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Application Note: AccuSine PCSn 3-Phase / 4-Wire Active Harmonic Filters

Summary

Semiconductors are common in electrical equipment, and their use will continue to increase, even though they can introduce damaging harmonics into power networks. Active harmonic devices make it easier to mitigate these negative effects. Further, HMI advancements simplify commissioning of Active Harmonic Filters, and advanced power monitoring also helps users to manage their network power quality.

Introduction

Curbing energy consumption to reduce global warming means electrical equipment manufacturers must make increasing use of semiconductors (Table 1) in order to reduce energy consumption and improve process efficiency; however, in many cases these devices cause high frequency current (referred to as harmonics) to circulate in the electrical network, which in turn distorts the voltage supply.

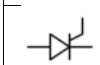
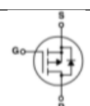
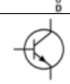
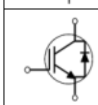
Semiconductors are used in very common loads such as:

- Switch Mode Power Supply (SMPS) used to power computers, televisions, office peripherals
- Light Emitting Diode (LED) used in lighting fixtures
- Compact Fluorescent Light (CFL) used for lighting
- Variable Speed Drive (VSD) used to control various processes, pumps and fans
- Rectifier used in battery chargers and other industrial processes

Over the years multiple methods have been used to control harmonic emission, such as passive Harmonic Filter, multi-pulsing rectifier bridge, active front-end rectification and more. This paper focuses on a state-of-the-art mitigation solution that found its place in the power quality market over the past 20 years: the Active Harmonic Filter (AHF). There are two types of AHFs; 3-phase / 3-wire devices, mostly used for harmonic mitigation for 3-phase nonlinear loads, and 3-phase / 4-wire devices generally used for single-phase nonlinear loads connected phase to neutral. This application note concentrates on the latter, the 3-phase / 4-wire AHF. These devices are known as AccuSine PCSn in the Schneider Electric Power Quality portfolio.

Table 1

Semiconductors and their symbols

	Diode
	THYRISTOR
	MOSFET
	BJT
	IGBT

Impact of harmonics on distribution networks

Harmonic currents flowing in our networks can cause:

- Overload of electrical distribution due to increase of effective current (RMS)
- Overload and premature aging of generators, motors, transformers
- Circulation of harmonics causing temperature to rise due to skin effect and eddy current losses
- Overload of power factor correction capacitors due to high frequency current absorption caused by their low impedance to harmonic frequencies
- Overload of neutral conductors due to zero sequence harmonics generated by single-phase nonlinear loads (**Figure 1**)

Harmonics in voltage in our networks can cause:

- Supply voltage distortion, leading to linear loads drawing nonlinear current
- Distorted voltages, which stress electrical equipment dielectric and reduce their life expectancy
- Disturbances of sensitive electronic loads
- Interference in communication network

Special attention must be taken when assessing the impact of zero sequence harmonic orders (3rd, 6th, 9th, 12th, 15th H) in 3-phase / 4-wire networks as these currents add up in the neutral conductor.[1] As mentioned previously, there is a risk of neutral overload and/or four current-carrying conductors de-rating; however, it goes further. The circulating current in the neutral can create a difference in potential between the neutral-to-ground. This voltage drop across the neutral conductor can disturb the potential reference provided by the protective earth (PE) for electronic equipment which can lead to their erratic behavior. For example, computer vendor specification typically calls for less than 0.5 – 3 Volt RMS neutral to ground, regardless of frequency. Obviously, if this difference of potential between the neutral to ground becomes unreasonably elevated, it can also create a safety hazard for people.

These electrical disturbances lead to production downtime, increased maintenance and loss of production, which effect the bottom line of all businesses.

[1] To find out more about harmonic profile of single-phase nonlinear loads, please see Cahier Technique No.202 “The singularities of the third harmonic”.

