ELECTRIC POWER RESEARCH INSTITUTE

Technology Assessment and Application Guide for an Active Harmonic Filter (AccuSine®)

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Technical Update, March 2008

EPRI Project Manager

Bill Howe

ELECTRIC POWER RESEARCH INSTITUTE

3420 Hillview Avenue, Palo Alto, California 94304-1395 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

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Electric Power Research Institute (EPRI)
942 Corridor Park Blvd.
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Principal Investigator
T. Geist

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REPORT SUMMARY

This report describes and documents construction, performance, and application of an active harmonic filter. The system, which is called the AccuSine® Power Correction System (PCS), is manufactured by Schneider Electric, North American Operating Division (Square D), at a facility in Salem, Oregon. The system is designed to inject harmonic and reactive current to limit harmonic distortion and improve the displacement power factor for the electrical distribution system in any facility. The report describes the various subsystems within the AccuSine, the operation, results of characterization tests, and issues related to application and installation.

Background

Mitigation of excessive harmonic currents in building power distribution is often needed. While passive techniques exist, active-mode harmonic filters provide many advantages in addressing harmonic current reduction. Square D offers the AccuSine Power Correction System. The AccuSine PCS is an active harmonic filter system based on an inverter and capacitor storage bank.

Objectives

- To provide an overview of active harmonic filter systems.
- To describe the AccuSine PCS system.
- To describe practical applications.
- To document verification testing.

Approach

An engineer from the Electric Power Research Institute (EPRI) visited the Schneider Electric facility in Salem, Oregon. The engineer served as a witness to a verification test of the AccuSine PCS in reducing harmonic current produced by a real dc drive and motor load. Moreover, the engineer held discussions with production and application personal and reviewed application literature.

Results

Testing verified that the AccuSine PCS can reduce harmonic currents generated by non-linear loads on a power system. Use of the AccuSine PCS can free up system capacity allowing additional loads, increased component lifetime due to reduced heating, reduced line losses from a reduction in harmonic currents, elimination of power factor penalties, and reduction in depth of voltage sag due to current in-rush. An AccuSine PCS can be used in place of passive filters and higher-number rectifiers such as 12 or 18 pulse rectifiers.

EPRI Perspective

By providing utilities with a technical understanding of the performance and application of the AccuSine PCS, EPRI is enabling them to better service numerous key customer segments. With knowledge of this state-of-the-art technology, electric utilities are in a unique position to help their clients value and implement new power quality mitigation solutions. Such solutions may be better and more cost-effective than solutions based on traditional technology.

Keywords
Power quality
Active voltage compensation
Active harmonic filter
Active power filter
Harmonic reduction

CONTENTS

1
INTRODUCTION

EPRI has conducted limited testing of the Schneider Electric/Square D AccuSine Power Correction System (PCS), an Active Harmonic Filter (AHF). Testing was conducted at the Square D facility in Salem, Oregon. This report seeks to give an overview of active harmonic filters and the layout of the AccuSine PCS, provide results of tests conducted by EPRI and summarize application of the AccuSine PCS in real world situations.

Company Overview

Schneider Electric is a global supplier of electrical components and equipment. The company has a presence in 190 countries with products marketed under three global brands: Square D, Telemecanique, and Merlin Gerin. Schneider Electric recognizes four key electric products markets: Energy Infrastructure, Industry, Buildings, and Residential. The AccuSine PCS is manufactured under the Square D brand at a facility in Salem, Oregon. Square D is a well recognized maker of general electrical and wiring products in the U.S. market.

System Description for AccuSine

Power electronic devices that have rapid and frequent load variations have become abundant today due to their many process control related and energy saving benefits. However, they also bring a few major drawbacks to electrical distribution systems; harmonics and rapid change of reactive power. Harmonics may disrupt normal operation of other devices and increase operating costs. Plus, rapid reactive power changes demand timely reactive power (VAR) compensation. Symptoms of problematic harmonic levels include overheating of transformers, motors, drives, and cables, thermal tripping of protective devices and logic faults of digital devices. In addition, the life span of many devices can be reduced by elevated operating temperature. Lack of timely and adequate VAR compensation can lead to voltage fluctuations in the electrical distribution system, impacting equipment operation, as well as product quality.

To combat these problems, Schneider Electric has released the Square D AccuSine Active Harmonic Filter (AHF). The Square D AccuSine AHF injects complementary harmonic current to cancel harmonic current in the electrical distribution system to reduce harmonic level results and/or correct power factor. The AccuSine PCS AHF (seen in Figure 1-1) provides an effective means to mitigate harmonics, reduce process-related voltage fluctuations, and improve equipment operating life and system capacity.

Figure 1-1
The AccuSine Active Harmonic Filter by Schneider Electric/Square D

As diagramed in Figure 1-2, the AccuSine PCS measures the entire load current I_L, removes the fundamental frequency component, and injects the inverse of the remaining waveform I_a for nearly complete cancellation of harmonic current in I_s. AccuSine PCS's full spectrum circuitry is not focused on specific frequencies; rather it creates a waveform "on the fly" based upon the input of its sensing circuitry, regardless of the particular frequencies that the nonlinear load current contains. AccuSine PCS monitors the load through current transformers mounted on the AC line (CT in Figure 1-2 below), feeding the loads of concern. This information is analyzed by the logic to determine the amount of correction to be injected into the AC lines from the parallel installed AccuSine PCS. The control algorithm is analog with no Fast Fourier Transform (FFT) processing used. This allows the system response to be very fast, injecting the correction current within several hundred microseconds. In this manner, all non-fundamental "noise" is removed for the electrical source. This "noise" may contain non-integer frequencies, also known as inter-harmonics.

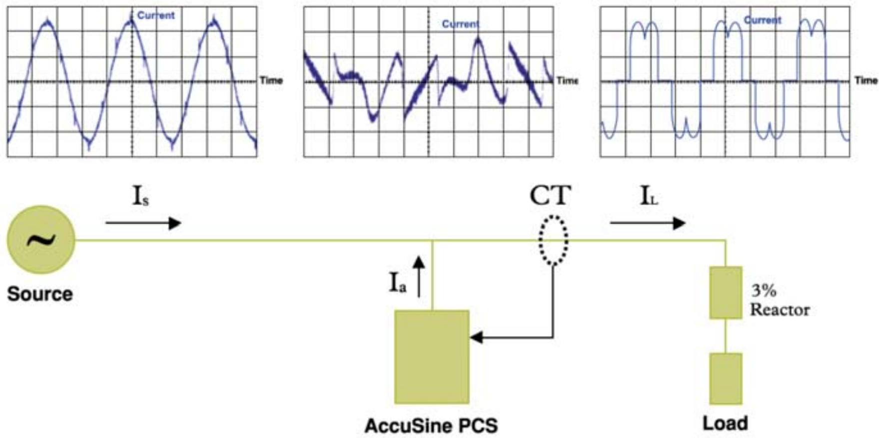

Figure 1-2
Simplified Block Diagram of the AccuSine PCS Active Harmonic Filter[1]

The 3% reactor is required in series with the load to maximize the harmonic cancellation by the AccuSine AHF. The key components of the AccuSine system are shown in Figure 1-3. Wiring connections to the AHF are made at the top of the main cabinet. The DC capacitor bank that feeds the inverter is located just below the input wiring. The inverter and control electronics are located below the capacitor bank. An output filter is located in the base of the system cabinet.

