



# METHODS GUIDE

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# Introduction

## Legal Notice

The intent of this guide is to assist *bona fide* customers and agents of Vitrek, in interpreting the various measurement results provided by Xitron's products. No rights are granted for use of any patented, copyright, confidential, or proprietary information contained in this guide for any other purposes.

## Scope

This guide contains details regarding the techniques used in all Vitrek Power Analyzers to produce the measurement results. The actual method used may vary from that described. In certain cases, a technique may be considered proprietary by Vitrek. In those cases of proprietary considerations, a given description may be incomplete. Vitrek reserves the right to change the method of implementation at any time, without notice.

This guide is not intended as a complete description of general Digital Signal Processing (DSP) techniques; refer additionally to the many excellent publications available regarding general DSP.

It is assumed that you, as a user, are aware of a mathematical technique called a "Fourier Transform". This guide does not contain any mathematical information regarding this, nor does it contain a description of the actual method used to implement this. We recommend that you consult the many publications regarding the mathematical derivation of the Discrete Fourier Transform (DFT) and the Fast Fourier Transform (FFT).

Certain Vitrek Power Analyzers produce additional measurement results data to those normally provided by Power Analysis equipment, examples of these

are IEC1000-3-2 and IEC1000-3-3 compliance test results. This guide does not include any description of these measurement results.

Upon publication of revision B of this Methods User Guide, the 256x and 257x families of products were not released for sale. Although some details regarding these products are contained in this document, more details will be available after the release of these products.

## Symbols & Terms Used in this Guide

This section contains definitions for the symbols and terms commonly used in this guide.

V Voltage input signal

A Current input signal

H Harmonic number, 1 is the fundamental, 2 is the 2<sup>nd</sup> harmonic, etc.

$X_N$  N<sup>th</sup> sample of input signal X

$|X|$  Modulus of X, or the value of X ignoring it's polarity.

max(X) Maximum value of X

min(X) Minimum value of X

$\sum_M X_N$  Sum of samples  $X_N$  over M samples

re( $X_H$ ) Real amplitude of harmonic H of input signal X

im( $X_H$ ) Imaginary amplitude of harmonic H of input signal X

ph( $X_H$ ) Phase of harmonic H of input signal X





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# Sampling Systems & Measurement Periods

This section describes the sampling system generally used in Vitrek products and the different measurement periods encountered in DSP based signal analysis products.

## Digitally Sampled Systems

In digitally sampled systems the input signals are scaled, converted into voltages if needed, and then sampled at known increments of time to produce a “stream” of digital representations of the instantaneous amplitude of each signal.

### General Methods

In systems that require many different measurements of the input signals, such as power analyzers, each is performed by separate mathematical operations.

### Non-Linear Measurements

Most of the signal analysis operations required to produce the desired measurements are non-linear. In digital systems the primary accuracy determining circuitry is purely linear, and the high-speed sampling techniques available today provide excellent linearity and DC performance. Each measurement result is limited by the resolution of Analog to Digital converters, processor, and software being used, and their ability to perform those operations within the time allowed.

### Frequency Aliasing

In digitally sampled systems, your final results data depend on whether any input signal anomaly was captured by the samples taken of the input signals. Thus, the results obtained have a “probability” of capturing non-repetitive signal content having a period less than the sample period. This non-deter-

ministic nature can be overcome by limiting the bandwidth of the signals to less than the sampling frequency. Note that this filtering adjustment, called “anti-alias” filtering, may unnecessarily limit the bandwidth of all measurement results.

When performing harmonic or spectral analysis, it is imperative that the signals are limited in bandwidth. If this is not done, then signal content may “appear” to have a different frequency than it actually has. This is caused by the frequency of a sampled signal being maintained at less than one half of the sampling frequency. Frequencies above this limit appear to be equal to the sampling frequency minus the input frequency for frequencies between one half and one ( $\frac{1}{2}$  and 1) times the sampling frequency. This affect<sup>+</sup> is often called “frequency folding.”

Thus, when using digitally sampled techniques, measurements that rely on knowledge of the signal frequency must be bandwidth limited to (at most) one half of the sampling frequency. It should be noted that most of the basic measurements made by power analyzers do not rely on knowledge of frequency, thus do not require anti-alias filtering. In practice only measurements of harmonic content and frequency require this, as does any filtering performed on the samples.