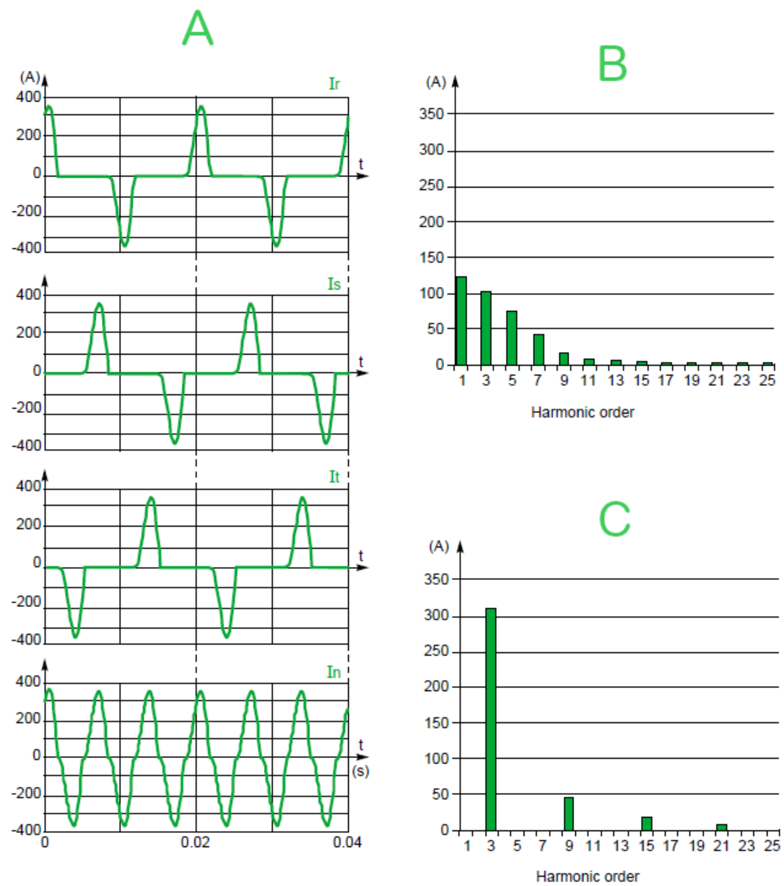
Figure 1

A: Phase (Ir, Is, It) and neutral (In) current supplying non-linear single-phase loads

B: Phase current harmonic spectrum of non-linear single-phase loads

C: Neutral current harmonic spectrum of non-linear single-phase loads

[Extracted from Schneider Electric Cahier Technique no. 202]



What constitutes an AHF in 3-phase / 4-wire network?

The 3-phase / 4-wire AHF are static power electronic products that employ digital logic and IGBT semiconductors to synthesize a current waveform that is injected into the electrical network to cancel harmonic currents caused by single-phase and 3-phase nonlinear loads. They employ current transformers to measure the load current to determine the content of harmonic current present. By injecting the synthesized current, network harmonic currents are greatly mitigated, thus reducing the heating effects of harmonic current and reducing voltage distortion. The device's output is configured to connect to the electrical network phases and neutral (**Figure 2**).

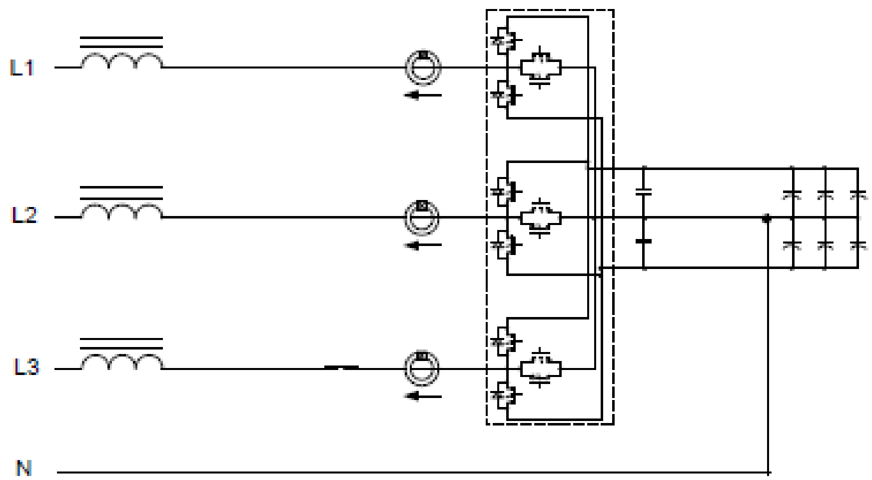


Figure 2
3-phase / 4-wire AccuSine PCSn simplified schematic diagram

The 3-phase / 4-wire AHF can also correct for poor displacement power factor (DPF) and for unbalanced load current. DPF correction can be provided for either leading (capacitive) or lagging (inductive) loads that cause poor DPF. Mains current balancing is achieved by measuring the present negative and zero sequence current, then the AHF injects the inverse of those currents to balance the current in the upstream network.

AHF are gaining in popularity for many reasons. They:

- Can correct three main power quality (PQ) problems
- Compensate PQ problems in real-time
- Can mitigate a wide harmonic spectrum, 2nd to 51st harmonic order
- Can meet the most stringent harmonic standards in the world, for example the IEEE 519
- Are easy to size, eliminating the need for complex harmonic studies
- Cannot be overloaded unlike passive filtering devices
- Offer advanced monitoring capability (**Figure 3**) with capabilities for connection to edge controls (PME) and ultimately to cloud advisory solutions (PA) (**Figure 4**)
- Are compact and shunt connected
- Are scalable – multiple units can be installed in parallel for high power application
- Allow for harmonic mitigation of all the types of nonlinear loads