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[1] Figure courtesy of Schneider Electric

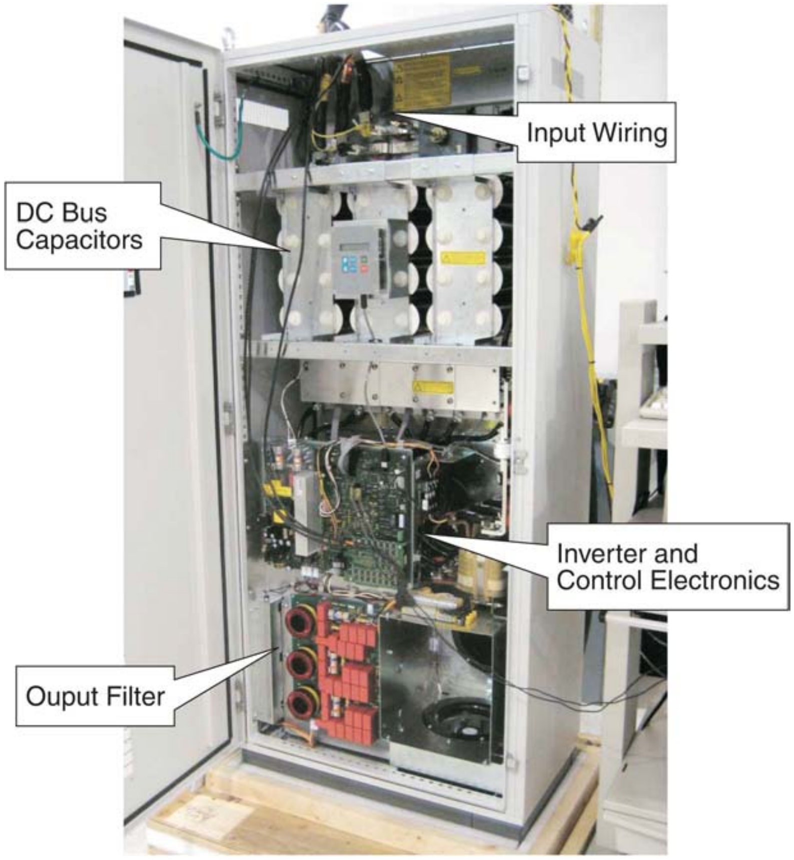

Figure 1-3
The major system components of the AccuSine PCS

The AccuSine PCS can be used to correct high levels of harmonic distortion from non-linear loads in a broad array of applications. These are detailed in Table 1-1. Three main modes of operation are provided:

1. Harmonic Mode – only harmonic currents are cancelled. No correction is made for power factor.
2. Power Factor Mode – the user programs a target power factor. The AccuSine PCS injects reactive current in attempt to achieve the target power factor. Harmonic correction is disabled.
3. Harmonic/PF Mode – the unit cancels harmonic currents and attempts to inject reactive current to achieve the desired power factor.

Table 1-1
Typical Applications[2]

Applications	Requirements	Benefits
Water and wastewater treatment plans, textile mills, paper mills, pharmaceutical facilities, steel mills, package sorting facilities, oil platforms and marine vessels	Total voltage distortion • THD(V) to be <5%, total demand distortion • TDD to meet equipment operating environment to prevent damage to other equipment in the facility	• Reduce harmonics to meet industry standards • Reduce harmonic effects on equipment • Increase system capacity by improving total power factor
Smelters, induction furnaces, DC drives, and cranes	Fast reactive power compensation in rich harmonic operating environment	• Eliminate highly fluctuating harmonic content • Provide real-time supply of reactive power to improve system voltage regulation
Data centers, hospitals, and microelectronic manufacturers	Critical uptime requirement incorporate backup power systems with generators, UPS	• Reduce harmonics • Correct leading power factor when blade servers are used on the output of UPS
Welders, linear induction motors, windmills, X-ray, and MRI machines	Ultra fast VAR compensation	• Provide ultra fast VAR compensation to ensure stable voltage level for the process • Eliminate flicker • Improve diagnostic machine up time

An important prerequisite when applying AccuSine PCS is to install a 3% or higher impedance line reactor or equivalent in front of each non-linear load, such as VFD, UPS or SCR power supply. This impedance reduces the base harmonic current amplitude significantly and permits the AHF's to achieve very high levels of total demand distortion (TDD) reductions.

For a new facility or facility with a known load list, Schneider Electric has provided the AccuSine PCS selection program to calculate the AccuSine system rating required to meet the system objective. An Excel™-based tool, the AccuSine PCS selection program can be downloaded from Square D's website www.reactivar.com.

Advantages of Use

- Free up system capacity, which can be used for additional loads
- Increased component lifetime due to reduced heating
- Reduced line losses
- Elimination of power factor penalties
- Minimize in-rush induced voltage sags

[2] Data courtesy of Schneider Electric

2
CHARACTERIZATION TESTS

Test Description

EPRI conducted a simple application trial at the Square D facility is Salem, Oregon. A typical non-linear load composed of a pair of twin dc motors coupled to generators was used in this testing. The motors, seen in Figure 2-1, were powered by two SCR-based adjustable speed drives (ASD) (not shown). The motors were referred to as bull-1 and bull-2. The drives were operated with 480V-3 phase wye-connected-power with a total load current of up to 900A. A neutral voltage connection, derived on the motor control board, was used for probing single phase voltages with an oscilloscope. An AccuSine AHF capable of providing 300A of correction current was tested.

Current and Voltage waveforms were monitored along with distortion and power factor for two different load conditions and the three different modes of operation of the AccuSine PCS. A Voltech PM3000A was used to monitor the performance of the AHF during the tests.

Figure 2-1
Twin DC Motors Used in Testing the AccuSine PCS Active Harmonic Filter

Objective

Testing was designed to verify the ability of the AccuSine AHF to suppress harmonic currents in a functioning system.

Test Results

The system was operated in several different states. The AccuSine AHF was tested in harmonic correction mode, power factor correction mode, and dual mode. Data taken for various modes of operation is summarized in Table 2-1.