## Settling Time

Most of the measurement results used in power analysis require some form of filtering or “mean” operation. Examples of this include RMS (Root Mean Square), Average Rectified, and Watts (mean voltage signal multiplied by the current signal). When using analog techniques, this filter is some form of analog filter, typically a multi-pole RC filter of some type. When using digitally sampled techniques the actual frequency content of the input signals can be derived. Taking the mean over an exact multiple of cycles of the input frequency yields “perfect” filtering while incurring no settling time to a change in signal amplitude, at the expense of some settling time to a change in input frequency. In most power applications, the signal frequency is relatively stable, whereas the signal amplitude is not only unstable but also unknown. Thus, there can be a significant improvement in overall measurement speed if the measurements can be synchronized to the input signal frequency.

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<sup>+</sup> Named the Nyquist frequency after the mathematician who first noted the affect.

## Harmonic or Spectral Analysis

The samples obtained from an input signal can be mathematically operated on using a “Discrete Fourier Transform”, often called a DFT. The input signal (as represented by a stream of amplitudes) is multiplied by sine wave signals at each frequency of interest. When the mathematical operations involved are analyzed, it can be shown that the number of multiplications needed to perform this can be significantly reduced if the number of samples in an exact, pure, binary number. A modified form of the DFT is then used, called a “Fast Fourier Transform” or FFT.

## Measurement Periods

As described in the preceding paragraphs, there are advantages to certain of the mathematical operations being performed synchronously to the input signal. This can simply be achieved by performing the operations on a number of samples that correspond to an exact integer number of cycles of the input signal. In the case of a harmonic analysis, it is advantageous to perform the operation in this same manner, but using an exact binary number of samples as well.

Typically, the period of time between measurements is not significantly longer than that of a cycle of the input signal. Thus, to obtain the required degree of accuracy in synchronizing the measurements to the input signal, an extraordinarily high frequency of sampling is required. This is often not readily achievable.

If the sampling frequency were 100 times the input signal frequency, then the measurement can only be synchronized to within 0.5%. This would yield an inconsistency in the measurement results of about 1%, which is not usually accurate enough. To obtain accurate synchronization in this manner, 0.01% as an example, then the sampling frequency would have to be 10000 times higher than the input signal frequency. Even when measuring 50Hz power frequency, this requires a 500kHz sampling frequency. For a product to be accurate when used at all power frequencies, this simple technique cannot be applied.

To overcome this requirement for an extremely high sampling frequency, the sampling frequency itself is adjusted to ensure that the total period of a number of samples is exactly an integer number of cycles of the input signal. In this manner measurements can be performed synchronously to the input without needing the high sampling frequency.

In this manner, all digital sampling measurement techniques have a “measurement period” which is determined by the input signal fundamental frequency. Typically, this period would not always be equal to the same number of input cycles, but would be the closest number of cycles to some predetermined “nominal measurement period”. In this manner the sampling frequency does not have to vary by a wide degree, and the number of samples comprising a measurement does not greatly vary. This measurement period is always made up of an integer number of “sample periods” (the period between each sample).

Typically, a measurement period is made up of tens of thousands of sample periods. In this manner any random, high frequency, anomalies in the input signal can still be accurately measured. This is usually too high a number of samples to perform DFT (or FFT) analysis in a timely manner, as the number of multiplications required becomes extremely large. Harmonic analysis is typically performed on a sub-set of these samples, usually with additional bandwidth limiting to overcome any alias frequencies associated with this lower sampling frequency.

The DFT (or FFT) is then performed on this, additional, set of samples. The technique of making this sub-set of samples is often called “sub-sampling”. The total period of time to which this set of samples correspond need not be the same as that used for the measurement period, thus a “harmonic measurement period” is also encountered. The number of cycles of the input signal that are in each Harmonic Measurement Period sets the bandwidth of the measurement of each harmonic.

To recap the discussion of the various periods –

**Sample Period**—Sample Period is defined as the time period between each digital sample of the input signal.

**Measurement Period**—An exact integer number of Sample Periods. The Sample Period and number of samples being chosen such that the Measurement Period is equal to an integer number of cycles of the input signal.

**Harmonic Measurement Period**—Similar to the Measurement Period, but chosen to produce the desired bandwidth of harmonics measurements.