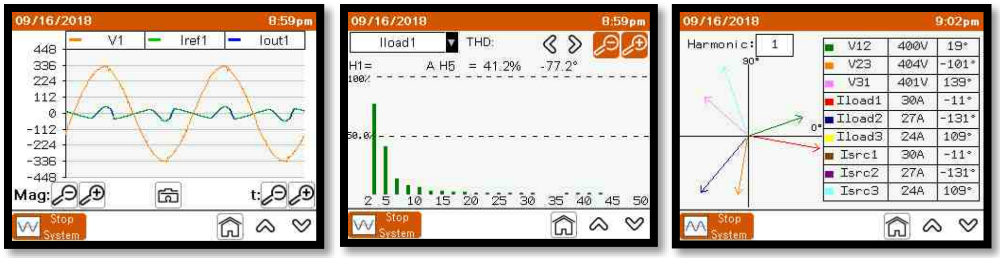


Figure 3
AccuSine PCSn advanced monitoring capabilities – Human Machine Interface screen captures

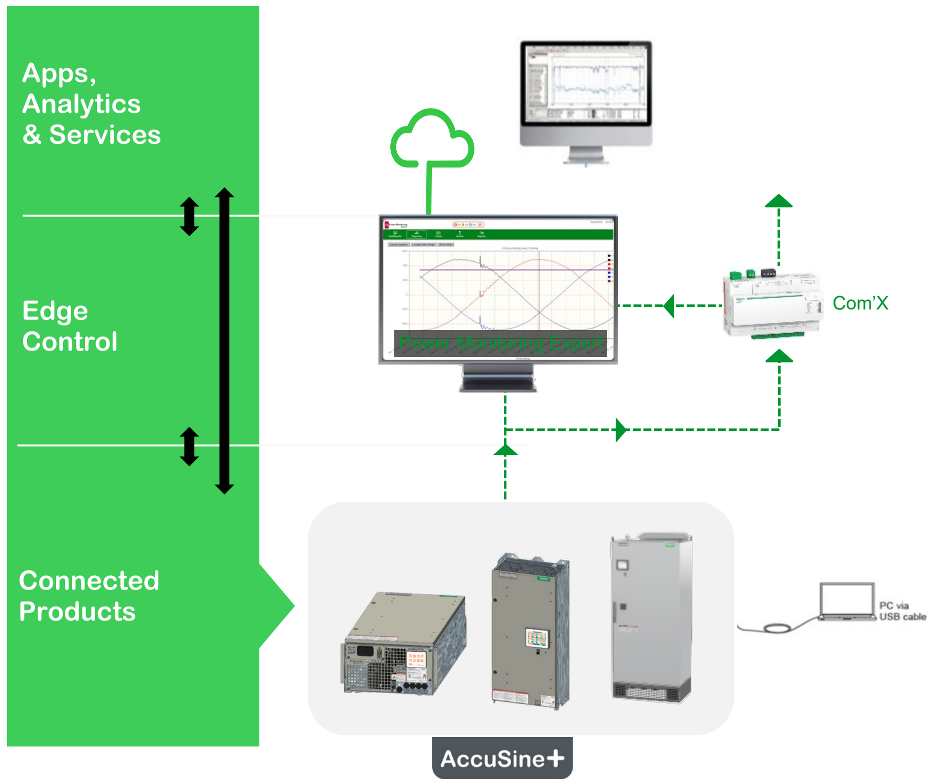
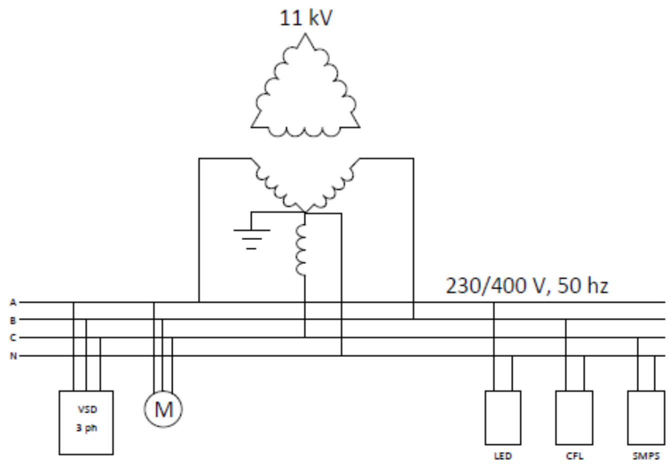


Figure 4
AccuSine range communication capability via Modbus RTU or Modbus TCP/IP

The AccuSine PCSn is generally applied in two different types of low voltage (LV) electrical distribution: IEC distribution layout and North American distribution layout, respectively. We will begin with a review of applications in IEC type networks (Figure 5). The advantage of the IEC distribution is they can feed single-phase and 3-phase loads directly without the use of auxiliary transformers. In these electrical networks, the single-phase loads connect between the phase and the neutral and are fed by a 230 Volt (V) supply and 3-phase loads are connected between the phases and are fed at 400 V. This type of distribution makes the use of the AccuSine PCSn ideal because it can compensate for typical harmonic spectrum from single-phase loads with dominant zero sequence harmonics and for spectrum of 3-phase loads with mostly positive and negative sequence harmonics, with typical dominant 5th, 7th, 11th and 13th harmonic orders. Also, the AHF will compensate for unbalance current created by any types of single-phase loads and they can correct for poor displacement power factor generally caused by inductive loads, like induction motors.