Table 2-1
Experimental Data

Operating Conditions	AHF Status	Voltage (V)	Iload (A)	ITHD (%)	VTHD (%)	TOTAL PF	Notes
Harmonic Only Mode; bull-1 and bull-2 100% load	OFF	478.9	916.2	32.7	2.6	0.796	
Harmonic Only Mode; bull-1 and bull-2 100% load	ON	477.3	883.8	4.7	2.4	0.843	
PF Only Mode; bull-1 and bull-2 100% load	OFF	480.6	970.8	33.1	2.2	0.794	
PF Only Mode; bull-1 and bull-2 100% load	ON	489.1	816.7	40.8	2.9	0.893	**1**
Harmonic and PF Modes; bull-1 and bull-2 100% load	ON	479.9	866.4	4.9	2.3	0.879	
Harmonic and PF Modes; bull-1 off and bull-2 100% load	ON	495.6	358.5	5.1	1.8	0.996	
PF Only Mode; bull-1 off and bull-2 100% load	ON	496.9	402.7	48.9	1.6	0.899	
Harmonic Only Mode; bull-1 off and bull-2 100% load	ON	488.7	433.8	4.9	1.9	0.828	

Note 1 - system reported that 492A was needed for full correction

Note that the AccuSine AHF system was not damaged by the need for excessive correction current shown under Note 1 in Table 2-1. The AccuSine AHF limits its own output current at its rated value. The net result of using an undersized AccuSine AHF is that the load harmonics and power factor are not fully corrected.

In addition to the tabular data, an oscilloscope was used to capture the voltage and current waveforms for the motor drive bus as seen in Figure 2-2. The top trace of Figure 2-2 is the Voltage waveform for a single phase at the at the adjustable speed drive power feed. The lower trace in Figure 2-2 is the current waveform. The I_{THD} was measured at 32%. Figure 2-3 shows the voltage and current waveforms at the input of the overall test system. ITHD was measured at 4.7%, indicating that the AccuSine AHF was providing about 300A of correction current.

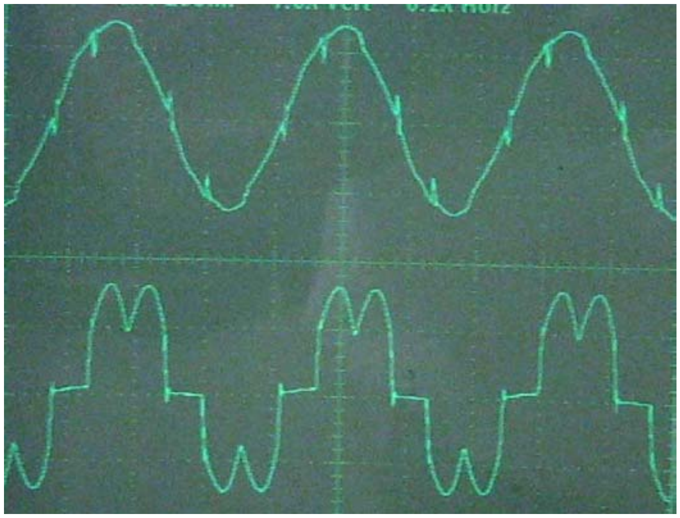

Figure 2-2
Input Voltage (Top Trace) and Current (Bottom Trace) to the SCR-ASD

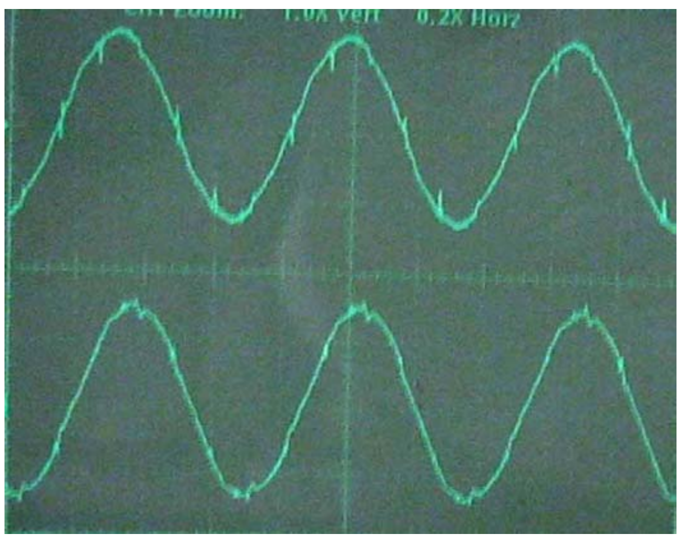

Figure 2-3
Input Voltage (Top Trace) and Current (Bottom Trace) at the input of the AccuSine PCS with the SCR-ASD as a load

3

APPLICATION OF THE ACCUSINE PCS

There are a number of mitigation methods that can be applied to reduce harmonic distortion in a user's facility. A good example is to consider variable frequency motor drives (VFD). In the past suppression of harmonic distortion for a VFD would be handled at the input of each VFD. Thus, for an installation with many VFD loads, each load would be individually addressed with harmonic suppression equipment. Table 3-1 shows several harmonic suppression techniques along with a relative cost factor for implementation.

Table 3-1
Harmonic Mitigation Methods Applied on a Per VFD Basis[3]

Solution	Advantage	Disadvantage	Typical % TDD	Typical Price Multiplier
Increase Short Circuit Capacity	Reduces THD(V)	• Increases TDD • Not Likely to Occur**	Dependent Upon SCR***	Cost of Transformer and Installation Change Out
C-Less Technology	• Lower TDD • Simplified Design • Less Cost	• Compliance is limited • Application limited • Size Limited	40 – 50% TDD	0.90 – 0.95%
Impedance (3% LR or 5% DC Choke	• Low Cost Adder • Simple	• Compliance Difficult	30 – 38% TDD	1.05 – 1.15
5th Harmonic Filter	Reduces 5th & Total TDD	• Does Not Meet Harmonic Levels at Higher Orders^	18 – 22% TDD	1.20 – 1.45
Broadband Filter	Reduces TDD (Thru 13th)	• Large Heat Losses • Application Limited	8 – 15% TDD	1.25 – 1.50
12-Pulse Rectifiers	• Reduces TDD • Reliable	• Large Footprint/Heavy • Good for >100 HP	8 – 15% TDD	1.65 – 1.85
18-Pulse Rectifiers	• Reduces TDD • Reliable	• Large Footprint/Heavy • Good for >100 HP	5 – 8% TDD	1.65 – 1.85
Active Front End Converter	• Very Good TDD • Regeneration Possible	• Large Footprint/Heavy • Very High Cost Per Unit • High Heat Losses	<5% TDD	2.0 – 2.5

* Price compared to a standard 6-pulse VFD.
** Utilities and users are not likely to change their distribution systems.
*** Increasing short circuit capacity (lower impedance sources or larger KVA capacity) raises TDD but lowers THD(V).
^ Can be said for all methods listed.