### **Examples–**

1) If the input signal frequency is 50Hz, the nominal sampling frequency is 200kHz, the nominal measurement period is desired to be 100ms, and harmonic analysis is to be performed every 16 cycles of input signal (yielding a  $1/16^{\text{th}}$  cycle bandwidth):

- Measurement Period = 20,000 times the Sample Period
- Harmonic Measurement Period = 64,000 times the Sample Period

Typically only a few thousand samples would be used for harmonic analysis, thus we choose to use every  $16^{\text{th}}$  sample for harmonic analysis, after limiting the bandwidth to less than  $1/32^{\text{nd}}$  the sampling frequency.

2) If a FFT were being used, then these numbers would be slightly adjusted such that the number of samples used for harmonic analysis is an exact pure binary number:

- Harmonic Measurement Period = 4096 times 16 times the Sample Period (for a 4096 sample FFT)
- (Thus) Sample Period =  $4.8828125\mu\text{s}$  (frequency = 204.8kHz)
- Measurement Period = 20480 times the Sample Period (i.e. 100mS)

## **Gaps Between Measurement Periods**

Depending on the techniques used, there may be gaps between the measurement periods and/or harmonics measurement periods when the processor is unable to start a measurement because computations are still in progress from the last period. In Vitrek Power Analyzers this is maintained at the minimum possible using high-speed DSP integrated circuits and real time computational techniques. In Vitrek power Analyzers of the 2503AH, 255x, 256x and 257x families, computation of measurement results is performed while capturing the samples for the next measurements. Thus, if the computations can be achieved in less time than a single measurement period, then there are no gaps (i.e. no “missing” portions of the input signal).

## **Sample Synchronization**

As can be seen from the preceding discussions, there are advantages to synchronizing the sample period such that an integer number of samples correspond to an integer number of cycles of the input signal. In Vitrek

Power Analyzers, starting with the 2503AH family, this is achieved by digitally synthesizing the sampling frequency.

This can, however, lead to a problem when measuring severely distorted waveforms. Since the sampling frequency and the input frequency are accurately locked, each sample will be essentially at the same phase delay within each cycle of the input signal. Thus any changes in the input signal, which happen between these sampling points will not be measured. This affect is actually another side affect of frequency folding or aliasing. If the bandwidth of the input signal is reduced to having no content above one half of the sampling frequency then this cannot be significant. In practice this cannot be achieved without significantly reducing the bandwidth of the product thus an alternative method must be used.

If exact synchronization is performed then this can be seen by applying a square wave input signal at high frequency and slightly changing the duty cycle of the waveform. It will be found that there are only certain measurement results which can be achieved, at very high frequencies this can lead to errors in measurements of tens of percent. In all Vitrek Power Analyzers the actual sample period is slightly “dithered” in a quasi-random manner to substantially reduce this affect. This is similar to the method used in digital oscilloscopes to display a signal having wider bandwidth than the sample rate (often called undersampling), where the input signal is sampled over many cycles, the trigger delay for each cycle being different than the others.

## Vitrek Power Analyzer Information

The figures given below are nominal only and are subject to change without notice.

### 2500 Family

ADC : single 12-bit resolution per input signal

DSP : 20MHz Motorola DSP56001 (DSP56001A in later units)

Sample Period = 5 $\mu$ s or 10 $\mu$ s

Measurement Period = 100ms to 5s (user definable)

Gap between Measurement Periods = 10ms to 20ms

Harmonics are not available.

## 2503 & 2503H Families

ADC : single 12-bit resolution per input signal

DSP : 28mHz Motorola DSP56001 (DSP56001A in later units), one per channel

Sample Period = 3.5 $\mu$ s or 7 $\mu$ s

Measurement Period = 10ms to 10s (user definable)

Gap between Measurement Periods = >5ms (extended to allow for a harmonic measurement period if needed)

Harmonic Measurement Period = 4 cycles of input signal or 10ms (fixed, whichever is longer)

Gap between Harmonic Measurement Periods = 50ms

Number of Samples used for Harmonic Analysis = 2048 (FFT)

## 2503AH Family

ADC : dual, interleaved, 18-bit resolution per input signal

DSP : 32mHz Motorola DSP56001 (DSP56001A in later units), two per channel

Sample Period = 2 $\mu$ s to 10 $\mu$ s (non-cumulative 30ns period resolution)

Measurement Period = 1ms to 20hour (user definable)