Figure 5
Typical IEC low voltage distribution network



The AccuSine PCSn should be connected in parallel with the loads and have sensing Current Transformers (CT) installed at the main incoming in a close loop configuration (**Figure 6**) or at the loads in an open loop configuration (**Figure 7**). The AHF rating is based on the standard Schneider Electric sizing tools where the effective current (RMS) is calculated based on the mode of operations required to achieve the desired Power Quality (PQ) results. During the equipment start-up, which is assisted by a step-by-step commissioning protocol, the technician will activate the AccuSine PCSn mode of operation required to achieve the project PQ objectives. All three modes can be enabled (1. harmonic mitigation, 2. load balancing & 3. DPF correction) and they will be managed in real-time by the AccuSine PCSn central processing unit (CPU).

Figure 6
AccuSine PCSn connection in IEC electrical network in a closed loop configuration

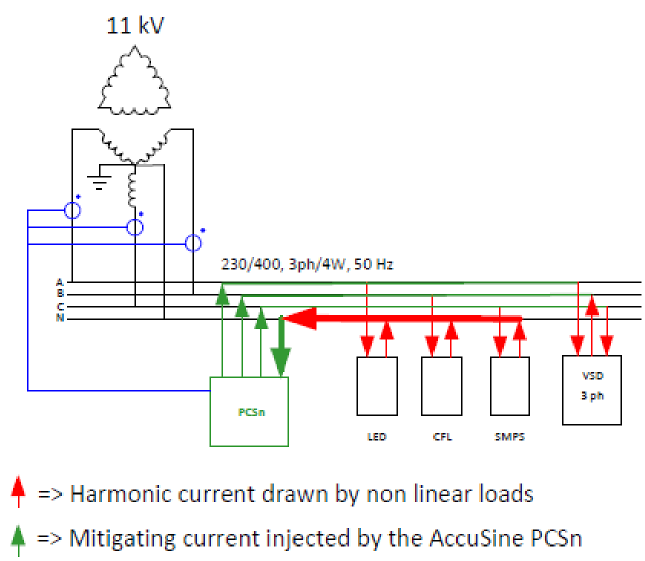
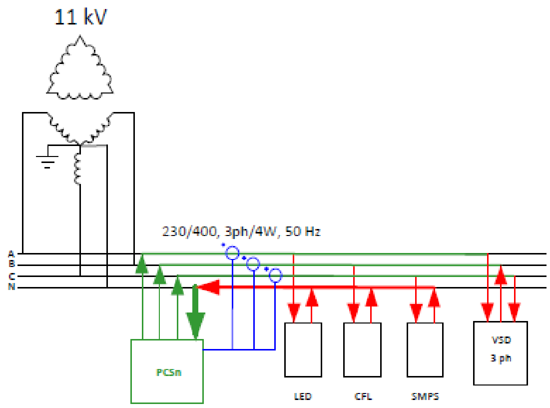


Figure 7
AccuSine PCSn connection in IEC electrical network in an open loop configuration

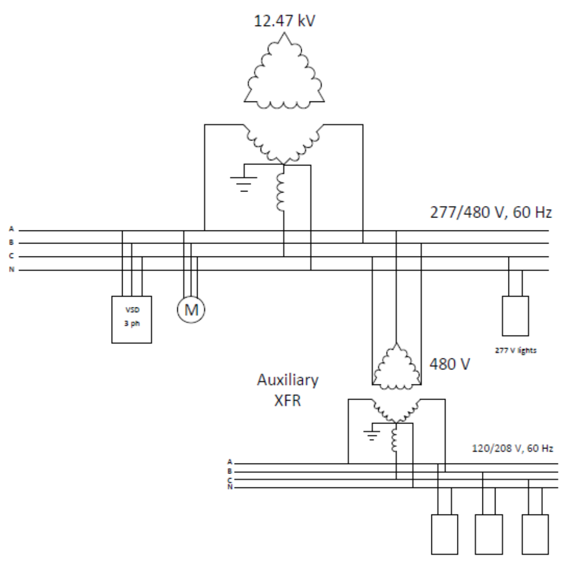


=> Harmonic current drawn by non linear loads

=> Mitigating current injected by the AccuSine PCSn

In the North American LV distribution, the use of 3-phase / 4-wire AHF is slightly different because most single-phase nonlinear loads are fed at 120 V by stepdown auxiliary transformers with 120/208 V output supply (Figure 8). Depending on your location, the primary voltage of the auxiliary transformers can be 480 V or 600 V. Some may argue that we have single-phase loads connected at 277 V or 347 V; however, these loads are a small fraction of the overall LV network demand and usually have negligible impact on the LV distribution power quality.