[3] Data provided by Schneider Electric

While application of impedances or filter at each VFD input is cost effective, a key factor is the limited ability of localized mitigation techniques to reduce the TDD. Only more costly solutions (12 and 18 pulse rectifiers) begin to match the harmonic suppression ability of the AHF. Note that when applied on a per device basis, an AHF system can greatly reduce the TDD, but is quite costly relative to simpler harmonic suppression methods. The cost advantage of AHF systems is realized when applied across a grouping of VFD loads, as shown in Table 3-2.

Table 3-2
Application of AHF for Multiple VFD Loads[4]

Solution	Advantage	Disadvantage	Typical % TDD	Typical Price Multiplier to Std. 6-P VFD Pkg.
AHF Applied to one VFD	• Reduce 2^{nd} – 50^{th} Orders	• Branch Circuit Protection Required • 3% Line Reactor	5% TDD	2.0 – 2.5
AHF Applied to two VFD	• Reduce 2^{nd} – 50^{th} Orders • Less Heat Losses • Less Footprint	• Branch Circuit Protection Required • 3% Line Reactor	5% TDD	1.65 – 1.95
AHF Applied to three VFD	• Reduce 2^{nd} – 50^{th} Orders • Less Heat Losses • Less Footprint	• Branch Circuit Protection Required • 3% Line Reactor	5% TDD	1.5 – 1.75
AHF Applied to four VFD	• Reduce 2^{nd} – 50^{th} Orders • Less Heat Losses • Less Footprint	• Branch Circuit Protection Required • 3% Line Reactor	5% TDD	1.35 – 1.6

As more VFDs are added to a single AHF system the price multiplier drops for a given level of targeted TDD. While IEEE-519 requires a TDD of between 5% and 20%, depending on the short circuit to maximum load current at the point of common coupling (PCC), the impact of harmonics on the user's facility may require more or less aggressive mitigations efforts.

In addition to correction of harmonic currents, the AccuSine AHF has the ability to inject reactive currents to adjust the displacement power factor (DPF). The user can set a target value of DPF which the AccuSine PCS will attempt to maintain through dynamic changes in system conditions. Table 3-3 shows a comparison of Passive L-C Filter DPF correction with the use of the AccuSine PCS.

[4] Data provided by Schneider Electric

Table 3-3
A Comparison of L-C Filter and AHF DPF Correction[5]

	Passive L-C Filters	**Active Harmonic Filters**
Increases Displacement Power Factor	Yes	Optional
Computer Simulations Required for Sizing	Yes	No
Target Harmonics	1 Order Only (Typically 5th)	2nd thru 50th or Discrete Orders Via FFT
Meet IEEE 519 or Equivalent Limits	Sometimes	Yes
Removal of Triplen Harmonics	No	Only 4-Wire AHF's
Performance Dependent on Network Impedance	Yes	No. However, 3% Line Reactors Required on all Nonlinear Loads
Danger of Overload	Yes, Due to Speed of Response and/or Changing Harmonic Loads	No. Current Limited to Maximum RMS Rating
Field Expandable	Usually	Yes. Addition of Parallel Unites Possible
Suitable for DC Drives	Yes	Yes
Suitable for AC Drives	Sometimes. Increasing Power Factor can be an Issue	Yes
Suitable for UPS Filtering	Sometimes. Capacitors on UPS Input can Cause Operational Problems	Yes
Suitable for Mixed Loads (Linear and Nonlinear	Yes	Yes
Response to Load Changes	Dependent on Controls. Typically 30 Seconds with Electromechanical Contactor Based Systems	Less than 1 Cycle Full Response or <3 cycles for FFT Logic
Installation Options	Indoor or Outdoor	Indoor or Outdoor
Available Voltages	<380V not Economical. 380-600V Most Common. MV also Common	208-480V 50/60 Hz. Higher with Step-Up Transformers

The AccuSine PCS comes in a number of footprints for both the US and world markets as shown in Table 3-4. These weights and dimensions are for systems configured for the US market and packaged in NEMA 1 enclosures. AccuSine PCS can also be configured in chassis, wall mount and free standing forms.

[5] Data provided by Schneider Electric

Table 3-4
AccuSine System Sizes[6]

Current Rating (A)	Height (m/in)	Depth (m/in)	Width (m/in)	Weight (kg/lbs)
50	1.321 / 52”	0.533 / 21”	0.483 / 19”	114 / 250
100	1.727 / 68”	0.533 / 21”	0.483 / 19”	159 / 350
300	1.905 / 75”	0.813 / 32”	0.508 / 20”	352 / 775

Production Schedule and Cost

AccuSine AHF systems can be ordered factory direct. They are in full production and have an order lead time of 6-8 weeks after receiving order. AccuSine Systems range in price from $14,500 (USD) for a 50A basic system to $45,500 (USD) for a fully configured 300A system.

Case Study 1: Flicker Control in a Quarry Application

A rock quarry was forced to remove a newly installed 315kW constant speed crusher from the power grid when operation of the device caused numerous consumer complaints regarding flickering lights. The quarry operator was forced to operate the crusher from a temporary 1000kVA diesel generator while the power quality issue was being resolved. A number of options were considered for correction of the problem including flywheels, hydraulic couplings and AC variable frequency drives. The final solution was to install a 600A active harmonic filter at the input of the crusher. Initial testing was conducted while the crusher was operated from the generator system to verify operation. The crusher was reconnected to the grid with the AHF in place and was able to operate with the flicker issues completely resolved. This particular application required the fast response of an analog AHF system, since the crusher load and harmonics varied quickly in time. Testing using the diesel generator indicted that the AHF was able to bring the power factor up from 0.55 to 0.95 (see Figure 3-1) and reduced the load kVAR demand from 80kVAR to 15kVAR (see Figure 3-2).