Gap between Measurement Periods = >2ms (extended to allow for a harmonic measurement period if needed, 0ms when using IEC1000-3-2 or IEC1000-3-3 modes)

Harmonic Measurement Period = 1 to 99 cycles of input signal or 1ms (user definable, whichever longer)

Gap between Harmonic Measurement Periods = (30ms-Harmonic Measurement Period) or 2ms (whichever longer, 0ms when using IEC1000-3-2 mode)

Number of Samples used for Harmonic Analysis = 512, 1024, 2048, or 4096 (FFT)

## **255x & 256x Families**

ADC : single 16-bit resolution per input signal

DSP : 80mHz Motorola DSP56303

Sample Period = 4.5 $\mu$ s to 10 $\mu$ s (non-cumulative 25ns period resolution)

Measurement Period = Harmonic Measurement Period

Gap between Measurement Periods = 0

Harmonic Measurement Period = 4 cycles of input signal or 1ms (fixed, whichever is longer, reduced to 2 or 1 cycle at very low frequencies).

Gap between Harmonic Measurement Periods = (12ms-Harmonic Measurement Period) or 0 (whichever is longer) times number of phases configured

Number of Samples used for Harmonic Analysis = 200 to 800 (DFT)

## **257x Family**

### **High Frequency Ballast Outputs**

ADC : single 12-bit resolution per input signal

DSP : 80mHz Motorola DSP56303 (100mHz in later units), two per ballast

Sample Period = 600ns to 2 $\mu$ s (non-cumulative 20ns period resolution)

Measurement Period = 1ms or 4 cycles (whichever is longer)

Gap between Measurement Periods = 0

Harmonic Measurement Period = 1ms or 4 cycles (whichever is longer)

Gap between Harmonic Measurement Periods = 5ms

Number of Samples used for Harmonic Analysis = 50 to 200 (DFT)

### **Ballast Line Inputs and Line Frequency Ballast Outputs**

Similar to the 255x family.



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# Computation of Measurement Results

This section describes the equations used by Vitrek Power Analyzers to mathematically produce each measurement result.

All Vitrek Power Analyzers perform all measurement result calculations that the analyzers are capable of calculating, at all times while measuring. The extent of the calculations that are performed is not dependent on the displayed results, or those requested via the IEEE488 interface.

Not all measurement results are available from all Vitrek Power Analyzers, consult the particular product's user guide for details regarding availability of results.

## Power Definitions

Most of the measurement results used in the power industry are physical quantities, and are therefore well defined in physical terms. However, some results are not physical quantities, but are mathematically derived quantities with no physical relationship. Unfortunately, not all of these are well defined, thus there exists some differences between manufacturer's products and customer usage in these results.

Of particular importance in this regard are the results for VAR, VA and Power Factor in certain circumstances. In the original definitions (derived late in the 19<sup>th</sup> and early in the 20<sup>th</sup> centuries) the definitions were clear, but were based on purely sinusoidal waveforms. These initial definitions were based on the concept of power being a vector, with Watts (the only physical power result) being the real part, VAR being the imaginary part, and VA being the length. Power Factor was defined as the cosine of the angle of the vector. This original concept was then used to derive equations for multi-phase results for 120° phasing of purely sinusoidal waveforms.

All Vitrek Power Analyzers use this vector concept of Watts, VAR, VA and Power Factor. The analyzers always compute multi-phase totals from "first

principals” using vector addition of the actual phases measured. This may not be the same as other manufacturer's power Analyzers.

By using the original vector definitions, all forms of multi-phase power are consistent with each other. Thus a 3-phase “wye” source with a “delta” load connected to two phases and neutral only, will measure the same total power whether the Analyzer is configured and wired for 3-phase 4-wire or 3-phase 3-wire.

The original vector concept yields a definition that  $VA^2 = W^2 + VAR^2$ . This definition is strictly adhered to in all Vitrek Power Analyzers.

A further area for definition is the polarity of VAR. Certain industries use a definition that inductive loads yield positive VAR, others that capacitive loads yield positive VAR. All Vitrek Power Analyzers yield positive VAR for capacitive loads (i.e., leading power factor), this may not be the same as other manufacturer's power analyzers.