Figure 8
North American typical low voltage distribution network



Harmonic Mitigation Transformers (HMT)

NOTE: K-factor is a load current waveform rating calculation. It rates the waveform's capability to produce harmonic-related heat loss in transformers and other magnetic components. It is used to select transformer K-ratings that match load current K-factor measurements.

Since the proliferation of nonlinear loads in the North American 120/208 V networks, the industry has been relying mostly on Harmonic Mitigation Transformers (HMT) to stop harmonics from propagating upstream from their point of installation. Normally these auxiliary transformers are either de-rated for installation in harmonic rich networks, or they are specially designed to withstand the additional burden caused by harmonics. For example, they could have K ratings of K-3 or K-13.

HMTs use the concept of sine wave recombination to stop the harmonic from flowing upstream of the auxiliary transformer primary windings. A standard HMT delta-wye transformer can "trap" the zero-sequence harmonics, especially the third harmonic, and the remaining harmonic spectrum find their way on the primary LV supply (Figure 9).

In order to improve the harmonic mitigating performance of HMT, network architects can combine two HMT with different winding configurations. For example, a delta-zigzag transformer with zero-degree phase shift and a delta-wye transformer with a 30-degree phase shift will cancel the 3rd, 5th, 7th, 17^{th} & 19^{th} harmonic orders, while the 11^{th} and 13^{th} harmonic orders remain with other higher frequencies with this combination of transformers. However, this approach doubles the distribution equipment requirement, which drastically increases the equipment and installation cost of an HMT mitigating solution (Figure 10). Another limitation of this "phase-shifting" concept is the loads at both HMTs must be equally loaded with the same amount of current for it to have perfect harmonic current cancellation. If both loads are not balanced, most of the harmonic currents will remain in the network.

Figure 9
HMT Delta-wye transformer "cancelling" zero sequence harmonics

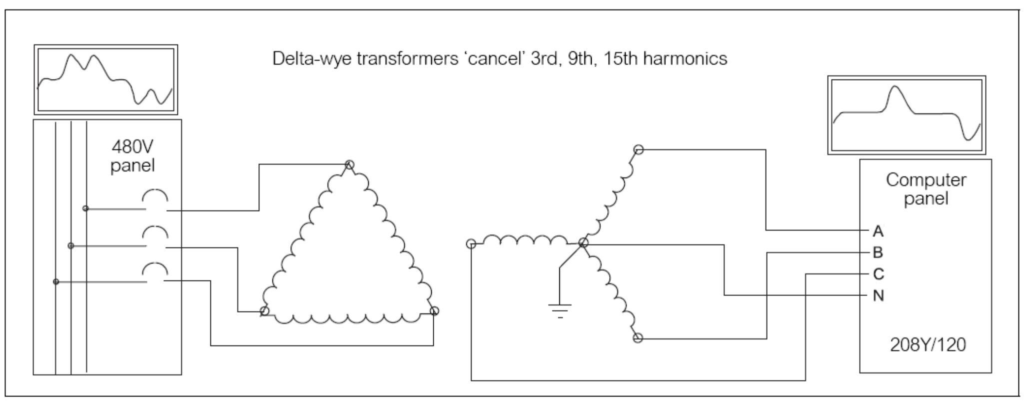
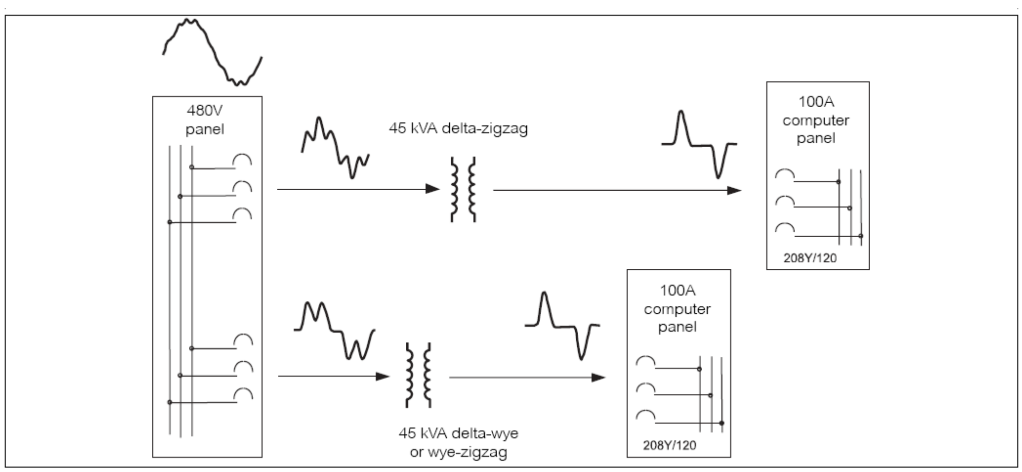