[6] Data provided by Schneider Electric

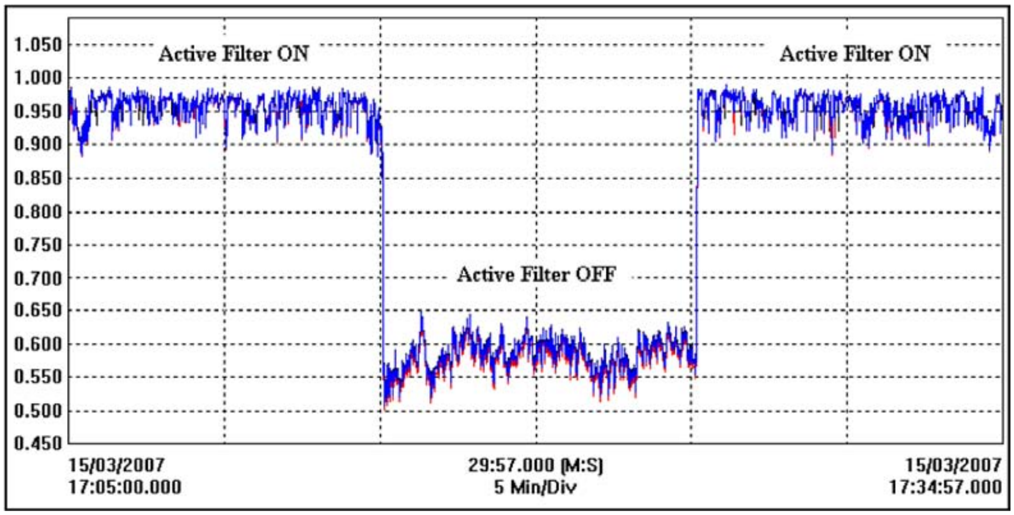

Figure 3-1
Power Factor with and without the AHF in a Quarry Application

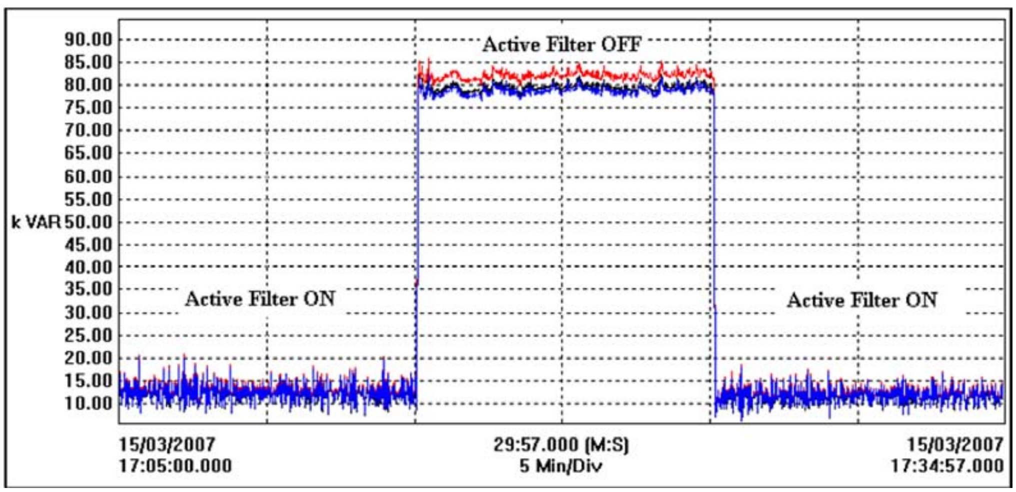

Figure 3-2
kVAR Consumption with and without the AHF in a Quarry Application

Case Study 2: Shipping Port Crane Power Quality Issues

Due to the short duty cycles and high power demands of cranes used to unload and load ships in port, a port operator's local utility required that harmonic limitations and PF correction be applied. The port operator was required to maintain a PF of 0.9 lagging with less than 5% total harmonic distortion. Passive 5^{th} order harmonic filtering initially installed with the port's crane systems maintained a leading power factor under most conditions and caused line over voltages of 2% to 8%. The port operator was forced to conduct a power quality survey of the ports power feed. Figure 3-3 shows a one-line drawing of the power distribution for one crane. A number of power quality issues were identified with the existing filter system including an excess of capacitance for most load conditions, indications of some resonance effects and excessive voltage swings as load varied. Review of the data indicated the need to have about 700kVAR of total correction to meet the utilities power quality specifications. The quick load variations (2-6 cycles response as various crane motors energize and de-energize) proved to be too fast for a typical FFT based AHF. Three 300A AccuSine systems were employed to meet the required correction current demands. After installation of the AHF system a power factor of 0.88 lagging was maintained while the THD(v) was reduced from over 4% to under 3% and THD(I) was reduced from 23% to less than 5%. The feed line voltage dropped from an initial value of 22,350V to 21,650V when the PF capacitors were removed from the system and the AHF was activated. This represents a desired 9.7% drop in line voltage.

