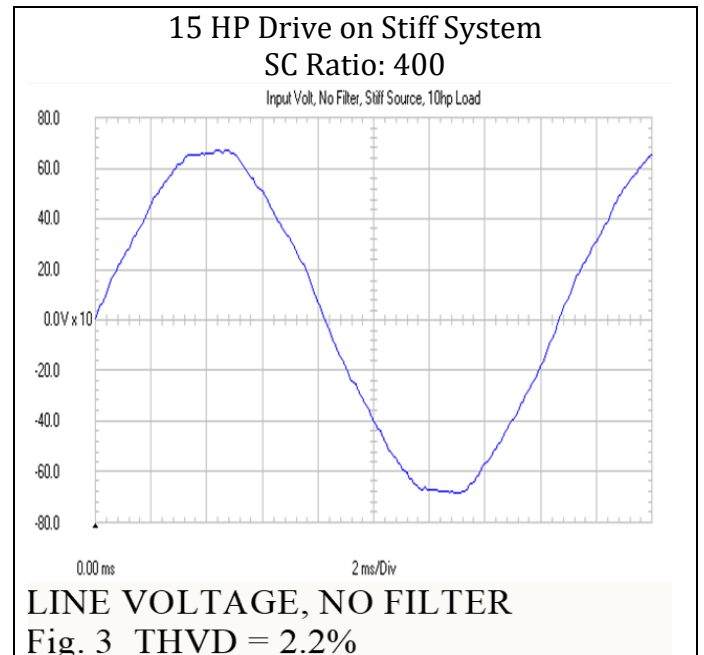
Current Harmonics Vary Based on How 'Stiff' the Source Is:

The next concept might be a bit harder to intuitively understand, so bear with me through the discussion... When we consider current harmonics, the magnitude of a measured and calculated current harmonic is a function of how stiff the source is... i.e. how easily the source can supply the current as the load demands it. A non-linear load draws current in pulses as the rectifier fires the SCR's or Diodes used to create the DC bus voltage. If the source is stiff, i.e. has a high short circuit ratio, the source is able to provide the current easily. But if the source is weak, i.e. a low short circuit ratio, the current pulse is drawn-out or widened, thereby lowering the calculated or measured current harmonic numeric value (Itdd and/or Ithd). See example below, where the load structures are kept constant, but the SC Ratio is changed, with the resulting changes in the measured Total Harmonic Current Distortion measurements. The example of the Stiff Source is a Utility supply and the Weak Source is a relatively small generator. Keep this relationship in mind when we examine the role of short circuit ratio, current harmonic and associated voltage distortion.





linear load current draw. In the case of harmonics, we are actually looking at the voltage regulation capability of the source based on an instantaneous change to the harmonic current draw and its instantaneous impact on the source voltage, versus a longer period event, like a motor start or introduction of a large linear load package. The graphic below will highlight this and is based on the same circuit as the earlier discussion of current harmonic and short circuit ratio.

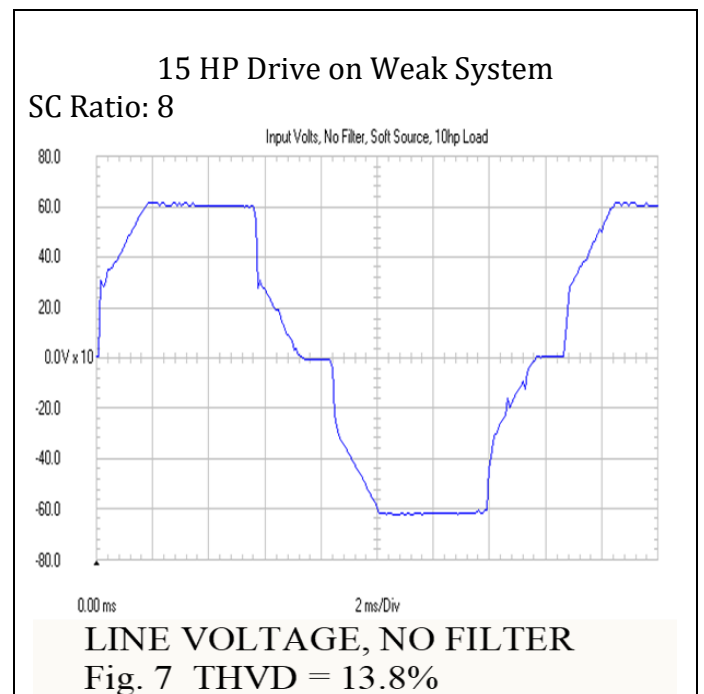


Voltage Distortion Will Vary Based on How Stiff the Source Is:

The higher the Short Circuit Ratio, i.e. the greater the available short circuit with respect to the associated demand load, the lower the voltage distortion created by any injected current harmonic. To understand this better, let's introduce source regulation into the discussion. Here again, Wikipedia does an excellent job of defining regulation...

