When is Enough - Enough or Maybe Too Much?
Design Considerations for Harmonic Mitigation Strategies

Michael A McGraw, Five Star Electric, Inc.

When you were growing up, who else was greeted by their parents getting a bit testy and saying, “Enough is enough”, followed by telling you to “cut it out”. My parents were quite forceful since I was a bit stubborn. Funny how what goes around comes around, since I find myself saying the same thing, not to my kids but on harmonic circuit designs.

The more harmonic mitigation within a circuit and the more complex the selected solution, the greater the chance of creating unintended consequences, which can compromise the integrity of your distribution system.

Recently, working on a “what if”, I was asked the title question. The project engineer had experienced operating challenges after a circuit update… numerous issues, and he was convinced that the advent of the harmonic design created the issue. In his case, the issue was that the harmonic solution he implemented added too much capacitance reactance which triggered excess voltage boost and a high frequency ringing within the circuit. The current harmonic at the PCC (Point of Common Coupling) far exceeded the requirements. Disconnecting a few harmonic mitigation devices gave him excellent harmonic performance and resolved the resonance condition causing his operational issues.

The intent of this discussion is to highlight some key points that should be considered when designing IEEE-519 compliant circuits, either new installations or retrofit/modifications. Consideration of these concepts and qualifications will help in developing a qualified design and implementation.

Key considerations will include:

- Intent of the Harmonic Treatment Design
- Potential Unintended Consequences
- Complexity and Serviceability
- Cost/Benefit Considerations
- The Concept of Std. Compliance and Design Headroom

Intent of the Harmonic Treatment Design

This is a question that needs to be answered even before you start the design challenge.

- Why do we need harmonic mitigation within the circuit?
- If the harmonic treatment is to be implemented within an existing circuit, what conditions or operating challenges are necessitating the mitigation program?
- If harmonic mitigation is part of a circuit retrofit or modification, are we expecting the harmonic distortion from the non-linear loads to create operational challenges or are we just trying to assure compliance with an engineering standard?
- For new projects or circuits, are we accounting for future expansion or modification and are the existing load profiles well understood within the process?

These four questions are rarely reviewed before someone initiates an engineering design. In some cases, the questions are reviewed but the answers are not properly developed. I’m not advocating for a full-blown study, just a common-sense review to determine if you really need harmonic mitigation within the circuit and how elaborate the design needs to be.
Keep in mind, adding harmonic mitigation makes the circuit more complicated, increasing the likelihood of creating unintended conditions such as:

- Increasing system impedance which can contribute to voltage drop, decreasing overall system efficiency, and raising operational costs.
- Over-excitation (voltage boost) to the load structure thus increasing the possibility of over voltage trips and secondary resonance. To avoid this there are options that can be incorporated into the design, but these options can introduce additional complexity which makes routine maintenance and service more difficult for service teams and significantly increase the cost of the installation.
- Creation of resonance conditions with upstream or source circuit components which might create voltage transients, reflective wave/ringing voltage conditions, voltage surges, and function to raise associated voltage distortion (Vthd) within the distribution grid.
- Unwanted interaction with Source/Background Voltage Distortion (Vthd-bg) or Source Voltage Imbalances (V-imb) which can interfere with the effectiveness of the harmonic mitigation equipment.
- Compatibility with backup generators or alternate source strategies already existing within the overall system?

Potential Unintended Consequences

I touched on some of these within the Intent Section, but below is an expanded discussion:

- Increased system impedance can lead to voltage drop. This leads to an increase in load current, causing unintended efficiency losses due to additional heating. The higher current levels will also increase the thermal state of the load equipment, lowering the life expectancy of the associated components.
- Over-excitation (voltage boost) caused by excessive capacitance reactance can result in nuisance trip conditions, damage to vulnerable control components, and interference with VFD/ASD ramp operations. Adjusting the source voltage using auto transformers or the use of capacitor switching contactors adds significant burden to your capital budget. The addition of capacitance reactance upstream of a VFD can create resonance between the harmonic equipment and the VFD/ASD load itself damaging either or both assemblies.
- Harmonic Resonance with upstream sources is seldom anticipated but can have damaging effects on the entire distribution system. This needs to be considered but is rarely reviewed. Sometimes it can be present in the form of an elevated system Voltage Distortion (Vthd) which may not be of significant consequence. Other times, high frequency resonance, repetitive voltage transients, and ringing/reflective wave voltage anomalies introduce damaging conditions that will be seen throughout the distribution system. Consideration of the consequences of Active Front End and Active Harmonic Filter designs for Supraharmonic current injection is important. An IEEE/PCIC paper I co-authored has a great reference on this concept:

  ACTIVE HARMONIC MITIGATION – WHAT THE MANUFACTURERS DON'T TELL YOU, Copyright Material IEEE Paper No. PCIC 2018-43, https://www.mirusinternational.com/downloads/Active%20Harmonic%20Mitigation%20-%20What%20Manufacturers%20Don't%20Tell%20You,%2018.05.25....pdf

- Within the design, consideration of the Source/Background Voltage Distortion levels and Voltage Imbalance must be reviewed. The harmonic mitigation strategy must be verified in its ability to withstand these two elements. Designing a harmonic strategy that cannot function properly within circuits that can have voltage distortion levels within IEEE519 guidelines is not practical. IEEE519 allows for up to 8% Vthd (Voltage Total Harmonic Distortion), so specifying equipment whose voltage distortion withstand is less than this limit is not advisable. Harmonic mitigation performance should be warrantied through a background/source Vthd of 5% and a Source Voltage Imbalance of 3% at a minimum for the design to be an effective solution and assure compliance with your target Harmonic Standard requirements.

- Backup or Supplemental Source compatibility is critical. In most cases, these configurations will involve backup diesel generation. Generators are a very weak source as compared to a Utility source. This means that based on any given current harmonic injection the associated voltage distortion will be much higher. Also, generators are very limited as to their capacitance reactance withstand. For backup source situations, you must perform a harmonic simulation under both a Utility source condition and under a backup source condition. You must also compare the capacitance reactance of your design to the backup source capacitance reactance withstand curves to ascertain you will be within the sources ability to handle the load. The provider and/or manufacturer of the harmonic solution should be required to submit confirmation of the compatibility within the approval process.

Complexity & Serviceability

How many times have we chosen a solution and ignored possible "side effects". I had a medical treatment once for an arthritic condition, only to be hospitalized with critically high blood pressure. The ER physician said, "Well that sometimes happens." Two days later I was discharged. No question I was not prepared to handle the "unintended side effects" of the treatment. So, a short discussion of how to avoid complications might be in order.

Keeping the harmonic mitigation design simple and easy to understand is important. The simpler the design:

- The fewer the potential consequences of its application.
- The easier it is to perform start-up and ascertain proper operation.
- The less likelihood of needing emergency services you cannot handle yourself.

But sometimes the best solutions need to be complex and when that is the case, three key requirements should be considered:

- During the Installation and Start-Up require comprehensive testing and documentation to ascertain suitability of purpose and proper operation before commencing full operation. A reference document you may want to review is:

  FSE-MM-10252025, "An Ounce of Testing Can Save a Pound of Cure"
  (https://vfd.com/wp-content/uploads/FSE-MM-10202025-LV-VFD-Testing-Guide.pdf).

  This document may help you understand some of the LV VFD testing criteria you may want to consider and function as food for thought for your application. The paper was written around LV applications but can be adapted for a variety of source parameters.
- During the Start-up, the supplier or manufacturer must provide service training to your operating personnel and service/maintenance team. This training should include class instruction, field inspection training and maintenance/service details.
- Consider a service contract for routine inspection, testing and service. It is critical that this service contract be provided and available locally only and does not require service technicians being deployed from locations that will require long lead times for scheduling and travel.

Cost/Benefit Considerations

The concept of diminishing return must be examined during the design stage. From an accounting and budgeting perspective you want the best solution available but at a reasonable cost.

- Cost/Effectiveness Matrix: There are a few published articles and discussions which index harmonic mitigation strategies with anticipated performance and expense indexing… below is my shorthand version.