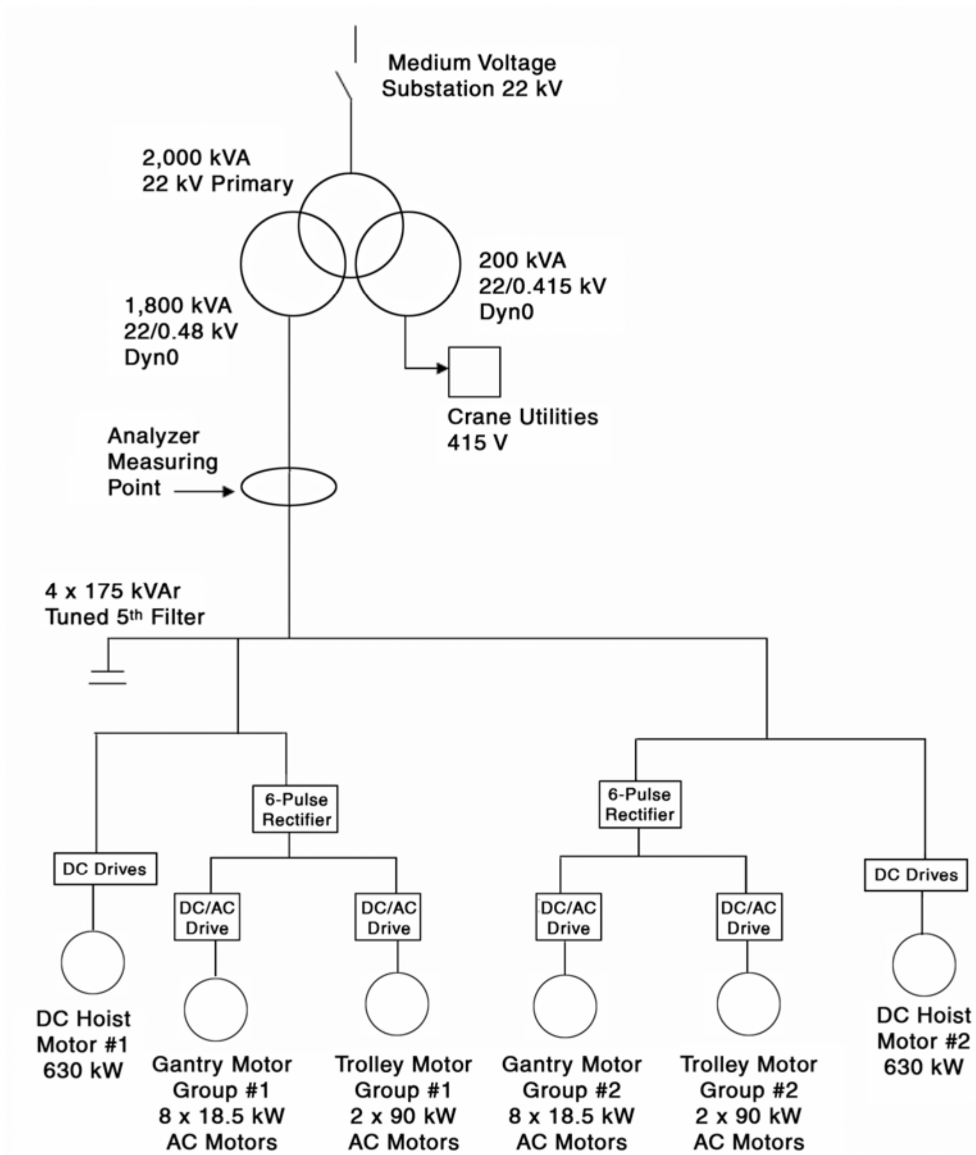

Figure 3-3
One Line Drawing of Shipyard Crane Wiring

4
SUMMARY

This report gives an overview of Active Harmonic Filters and describes the AccuSine PCS AHF with results of a simple verification test conducted by EPRI. The AccuSine is manufactured by Square D in Salem, Oregon. Square D is a part of the Schneider family of brands with a presence in 190 countries worldwide.

The AccuSine provides a means of addressing harmonic current distortion at the feed point of a non-linear load. This allows the end user to "contain" the harmonic currents at the problem load or loads. The AccuSine uses an analog processing algorithm to provide a fast time response (~ 100us) to unwanted harmonic currents. The device can suppress harmonic currents up to order 50. Current distortion from non-linear loads such as motor drives, power supplies, MRI machines, and welders can be suppressed by the AccuSine.

The AccuSine uses a capacitor bank to establish a DC bus used in driving an inverter. The inverter is controlled to produce currents that act to cancel out the harmonic currents found at a non-linear load's input. This allows the facility power to "see" a well behaved load with excellent power factor and low distortion. The system can be operated to correct for harmonic currents only, for power factor only or for harmonic currents and power factor.

A comparison of cost multipliers for various harmonic suppression options with the AccuSine AHF indicate that suppressing harmonic currents from a grouping of loads, as opposed to a single load provides for the most cost effective operation of the AccuSine system.

The operation of the AccuSine PCS was witnessed at the Square D facility using a test setup comprised of twin DC motors driven by an SCR based ASD. The AccuSine reduced current distortion from 32% (at the input to the motor drive) to 4.7% at the input of the AccuSine. Testing also verified the intrinsic current limiting capability of an AHF system.

The AccuSine operates from 208V to 480Vac in 3 phase, 3 or 4 wire systems. AccuSine systems rated for 50, 100, and 300A of correction current are available in a number of different package options. The AccuSine meets UL standards and can be purchased with an optional CE EMC certification for IEC/EN60439-1, EN61000-6-4 Class A, and EN61000-6-2.

5
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Weblinks

AccuSine website:

http://www.squared.com/us/products/power_management.nsf/unid/4CF540FFB16F65D385256C7D006D6717/$file/activepfcpage.htm

AccuSine Sizing Tool website:

http://www.reactivar.com

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SPECIFICATIONS[7]

AccuSine PCS	
Standard RMS Output Current Ratings	50A, 100A, 300A
Nominal Voltage	208-480V +/- 10% auto sensing
Other Voltages	With transformer
Nominal Frequency	50/60 Hz +/- 3 Hz auto sensing
Number of Phases	3P/3W, 3P/4W
Power Electronics	IGBT
Topology	Analog/digital interface
Operation with Single Phase Loads	Yes
Current Transformers	500/5, 1000/5, 3000/5, 5000/5 (400Hz)
Number of CTs Required	2 or 3
Normal Spectrum of Compensation	2nd to 50th harmonic global
Attenuation Ratio	>10:1
Parallel Multiple Units	Yes, up to 10 per set of CTs (any rating combinations)
CT Location	Either source or load sensing
Power Factor Correction	Yes, leading or lagging injection to target power factor
Response Time	100 microseconds for step load changes, 1 cycle full response
Overload	Limited to nominal output, continuous operation
Dynamic Current Injection	Up to 2.25 times rated current
Display	High quality 3.8" QVGA screen
Languages	English, with other language capability
Operators	Magelis XBT graphic touch screen terminal
Display Parameters	■ AC line voltage, DC bus voltage, load power factor unit output power factor ■ Load harmonic current, load reactive current, output harmonic current, corrected load current ■ Various fault codes, set up parameter points start, stop control screen
Communication Capability	Modbus, Modbus TCP/IP
Heat Losses	N1 unit: 1800W for 50A, 3000W for 100A, 9000W for 300A N12, IP units: 2150W for 50A, 3700W for 100A, 10,000W for 300A
Noise Level (ISO 3746)	<80 db at one meter from unit surface
Color	NEMA 1 Quartz Gray, all others RAL7032
Operating Temperature	0° to 40°C continuous
Relative Humidity	0-95% non condensing
Seismic Qualification	IBC and ASCE7
Operating Altitude	<1000m, (derating factors apply for higher altitudes @10% per 1000m)
Protection (enclosure)	NEMA 1, NEMA 12, IP30, IP54
Optional: CE EMC Certification	IEC/EN60439-1, EN61000-6-4 Class A, EN61000-6-2

[7] Courtesy of Schneider Electric

B

TUTORIAL ON ACTIVE HARMONIC FILTRATION

Active Harmonic Filters (AHF) (sometimes called Active Power Filters) are used to suppress unwanted line distortion at the power feed point of a system. An AHF can be applied at a plant power entrance or at the input of a specific non-linear single load or a grouping of loads to ensure compliance with ANSI/IEEE 519 THD specifications. Figure B-1 shows a simplified block diagram of an AHF. Note that this topology is referred to as a shunt AHF and can only correct for current distortion.