The original Power Factor definition leads to the modern definition, that  $PF = W/VA$ . This is the definition used by all Vitrek Power Analyzers. From this, it follows that Power Factor takes the polarity of Watts, since VA is a pure scalar (thus has no polarity). In some cases the polarity of Power Factor has been used to signify a lead/lag indication rather than the polarity of Watts, in Vitrek Power Analyzers the polarity of Power Factor is always the same as the polarity of Watts (the polarity of VAR indicates lead/lag).

Note that power may occur in all four quadrants, that is Watts and VAR may take either polarity, independently. All Vitrek Power Analyzers fully implement this.

These differences in definitions between portions of the industry are minimally important, except when the signals have significant amounts of harmonic or non-harmonic content. Then large differences in results can occur. All Vitrek Power Analyzers are consistent in the definitions used, and all produce sufficient results to allow users to compute results using any of the definitions.

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## General Methods

### Low-Pass and High-Pass Filters

Throughout each product there are several instances where either low-pass or high-pass filters are used. In all cases discussed in this guide, these filters are of the Infinite Impulse Response (IIR) type. Both Elliptic and Butterworth response type filters are used. (Elliptic being generally used for sample bandwidth reduction purposes. Butterworth being generally used for result filtering purposes.)

### Intermediate Results

To avoid the possibility of the user viewing a measurement result before it has been completely calculated, most results are calculated as an intermediate result. After all computations have been completed, then the respective final result is updated.

In the 2503AH family these “final” results are again buffered by separate storage for each usage; i.e., each display line, printout result or IEEE488 interface result.

### Measurement Results Data Averaging

In the 2503AH family (called a “display line filter”), and the 255x, 256x and 257x families (called “measurement average”) all results data may be filtered over a definable “period”. Filtering is achieved when each actual result is updated from the respective intermediate result using a single-pole (2503AH family) or two-pole (other products) low-pass filter. These filters are automatically bypassed when a large change in the results data is encountered, or after any implemented reconfigurations of the measurements.

## Sample Preparation

The computational operations described in this paragraph are performed “in place” on all sample streams.

In all Vitrek Power Analyzers the input signal samples are passed through a multi-pole low pass filter. In most products, you can be set the corner frequency of this filter or it can be bypassed.

In the 2500 family, the samples provided by this filter may be sub-sampled to produce a lower sample frequency.

In the 255x, 256x and 257x families of products, you have the option to remove the samples of the DC content. You can achieve this by maintaining a “long-term” mean value of the samples using a very low frequency multi-pole low-pass filter, and subtracting the output of this filter from each sample. In this manner, none of the measurement results data will include any DC content when this option is used. These products have no “AC only” measurement results; this is achieved using this filtering method, which you, as the user, control.

## Results Computed Each Measurement Period

### Basic Non-Harmonic Measurements

Most measurement results are computed from the set of “basic” measurement results shown in this section. These results are computed using every available sample, the number of samples used can exceed 10,000,000,000 in some circumstances.

### Frequency Measurements (2500 and 2503/2503H Families)

The selected synchronization input signal is 3-pole band-pass filtered and zero crossing detected (with hysteresis) using analog circuitry. The processor counts the number of pulses of a clock signal between the first and last edges encountered during a measurement period, and also counts how many such edges were encountered.

If

$N_{EDGES}$  = the total number of same direction edges (including the first and last) in the measurement period

$N_{CLOCKS}$  = the number of clock pulses counted between the first and last edge

$F_{CLOCK}$  = the frequency of the counter clock

Then

$$Frequency = \frac{F_{CLOCK} (N_{EDGES} - 1)}{N_{CLOCKS}}$$

**Note:** In the 2503 and 2503H families the outputs of each channel's analog circuitry is also used for inter-phase phase shift purposes by counting clock pulses between each channel's output and computing the time delay. These are the only Vitrek Power Analyzers, which measure phase in this manner.

## Frequency Measurements (255x, 256x, 257x Families)

The configured synchronization input signal samples are 8-pole band-pass filtered and zero crossing detected (with hysteresis). The upper frequency of the band-pass filter is automatically altered to track the measured frequency result last established. If no frequency result has been established, or the filtered signal is “lost” then the filter is automatically expanded to include the entire configured range for synchronization frequencies. The hysteresis is automatically adjusted to follow changes in input signal level. The processor counts the number of samples between the first and last edges encountered during a period set by the lowest frequency which is to be measured, and also counts how many such edges were encountered. The last edge is used as the first edge of the next period.