Figure 10
Two HMT "cancelling" the 3rd, 5th 7th, 17th & 19th harmonic current

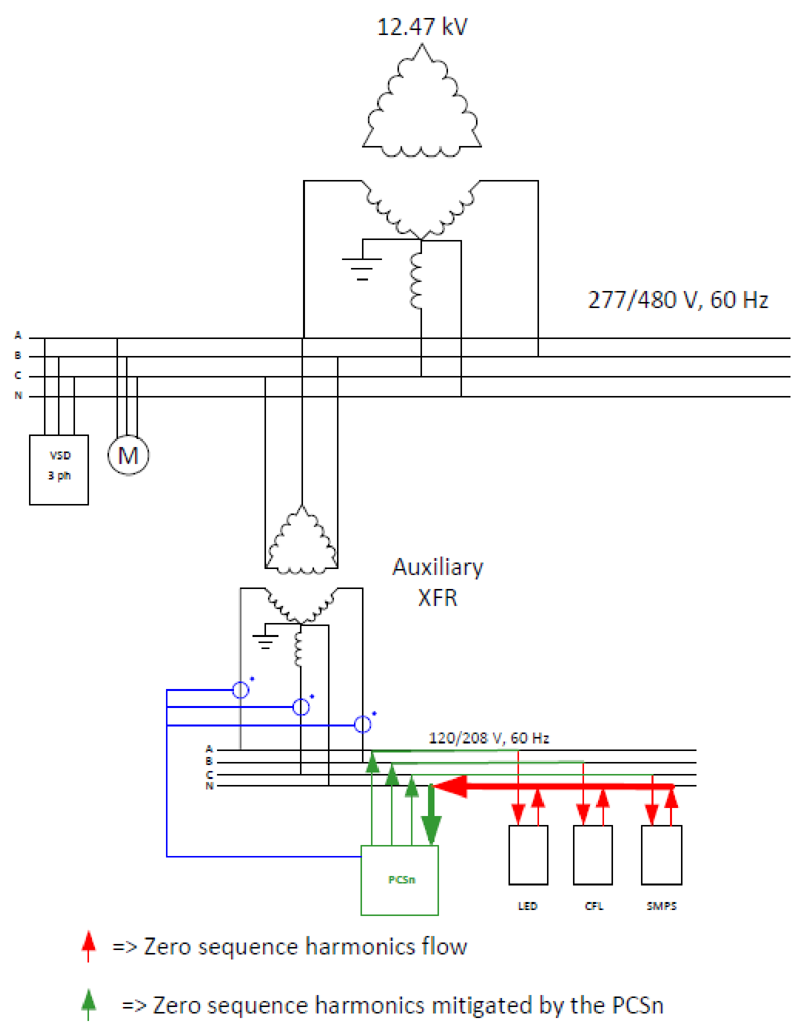
[Extracted from Square D Harmonic Mitigation Transformers, Application Guide, Class 7400]



Many network architects may ask why they should consider alternative harmonic mitigating solutions for 120/208 V network since HMT are typically reliable and seem to provide enough harmonic mitigation. HMT have their limitations because they are passive devices, they only tackle harmonic mitigation where a few harmonic orders are suppressed, and they don't reduce the voltage distortion on the 120/208 V bus. The relatively poor reduction in THDv is because harmonic currents are still flowing through the main network impedance, in this case the HMT itself, which creates voltage drop at the harmonic frequencies and, in turn, increases the THDv locally. Looking into new active technologies that have more to offer makes sense. The added benefits of using an AccuSine PCSn on our 120/208 V distribution networks: It will correct three PQ problems in real time, reduce THDv on the 120/208 V bus, offer advanced monitoring functions, communicate with BMS systems and, last but not least, tackle the entire harmonic spectrum (up to the 51st order) generated by the nonlinear loads.

An AccuSine PCSn connects to a 120/208 V network in similar fashion as an IEC installation, except it connects on the load side of an auxiliary transformer (**Figure 11**).

Figure 11
AccuSine PCSn connection in North American 120/208 V LV distribution network. A closed loop configuration is represented in this example



Real life application

An example of an application in a college science pavilion supports the use of an AccuSine PCSn on a 120/208 V network. In this case, harmonic mitigation had been requested by the insurance company in order to avoid the neutral conductor overload and to keep the stress as low as possible on the standard auxiliary transformer. Further, the school wanted a clean source of power for their laboratories and used the harmonic mitigation device as a teaching tool for their students. The AccuSine PCSn was the perfect solution because of its mitigating capabilities and its HMI that offers a window into the LV network with its touch screen display and communication capabilities. The results are highlighted in Table 2, in the bar graph (Figure 12) and in the HMI screen (Figure 13).

Please note that power quality measurements were done via a third-party analyzer (Hioki PW3198) and that the data was collected in a five-minute window with a relatively stable demand.