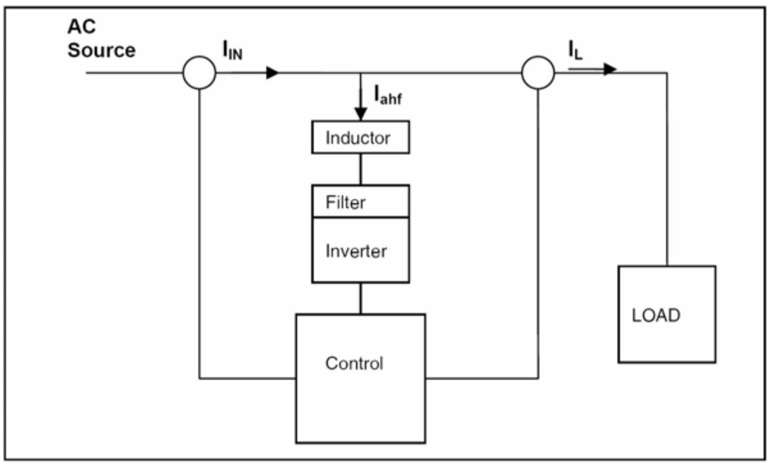

Figure B-1
Simplified Block Diagram of an Active Harmonic Filter (AHF)

The AHF system uses an inverter module to generate currents that are in opposition to the unwanted currents (harmonics) found in IL at the load. As stated, the load can be a single device or an array of devices that produce unwanted line current harmonics. Here,

$$I_{IN} = I_L - I_{ahf} \quad \textbf{Equation B-1}$$

If I_{ahf} contains only the harmonics found in I_L and they are exactly out of phase with the I_L harmonics, then I_{IN} will contain only the fundamental current portion of I_L.

AHF systems can be used to eliminate harmonic current for single and 3-phase systems. For 3 phase systems there are 3 wire and 4 wire AHF implementations. The 3 wire systems are used to suppress harmonic currents only on the 3 phase feeds and do not attempt to correct for currents appearing in the system neutral. 4 wire systems remove harmonics not only from the phase currents but also from the neutral. Multiphase AHF units can also address multiphase load imbalance if so designed. The AccuSine AHF described in this report is a 3 phase, 3 or 4 wire system.

The inverter is operated at a frequency well above the line frequency, in the range of 10 to 20 kHz. This operation frequency is a key limiting factor in the response of an AHF. Since the inverter acts as a sampling device, it can only correct for harmonic content at the AHF output at frequencies below ½ the PWM drive frequency (the so-called Nyquist limit). For example, an inverter that is clocked at 10 kHz can only be used to suppress harmonic current content this is at less than 5 kHz. In practical systems some margin is used so that unwanted aliasing does not occur in the current cancelation. Thus, a 10 kHz inverter might only be used to correct for harmonic current content under 3 or 4 kHz. Proper filtering must be applied at the inverter output to ensure that switching transients from the inverter do not corrupt the line power. The AccuSine AHF can suppress harmonics up to order 50 (approximately a 3 kHz response).

Control of the AHF

The inverter module shown in Figure B1 must be controlled to produce currents that act to cancel the harmonic currents seen at the load (I_L). The inverter is operated using pulse width modulation (PWM). The PWM signals are derived from currents and voltages (depending on the control scheme) measured within the system. An AHF can be operated in open or closed loop fashion. An open loop system simply subtracts some fraction of the load harmonics from the AC power source. In Figure B1, only I_L would be monitored and a constant fraction of the harmonic content of I_L would be subtracted from I_{IN}. While this will reduce harmonic current levels, it cannot ensure complete elimination of the harmonic currents under all conditions. Closed loop systems constantly monitor the source and load currents to continually optimize the harmonic subtraction. Controls can be implemented in analog circuit form (using phase-locked-loops (PLL) and filters) or with digital signal processors (DSP). Analog controls can provide a very fast time response, but are less flexible in adjustment and set up. DSP solutions provide a broad array of control technique options and can offer detailed operational data. DSP solutions tend to have slower time response characteristics due to latency in the DSP itself and due to the need for a sufficient number of data samples to be accumulated. The AccuSine AHF uses an analog control scheme to provide a fast time response.

Analog Based Control

For analog control of an AHF system, such as the AccuSine, a key requirement is to detect and removed the fundamental component of the load current, I_L. This can be done using a PLL to detect the fundamental frequency and an adaptive notch filter to remove the fundamental frequency component. This produces an error voltage that represents only the harmonic content of the load current which is then fed to the inverter PWM control. This scheme can be very fast, with only the PLL lock time and the filter and inverter control response times limiting current corrections at the AHF output. The AccuSine provides a response time of 100 microseconds. An analog control, as described, provides no information to the end user about the nature of the harmonic content of the load. The analog system represents a “fixed” solution to harmonic suppression, as the control algorithm is “hard wired” at the device level.

DSP Based Control

DSP control of AHF systems has become much more common in recent years due to the proliferation of high speed, high quality DSP processors. These are commercially available integrated circuit based processors that can implement software digital signal processing routines. The key advantage of the use of a DSP processor is the flexibility and precision with which filters and computation algorithms can be implemented. Unlike an analog filter that might require changes in resistance or capacitance values at the circuit level to be updated, a DSP processor allows the same convenience as found in programming a computer. Users can develop libraries of routines, just as in computer programming, allowing large blocks of complex coding to be used as building blocks for control designs. In addition, a broad array of data can be display to the end user about the harmonic content of the load in near real time fashion.

One drawback of a DSP based AHF system is response time. DSP AFH systems will in general, have a slower response than can be achieved with an analog design due to the latency of the DSP process. Some vendors report harmonic suppression within ½ cycle of the AC line (around 8 ms) for what appear to be DSP based designs. It is not unusual for the response time to be 10's or 100's of milliseconds for DSP systems. Clearly, some DSP based designs are not configured to suppress or correct fast transients that persist for only a fraction of a full cycle of the AC line.

Figure B-2 shows a simplified block diagram of a DSP based AHF. In addition to the current measurements shown, the DSP may also acquire data from any number of other voltage and current sensors.