If

$N_{EDGES}$  = the total number of same direction edges (including the first and last) in the measurement period

$N_{SAMPLES}$  = the number of samples counted between the first and last edge

$F_{SAMPLE}$  = the sampling frequency

Then

$$Frequency = \frac{F_{SAMPLE} (N_{EDGES} - 1)}{N_{SAMPLES}}$$

*Notes:*

1) The measurement period used for frequency is not the same as that used for all other results.

2) Since  $F_{SAMPLE}$  is adjusted to be an integer derivation of the *Frequency* result, this technique offers virtually perfect synchronization capabilities.

3) The *Frequency* result is non-linearly filtered to prevent positive feedback between the *Frequency* result and  $F_{SAMPLE}$ .

## Frequency Measurements (2503AH Family)

All input signals are separately sampled using 8-bit ADCs sampling at 2mHz. These samples are 12-pole band-pass filtered and zero crossing detected (with hysteresis). The frequencies for the band-pass filter are automatically altered to track the measured frequency result last established. If no frequency result

has been established, or the filtered signal is “lost” then the filter is automatically expanded to include the entire configured range for synchronization frequencies. The hysteresis is automatically adjusted to follow changes in input signal level. The processor counts the number of samples between each pair of edges encountered and saves each result, each edge being the last edge of the previous pair and the first edge of the next pair. Statistically based analysis of the set of counts between each edge pair is performed to produce “total” numbers of samples and edges, which are then mathematically processed similarly to the equation used in the 255x, 256x, 257x Families (above). This process is repeated a maximum of three times for each set of samples, the band-pass filter being adjusted each pass to reflect each frequency calculation result with the following conditions:

- The measurement period used for frequency is not the same as that used for all other results.
- $F_{SAMPLE}$  is the (fixed) sampling frequency for this purpose only, a separate sampling system is used for all other measurements.
- The clock used to generate this  $F_{SAMPLE}$  is the same clock used to generate the main  $F_{SAMPLE}$ , thus there is virtually perfect synchronization.
- A separate DSP is used (for each channel), dedicated to performing these tasks and to using these samples for range selection purposes.

Because the “lock” of the bandpass filter is achieved on the same set of samples as that from which the frequency was derived, this technique achieves full frequency measurement accuracy in a single frequency measurement period.

Due to the statistical analysis performed, this technique can still accurately measure frequency when up to 10% of the cycles are severely distorted or missing.

Results from the statistical analysis are used to limit the resolution of results relying on accurate synchronization, and in the selection of the “best” source of synchronization.

## **Peak Measurements**

Input signal peak measurements are simply the maintenance of the largest sample made of each input signal. The intermediate result is initialized each measurement period, so that the final result is the largest peak for each, separate, measurement period.

All Vitrek Power Analyzers maintain the largest peak for both voltage and current signals, irrespective of polarity.

$$V_{peak} = \max(|V_N|) \qquad A_{peak} = \max(|A_N|)$$

Some Vitrek Power Analyzers maintain separate highest and lowest peak values, i.e., the “top” and “bottom” of the waveform envelope.

$$V_{highest} = \max(V_N) \qquad A_{highest} = \max(A_N)$$

$$V_{lowest} = \min(V_N) \qquad A_{lowest} = \min(A_N)$$

Other than in the 2503AH family, these results are used for range selection purposes in all products that have autorange capabilities.

This does not necessarily yield the “single cycle” peak of the input waveform. If the waveform contains any amplitude modulation, then the peak indicates the overall envelope of the entire waveform, inclusive of the modulation signal, as measured over the defined measurement period.

## DC Measurements

$$V_{DC} = \frac{\sum V_N}{M} \qquad A_{DC} = \frac{\sum A_N}{M}$$

## Average Rectified Measurements

These results are also referred to as “Mean Modulus”, “Rectified”, or “Average”.

$$V_{RECT} = \frac{\sum |V_N|}{M} \qquad A_{RECT} = \frac{\sum |A_N|}{M}$$

## AC+DC RMS Measurements

$$V_{RMS} = \frac{\sqrt{\sum (V_N)^2}}{\sqrt{M}} \qquad A_{RMS} = \frac{\sqrt{\sum (A_N)^2}}{\sqrt{M}}$$