Table 2
Power data recorded at the incoming of the 120/208 V distribution panel

Parameters	AccuSine PCSn OFF	AccuSine PCSn ON
Total Real Power (kW)	85.8	85.8
Total Apparent Power (kVA)	87.3	85.8
Total Reactive Power (kVAR)	16.2	1.7
Displacement Power Factor	98.5 lag	99.9 lag
Unbalance current (%)	1.41	1.03
Unbalance voltage (%)	0.38	0.35
THDv (%)	1.95	1.26
THDi (%)	17.14	1.19
Neutral current (A RMS)	137.4	*48

*Note that in Table 2, above, PCSn neutral current injection was limited by the neutral conductor connected to the PCSn. While attenuation level was good, it could have been improved with a larger conductor. The PCSn had the capacity to mitigate almost all the neutral current.

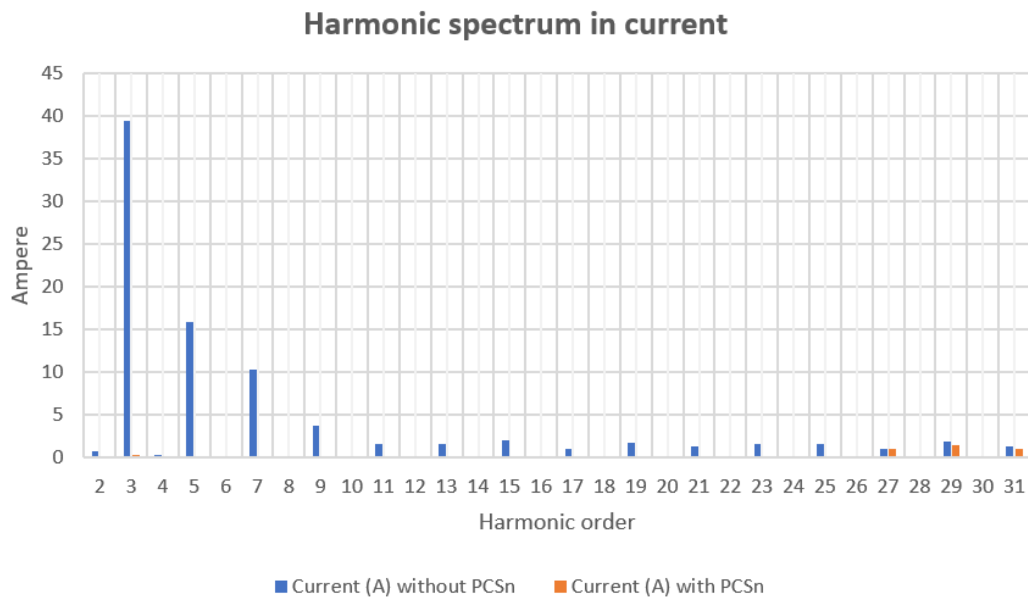


Figure 12
Harmonic in current with PCSn OFF & ON. Note: fundamental current is ~250 Ampere

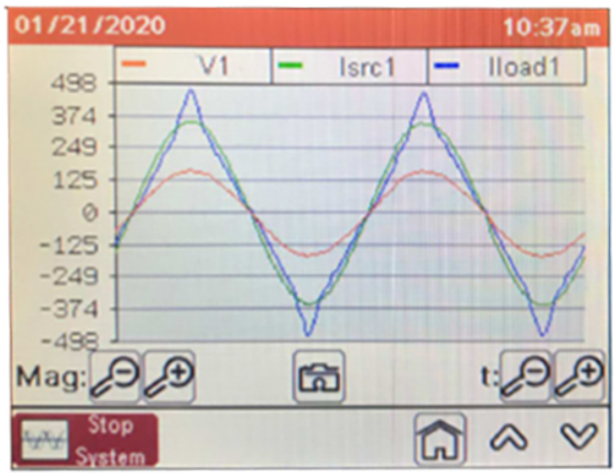


Figure 13
AccuSine PCSn HMI screen

Blue waveform = current without AccuSine

Green waveform = current with AccuSine

Orange waveform = voltage with AccuSine

In some applications the use of 3-phase / 3-wire AHF may be required to tackle the bulk of the harmonics generated by 3-phase nonlinear loads while there is still a need to mitigate zero sequence harmonics generated by single-phase nonlinear loads, which require the use of a 3-phase / 4-wire AHF. That is where the flexibility of the AccuSine Plus range comes into play. One can install a high power AccuSine PCS+ to mitigate the positive and negative sequence harmonics flowing on the phase conductors and use a low rating AccuSine PCSn to mitigate the zero sequence harmonics. There are two possibilities; the PCSn and the PCS+ can be installed on the same bus where they would share the same CT signal and would be programmed with distinct harmonic spectrum to be mitigated (Figure 12. (Note that the CTs are not represented on the three-line diagram.) The other possibility is to have the AccuSine units connected in a cascading fashion on their respective bus (Figure 13). In such a layout, each AccuSine has its own sensing CTs. (Again, CTs are not represented on the drawing.)