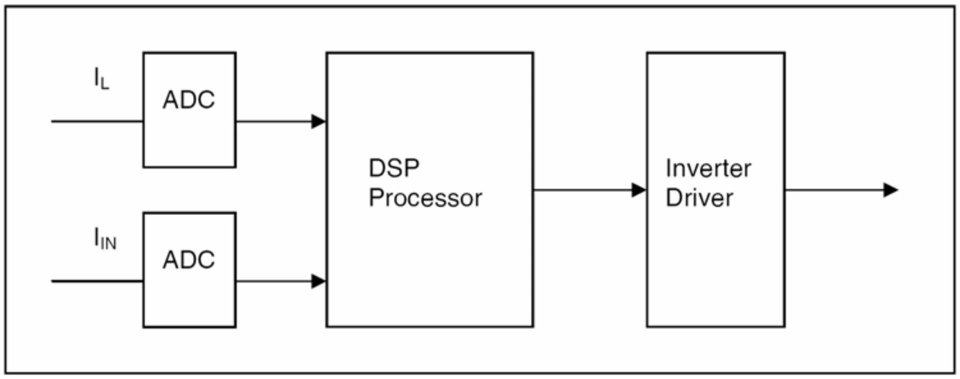

Figure B-2
Simplified Block Diagram of a DSP Based AHF

All of the various DSP techniques require that the analog current signals used in control be converted into digital signals using an analog to digital converter (ADC). ADCs come is a wide variety of speeds and precision levels. The ADC represents time latency in the control loop that must be kept small or be accounted for to provide for proper cancellation of harmonic currents. A single ADC converter can be used to digitize all of the analog signals if it is sufficiently fast using a front end multiplexer. The multiplexer is a switching mechanism that briefly selects each of the analog inputs in sequence. The ADC is connected to each channel only long enough to convert the voltage/current signal into a digital value. In order to ensure that samples from various elements are taken simultaneously, multiple ADCs may be employed one for each analog input. The ADC sampling frequency must allow for proper digitization of signals at up to the harmonic frequency of interest without producing unwanted aliasing terms. In general, the ADC will be preceded by an analog anti-alias-filter, which limits the bandwidth of the analog signal to less than ½ the ADC sample rate. This is to prevent unwanted aliasing of the frequency content of the ADC data. ADCs that employ over sampling techniques allow for much less stringent analog filter designs and are readily available.

Data from the ADC converters is transferred to the DSP IC as binary number values. Each number represents the analog value found at a specific point in time. Depending on the DSP implementation, these values may be directly processed or moved to a memory for future processing.

The error signal produced by the DSP is digital in form and must be converted to an appropriate pulse stream or analog output signal for controlling the inverter PWM. There are a number of modulation techniques that can be used to control the inverter. Pulse width modulation (PWM) is one of several possibilities.

The system transient response will be dominated by the time required for the DSP processor to convert the stream of ADC values into PWM control signals. The time delay will in turn be heavily dependent on the processing algorithm used within the DSP.

There are a number of possible DSP control algorithms that can be used in processing the system voltage and/or current signals to realize control of the AHF inverter. Vendors do not generally disclose the algorithms they are using in a particular AHF. Algorithms will also vary based on their ability to suppress imbalance currents in a multiphase system and to deal with neutral current distortion correction. Many different schemes have been described in open literature and some are listed here under two key categories: Time Domain and Frequency Domain.

Time Domain:

- Instantaneous control or Instantaneous p-q Control – Load voltage and current are converted to a rotating coordinate system (using the Park transform). The transformed voltages and currents are used to compute the instantaneous load power (p=real; q=imaginary). The dc components of the instantaneous power values are removed with the remaining ac components used to compute the compensation current (harmonic current). The inverse Park transform is then used to convert the needed harmonic current back to time domain values. Note that the term instantaneous does not infer a fast system time response, having only to do with the calculation or use of instantaneous current, voltage, and power values.

- Synchronous d-q Control – Load currents are converted to a rotating coordinate system (d=direct axis; q=quadratic axis; using the Park transform). Harmonic currents appear as time varying values with the fundamental currents appearing as dc values. The result is then high pass filtered to extract only the harmonic currents. An inverse Park transform is applied to produce the time domain compensation current value. Note that this technique does not require voltage information.

- Synchronous Harmonic d-q Control – nearly identical to the Synchronous d-q control, but the computation is done synchronously for each harmonic frequency of interest. Separate calculations are made at each harmonic frequency and then combined to produce the compensation currents.

Frequency Domain:

- Fourier based techniques - The time domain ADC samples (discrete numeric values corresponding to specific time values) are transformed into digital frequency domain signals (discrete values representing the frequency domain power spectral density of the ADC data) using Fourier analysis. This process takes a block (or set) of discrete ADC time samples and uses them to build a single frequency spectrum. There are a variety of Fourier algorithms and techniques which may be seen described in AHF literature such as Discrete Fourier Transform (DFT), Fast Fourier Transform (FFT) and Recursive Discrete Fourier Transform (RDFT). The number of ADC samples required to produce a frequency domain data set directly influences the latency of the DSP in processing signals. How the frequency data is used can vary greatly, with a number of processing techniques in use. Windowing, a shaping function applied across time samples, is sometimes used to control frequency domain distortion due to the use of a limited set of time data points.

- Wavelet transforms – (it is not known if these are being used in any commercial AHF systems) One inherent limitation of DSP applications that rely on the use of the FFT is processing of non-periodic signals. The FFT is defined for continuous, repetitive signals. Impulse and non-periodic currents at the load may not be dealt with correctly in an FFT based algorithm. The Wavelet transform may be a more effective approach to dealing with such waveforms.

Real Time Response

The term "real time" is often seen in the literature describing AHF units. The term is at best vague, and gives little indication of the true speed (in time) of a process. The term "instantaneous" should not be confused with the time domain system response, as it refers to the use of instantaneous power values to produce compensating currents. The actual transient behavior of a particular AHF will depend heavily on the form of analog or DSP control being implemented. Product literature indicates response times varying from 100us (for the AccuSine described here) to several seconds (Shallbetter RTX-FR) for AHF units. In general, techniques that seek to suppress specific harmonics or those that allow the end user to choose the harmonics to be suppressed rely on FFT techniques. The FFT must have a sufficiently long data set in time so that frequencies of interest can be resolved. This will generally require a half or full cycle of the AC line to build up the spectrum. These devices, in a sense, suppress the harmonics of a future AC line cycle with data from a previous cycle. As such, this technique can not suppress fast transients unique to one cycle of the AC line. Some AHF units, such as the AccuSine offer "fast" or "real time" modes of operation that focus on dealing with transient conditions during a single cycle. Whether this "fast" mode is analog or DSP based is not generally disclosed. The AccuSine uses an analog algorithm and provides a 100us response time to a step change with a 1 cycle full response.

Pertinent Standards

In the US there are a number of standards applicable to AHF systems. These include ANSI IEEE 519 (harmonic limits for power systems), FCC CFR 49 Part 15 (EMI/RFI considerations), UL 508C (UL safety requirements for power conversion equipment), and ANSI/IEEE 587, ANSI/IEEE C62.41 (Surge Immunity). International standards include EN61000-3-2 (Harmonics, devices under 16A), EN61000-3-3 (Voltage sag), EN61000-3-4 (Harmonics, devices over 16A), EN61000-4-5 (Surge Immunity), EN61000-4-2 (Electromagnetic compatibility), EN55011 – radio disturbance characteristics), EN60146 (Safety/Design), EN50178 (Vibration Testing, Safety/Design), CSA 22.2, No. 14 & 66 (Canadian CSA requirements for power electronics).

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Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com