## Single Phase AC+DC Watts Measurements

$$Watts = \frac{\sum_M (V_N A_N)}{M}$$

## Single Phase Non-harmonic Lead/Lag Indications

Non-harmonic current is “Leading” if –

$$\sum_M (V_N A_{N+1}) < \sum_M (V_N A_{N-1})$$

## Basic Harmonics Measurements

The 2503H, 2503AH, 255x, 256x and 257x Families can be configured to perform harmonic analysis. The basis of harmonics results is the results of either a FFT or a DFT performed on a set of voltage and current samples. The 2503AH Family allows the use of a “Window Function” in the computation of the FFT, all other products (and optionally the 2503AH Family) use a “Rectangular Window” (i.e. no window function). The resultant output of this Fourier Transform is an array of real and imaginary amplitudes for each harmonic. This is transformed into arrays of RMS amplitudes and phases for each harmonic, for voltage and current, by the following mathematics –

$$V_H = \sqrt{(re(V_H))^2 + (im(V_H))^2} \quad A_H = \sqrt{(re(A_H))^2 + (im(A_H))^2}$$

$$ph(V_H) = \tan^{-1}\left(\frac{im(V_H)}{re(V_H)}\right) \quad ph(A_H) = \tan^{-1}\left(\frac{im(A_H)}{re(A_H)}\right)$$

## Derived Voltage & Current Measurements

All other measurement results are derived from the “basic” results shown above in the manner described below.

### AC RMS Measurements

$$V_{AC} = \sqrt{(V_{RMS})^2 - (V_{DC})^2} \quad A_{AC} = \sqrt{(A_{RMS})^2 - (A_{DC})^2}$$



## Harmonic Range RMS and Triplens Measurements

$$V_{HMIN-HMAX} = \sqrt{\sum_{HMIN}^{HMAX} (V_H)^2} \quad A_{HMIN-HMAX} = \sqrt{\sum_{HMIN}^{HMAX} (A_H)^2}$$

Triplens, Even Triplens and Odd Triplens measurements are obtained as a special case of the more general harmonic range measurements (shown above). In these cases only the following harmonics are candidates for inclusion in the summation –

Triplens – 3, 6, 9, 12, 15, 18, 21, 24,...

Even Triplens – 6, 12, 18, 24,...

Odd Triplens – 3, 9, 15, 21, ...

## K-Factor Measurements

K-factor measurement results, measured from harmonic  $H_{MIN}$  to  $H_{MAX}$  (inclusive) are computed as follows –

$$K = \frac{\sum_{HMIN}^{HMAX} (H(A_H)^2)}{\sum_{HMIN}^{HMAX} (A_H)^2}$$

*Note:* For this equation to yield the standard result,  $H_{MIN}$  should be 1.

## Relative Single Harmonic Measurements

$$V_{relative_H} = \frac{V_H}{V_1} \quad A_{relative_H} = \frac{A_H}{A_1}$$

## Relative Harmonic Range Measurements

$$V_{relative_{HMIN-HMAX}} = \frac{\sqrt{\sum_{HMIN}^{HMAX} (V_H)^2}}{V_1} \quad A_{relative_{HMIN-HMAX}} = \frac{\sqrt{\sum_{HMIN}^{HMAX} (A_H)^2}}{A_1}$$

### Peak-Peak Measurements

$$V_{PKPK} = V_{HIGHEST} - V_{LOWEST}$$

$$A_{PKPK} = A_{HIGHEST} - A_{LOWEST}$$

### Crest Factor Measurements

$$V_{CF} = \frac{V_{PEAK}}{V_{RMS}}$$

$$A_{CF} = \frac{A_{PEAK}}{A_{RMS}}$$

### Form Factor Measurements

$$V_{FF} = \frac{V_{RMS}}{V_{RECT}}$$

$$A_{FF} = \frac{A_{RMS}}{A_{RECT}}$$

### Delta to Wye Voltage Conversion

If

$V_A$  = RMS voltage of phase A (measured from phase C)

$V_B$  = RMS voltage of phase B (measured from phase C)

$\phi_{BA}$  = phase between phases B and A

Then

$$V_{wye} = \sqrt{\frac{V_A^2 + V_B^2 + 2V_A V_B \cos(\mathbf{q}_{BA})}{2(1 - \cos(2\mathbf{q}_{BA}))}}$$

### Wye to Delta Voltage Conversion

If

$V_A$  = RMS voltage of phase A (measured from neutral)

$V_B$  = RMS voltage of phase B (measured from neutral)