“In electrical engineering, particularly power engineering, voltage regulation is a measure of change in the voltage magnitude between the sending and receiving end of a component, such as a transmission or distribution line. Voltage regulation describes the ability of a system to provide near constant voltage over a wide range of load conditions. The term may refer to a passive property that results in more or less voltage drop under various load conditions, or to the active intervention with devices for the specific purpose of adjusting voltage.”

So as current harmonic is drawn from a source, some distortion of the voltage will result, The stiffer the source, the greater the short circuit ratio, the tighter the source regulation, the lower the associated voltage distortion from the non-



As you can see, the stiffer the source, the less of an impact the current harmonic will have on distorting the source voltage, and for a weaker system the greater the impact on the source voltage.

Which is worse, Current Distortion or Voltage Distortion?

As we can see, they go hand in hand. But Voltage Distortion can have consequences within the entire system, since the distorted voltage then feeds all the loads within the circuit; whereas current harmonic tend to flow directly from the load to the source, and not move into parallel circuit structures. The following points should help you understand the consequences of both.

Current Harmonics increase the total current drawn within a circuit, increasing heating within upstream cables, transformers, and the source itself. Total efficiency is lowered due to primary system losses and the increase of secondary eddy losses within all the upstream system components. The current harmonic also creates harmonic kVAR (Harmonic Reactive Power Consumption) which is a significant contributing factor to poor 'Total' power factor (pf) seen within the system... versus just the displacement power factor (dpf) we were all taught about in school. The Utility measures Total Power Factor and uses this to calculate power factor correction surcharges. For a discussion on this, please see 'How Harmonics have led to Many PF Misconceptions'.

<https://www.mirusinternational.com/downloads/MIRUS-TP003-A-How%20Harmonics%20have%20Contributed%20to%20Many%20Power%20Factor%20Misconceptions.pdf>

Voltage distortion is created within the entire circuit including parallel circuits to the current harmonic load structure. This means we are now supplying distorted voltage to all the loads within the circuit, which can cause (i) equipment malfunction or failure, (ii) an increase in current harmonic profile of existing non-linear loads, (iii) interference with existing harmonic mitigation

equipment and (iv) even a triggering of harmonic current draw characteristics from linear load devices... the old saying, "garbage in, garbage out". So when a regular inductive load, like a lighting circuit or across the line motor, is fed with a distorted voltage, these non-harmonic loads will now draw current in a harmonic "non-linear" fashion. This then makes them a contributing factor to the overall harmonic mitigation challenge. Also, the resulting Voltage Distortion is reflected back into the Utility grid, which then can and will compromise other users further upstream or downstream of your position within that distribution grid.

Harmonic mitigation equipment effectiveness can be compromised due to source/background voltage distortion, as well as system voltage imbalance. There have been a number of published studies that highlight that Multipulse Drive harmonic performance can be significantly compromised with as little as 1 to 2% source voltage distortion and the same level of source voltage imbalance. So, the greater the overall voltage distortion within the circuit, the less effective many harmonic mitigation strategies and equipment will perform within that application. There are also studies that have been published establishing that Source Background Vd and Voltage Imbalance can compromise the effectiveness of Active Harmonic Solutions such as Active Front End Drives and Active Harmonic Filters. *Any harmonic solution selected for an application must be qualified as to its ability to withstand and perform to specification based on these source voltage conditions.* The 2014 version of IEEEStd519 allows for up to 8% Vthd, whereas the previous 1992 version limited Vthd to < 5%. So, by specifying the IEEE519-1992 recommendation of 5% Vthd, you are more proactive in controlling source background Vd that can compromise the effectiveness of your design.

"Chicken Or the Egg" question – As can be seen, it is easy to get into a circular argument where the current harmonic creates voltage distortion, which then creates more current harmonic... etc. but keep this one relationship in mind... *assuming the Utility supplied voltage is reasonably sinusoidal, without having current harmonics*

introduced within the circuit, you will not have a resulting voltage distortion. Ultimately, to assure the overall health of the electrical distribution system, we have to resolve the Voltage Distortion by controlling the injection of load current harmonics into the source impedance.