Figure 14

AccuSine PCSn and AccuSine PCS+ operating on the same bus

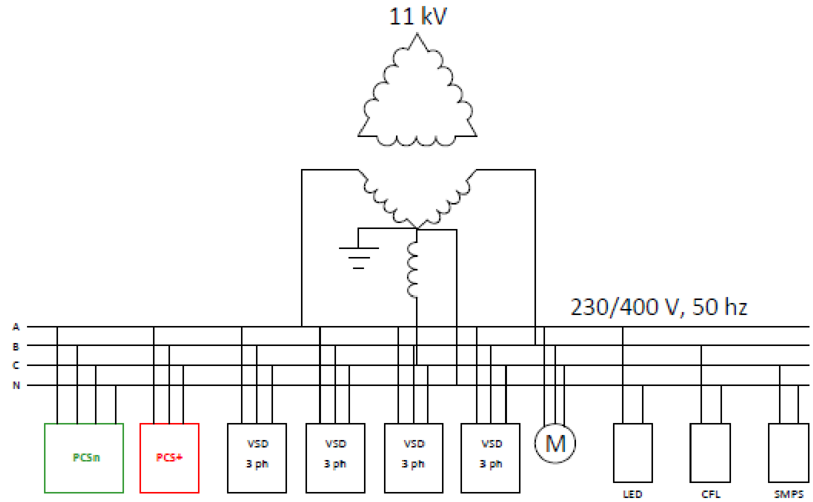
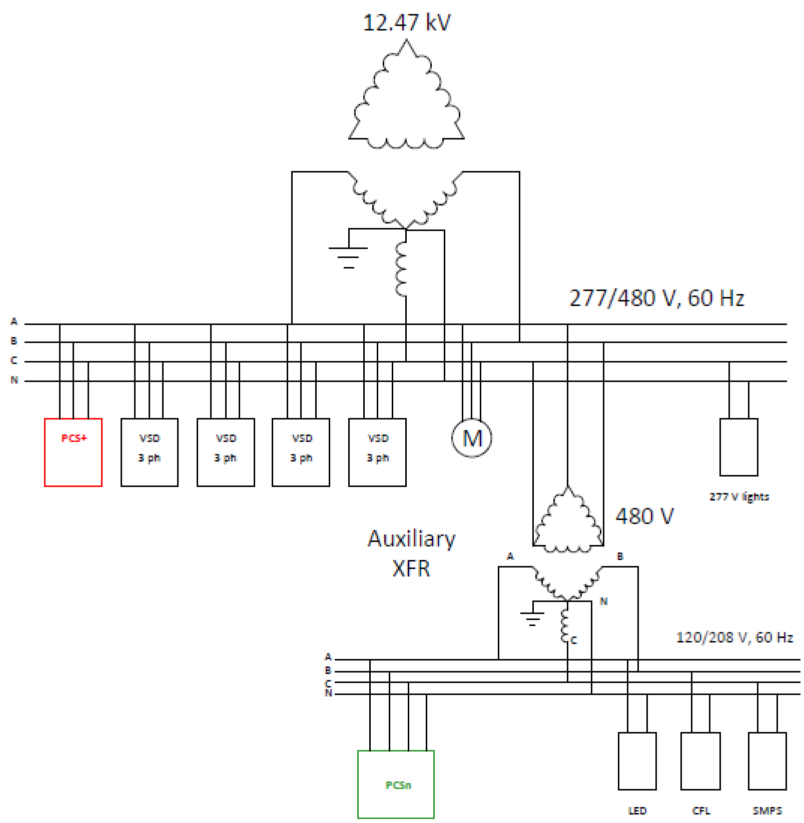


Figure 15

AccuSine PCSn and AccuSine PCS+ operating in cascade on two different bus levels



Conclusion

The amount of semiconductor use will continue to increase in the future and the deployment of active mitigating devices makes it easier to control their effects. Furthermore, the advancement in Human Machine Interface (HMI) simplifies the implementation of Active Harmonic Filters via easy commissioning. They also offer advanced power monitoring to the users allowing them to keep a close eye on their network power quality. It seems logical to fight fire with fire and use these power electronic devices to mitigate the negative effects semiconductors create in our low voltage network.

References

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3. Jacques Schonek, “The singularities of the third harmonic”, Schneider Electric Cahier technique no. 202, February 2001.

4. Jacques Schonek, “The neutral: A live and unique conductor”, Schneider Electric Cahier technique no. 212, June 2004.

5. Data Bulletin 7400DB0301: Harmonic Mitigation Transformers, Square D application guide, July 2003

6. User Manual PHA 596669-01: AccuSine PCSn Active Harmonic Filter, December 2019.

About the author

Remi Bolduc is the Competency Center Manager for Digital Power in Schneider Electric. He started his career with the Hydro-Quebec Utility in service and maintenance of HV Switchgear, followed by six years with S&C Electric in application of MV Switchgear. For the past 20 years, he has held various technical and commercial roles for Schneider Electric where he has specialized in Power Quality Correction. Mr. Bolduc graduated with a degree in Electrodynamics and has lectured in over 200 Power Quality seminars around the world.