Mitigation Device/Topology	IEEE-519 Compliance	Cost Profile	Notes
Line Reactors	**No**	**Inexpensive**	Will not lower the Ithd of the non-linear load to IEEE519 levels. Adds a high voltage drop into the circuit which can impact energy efficiency. May be utilized for small frame VFD applications where the demand distortion is not significant.
DC Chokes with 6 Pulse VFD's	**No**	**Inexpensive**	Will not lower the iTHD of the non-linear load/VFD to IEEE519 requirements. Typically reduces iTHD to around 25% to 35%. DC chokes can be easily utilized in conjunction with other harmonic treatments dramatically improving harmonic performance. Also, since the DC choke is integrated by the manufacturer, there is no concern over proper VFD sizing and coordination. Preferrable to AC Line Reactors.
Passive Filters	**Yes**	**Moderate Expense**	Will comply with IEEE519 Ithd requirements, increases net efficiency of the load drive by significantly reducing reactive power consumption. **Specification of a Reactive Power to filter power ratio (kVAR/kW) of 15% or less is important to avoid over-excitation, voltage boost, and to avoid potential resonance conditions**. Attempt to avoid having to add capacitor contactors to over control complexity and installation costs.
Multi-pulse Drives	**No**	**Expensive**	12P VFD designs are not IEEE519 compliant, 18P VFD's which utilize Auto Zig Zag transformer for the phase shift cannot withstand either 2% Vthd-bg or 2% V-Imb and effectively mitigate Ithd. Many manufacturers are discontinuing these designs since they now recognize they were vulnerable to performance compromise based on real world conditions.
AFE Drives (Active Front-End Drives) *	**Yes, through the 50th harmonic only**	**Very Expensive**	The drive cost indexed by HP is very expensive and cost prohibitive. Also introduces high frequency harmonics above the 50th (3- kHz) and not compliant with IEEE519 when reviewed through the rectifier switching frequency, i.e. 4 kHz – 8 kHz. Vulnerable to Source Background Voltage Distortion and systemic voltage imbalance.
AHF Filters (Active Harmonic Filters) *	**Yes, through the 50th, and if properly sized to the non-linear loads**	**Very Expensive**	Parallel Active Harmonic filters require additional circuit protective equipment feeding their installations, typically priced at over $ 30K a 200A module plus ancillary equipment requirements. Also requires CT installation and coordination for retrofit switchboard applications. It can be a source of higher order harmonic injection. An advantage is, it can programmed to treat displacement power factor challenges within the circuit, but this will take away capacity from harmonic current control capacity.

- Active solutions are more expensive from a cost/power standpoint, have higher associated maintenance costs, and are not user serviceable, should repairs be required.

The Concept of Std. Compliance and Design Headroom

The IEEE519 Std. is just like all standards, they are recommended requirements. That being the case, the specification and utilization of this standard for a design is voluntary. The Standard helps build a logical framework for circuit evaluation and should be seriously considered as a required compliance item within your specification. When evaluating your designs, consider building into your evaluation "Headroom", a lower requirement than the Itdd required by Table 2 of the current IEEE519-2022 version to account for the following conditions:

- Incorrect Assumptions relative to the non-linear load loading profile, within your modeling.
- Incorrect Assumptions relative to the Source Background Voltage Distortion and systemic voltage imbalance.
- Incorrect assumptions relating to the Linear Load profile within your modeling and to account for additional harmonic distortion from those linear loads due to a distorted supply voltage.
- Unknown circuit impedance conditions such as accurate cable detail and other unknown conditions that can contribute to inaccurate results. A conservative model for a current harmonic prospective would be to have no systemic impedance outside of the Utility or Source impedance.
- Other unknown conditions from the source and/or circuit.

I like to leave about a 15 - 20% margin between my modeling results and the intended target for iTHD or iTDD, when designing my circuits.

The last point I would make is what I call "Partial Mitigation". I have written about this before so a quick note might help you understand the concept, which can be further explored by downloading my paper,

"A Practical Guide to Partial and Staged, Harmonic Mitigation Strategies, MIRUS-TP006-A, [2020-05-12]",
https://www.mirusinternational.com/downloads/MIRUS-TP006-A-Practical-Guide-to-Harmonic-Mitigation-and-Staged-Implementation.pdf .

You do not have to meet IEEE519 levels at the input of all the individual non-linear loads within the circuit. Focus your attention on individual load compliance with IEEE519 limits for the largest offending loads, with some mitigation of the smaller non-consequential non-linear loads within the circuit. The goal is to control the associated voltage distortion due to the current harmonic injection into the system impedance, Table 1, IEEE519-2022 compliance, at the designated Point of Common Coupling (PCC).

For more information or discussion on this topic, please contact me directly at:

Michael A McGraw
Five Star Electric, San Antonio, TX
Email: mmcgraw@vfd.com or m.mcgraw1450@gmail.com
Cell: 713-208-8534

Contributor:
Austin Miller, Power Quality Applications & Sales Manager – U.S. Mirus International
Mobile: (276) 967-7621
Email: austin.miller@electro-mechanical.com