Harmonic Mitigation Strategy Development:

Harmonic Mitigation Strategies are wide and varied in nature. Some are complicated and technically sophisticated and can be very expensive. There is no one right way to attack the challenge. In most of my work within the field, multiple strategies are used to achieve the goal. I have distributed a number of discussions on this subject... but I tend to try to keep the strategies in line with the fundamental principal discussed above, as well as, keeping it simple to allow for easy field deployment and service. The following is a quick summary.

The goal will be to achieve the voltage distortion criteria, as detailed within IEEE Std519, through correction of the current harmonic, with the current harmonic requirements kept in mind. To this end, I prefer to use the voltage distortion criteria as set forth with IEEE519-1992 to set the mitigation goals, i.e. 5% or less V_{thd} versus the more relaxed 8% requirement adopted in the 2014 version. This allows for headroom within the harmonic modeling for conditions or loading structures and secondary impedance structures not recognized or understood, that may exist. Seldom do modeled results exactly match 'Real World' results.

Harmonic studies and strategies must have all potential/power sources accounted for within the strategy. Harmonic performance as previously discussed is significantly dependent upon source impedance. A Utility tends to be a relatively stiff source, while a Generator source tends to be very weak. If a backup generator or a co-gen capability exists... you must model and plan based on all these conditions. Results and strategies should be implemented on a worst case scenario. In the vast majority of my studies and field work, Generator Source systems require the greatest level of harmonic mitigation.

It is important to utilizing a qualified Harmonic Modeling Software that includes source background/source voltage distortion and can model the effects of system voltage imbalance Since many harmonic solutions on the market are very susceptible to these two conditions. If a manufacturer's modeling software does not take these two factors into consideration, then their results will not be accurate or predictive. In addition, they might not be including this parameter within their software since their product offering may not perform well with this qualifying condition. I use Mirus SOLV, a freeware package available from Mirus International, since it allows simulation with both Source Voltage Distortion and System Voltage Imbalance. (<https://www.mirusinternational.com/register.php?reg=1>)

Partial and Staged Harmonic Mitigation is a foundation principal of a well-qualified and effective plan. This is particularly important in retrofit harmonic mitigation deployment. Knowing harmonics are cumulative in nature and increased voltage distortion will increase harmonic currents from linear load sources, a partial or staged implementation strategy, can provide a more effective and economical solution, by allowing you to stage qualified implementations via actual testing versus a less accurate modeling program. On the majority of the projects I have worked on, as the staged implementation was progressing, measured results actually outperformed modeled results allowing the deployment of less harmonic mitigation equipment to save money on the project.

True cost, including all components of Total Cost of Ownership, should be evaluated when reviewing any harmonic solution. This is a subject all to itself. In essence, the energy efficiency of any harmonic solution must be anticipated when reviewing the mitigation strategy. I bring this subject up, since in many cases, Active Front End Drives and other active solutions are less energy efficient than a properly deployed 6 pulse drive with a suitably designed passive filter. In fact, multi-pulse drive solutions are also less efficient and effective in real world installations, due to the impedance structures associated with a phase

shift magnetic strategy and real world source voltage distortion conditions. In some cases, as much as 2% to 5% energy consumption impacts can be seen. Even a 2% difference in energy efficiency can increase your TCO significantly over both the short term and full life expectancy of the installation. The proper threshold for a drive/passive filter efficiency index should be 96.5% or greater at full load and any passive filter should be rated > 99.0% efficient as a standalone component.

For a more detailed comparison of harmonic mitigation strategies, please refer to Mirus International Technical Comparatives, AUHF-WP001-A1, 'Advantages of 6-Pulse VFD with Lineator AUHF vs Active Front-End (AFE) Drives' and AUHF-BC002-A4, 'Lineator vs Multipulse Drive'. TCO and other performance consideration is discussed and may provide you with assistance in understanding the challenges associated with some technologies.

Summary:

Having a fundamental and intuitive understanding of harmonics and system conditions is critical to determining the right harmonic mitigation strategy. The above discussions were intended as a general relationship discussion. Should you wish to discuss any of these points in further detail, please contact Mirus. Modeling services and Partial/Staged Implementation assistance is available upon request.

**Michael A. McGraw: Southern US Regional Manager, Mirus International Inc.
Waller, Texas Cell: (713) 208-8534, E-Mail: m.mcgraw@mirusinternational.com**