$\phi_{BA}$  = phase between phases B and A

Then

$$V_{delta} = \sqrt{V_A^2 + V_B^2 - 2V_A V_B \cos(\mathbf{q}_{BA})}$$

## Derived Power Measurements

### Single Phase AC Watts Measurements

$$Watts_{AC} = \sqrt{Watts^2 - (V_{DC}A_{DC})^2}$$

### Single Phase DC Watts Measurements

Note that this is the same as  $VA_{DC}$  by definition.

$$Watts_{DC} = V_{DC}A_{DC}$$

### Single Phase Single Harmonic Watts Measurements

$$Watts_H = (re(V_H) \times re(A_H)) + (im(V_H) \times im(A_H))$$

### Single Phase Harmonic Range Watts Measurements

$$Watts_{HMIN-HMAX} = \sum_{HMIN}^{HMAX} Watts_H$$

### Multi-Phase Watts Measurements

All forms, AC+DC, AC only, DC only, single harmonic, or harmonic range, of multi-phase Watts are obtained using the same equation. In each case, the individual phase Watts results used are those obtained with the bandwidth and phase selection specified for the multi-phase Watts result. Note that  $Watts_{DC}$  is the same as  $VA_{DC}$  by definition.

$$Watts_{TOTAL} = \sum Watts_{PHASE}$$

#### Notes:

- 1) When your instrument is configured for 1-phase 3-wire, 3-phase 3-wire 3-wattmeter, or 3-phase 4-wire, the  $Watts_{PHASE}$  used are for each configured channel or phase.
- 2) When your instrument is configured for 3-phase, 3-wire, 3 wattmeter method, the calculation is the same as when configured for the 3-phase, 3-wire, 2 wattmeter method but  $Watts_B$  is obtained using an internally generated

Watts result obtained as if the 2 wattmeter configuration was being used. The vector translations used in this circumstance are only valid for predominantly single frequency content signals. If either the voltage or current signals (or both) contain significant harmonic or non-harmonic content then the results may be invalid.

### Power Loss Measurements

This is calculated as follows, using the AC+DC Watts results.

$$Watts_{LOSS} = \sum Watts_{IN} - \sum Watts_{OUT}$$

### Efficiency Measurements

This is calculated as follows, using the AC+DC Watts results.

$$Efficiency = 100 \times \frac{\sum Watts_{OUT}}{\sum Watts_{IN}} \text{ in percent}$$

### Single Phase VAR Measurements

Both AC+DC and AC forms of single-phase VAR are obtained using the same equation. In each case, the Watts and VA results used are those obtained with the bandwidth selection specified for the VAR result. Note that DC VAR is zero by definition. The polarity of the resultant VAR is positive if the power factor is leading.

$$VAR = \sqrt{VA^2 - Watts^2}$$

### Single Phase Single Harmonic VAR Measurements

$$VAR_H = (re(V_H) \times im(A_H)) - (im(V_H) \times re(A_H))$$

### Single Phase Harmonic Range VAR Measurements

$$VAR_{HMIN-HMAX} = \sum_{HMIN}^{HMAX} VAR_H$$

## Multi-Phase VAR Measurements

All forms, AC+DC, AC only, DC only, single harmonic, or harmonic range, of multi-phase VAR are obtained using the same equation. In each case, the individual phase VAR results data used are those obtained with the bandwidth selection specified for the multi-phase VAR result. Note that DC VAR is zero by definition.

$$VAR_{TOTAL} = \sum VAR_{PHASE}$$

### Notes:

1) When your instrument is configured for 1-phase 3-wire, 3-phase 3-wire 3-wattmeter, or 3-phase 4-wire, the  $VAR_{PHASE}$  used are for each configured channel or phase.

2) When your instrument is configured for 3-phase, 3-wire, 3 wattmeter method, the calculation is the same as when configured for the 3-phase, 3-wire, 2 wattmeter method but  $VAR_b$  is obtained using internally generated VA and Watts results obtained as if the 2 wattmeter configuration was being used. The vector translations used in this circumstance are only valid for predominantly single frequency content signals. If either the voltage or current signals (or both) contain significant harmonic or non-harmonic content then the results may be invalid.

## Single Phase VA Measurements

All forms, AC+DC, AC only, DC only, single harmonic, or harmonic range, of VA results are obtained using the same equation. In each case, the Voltage and Current results used are those obtained with the bandwidth specified for the VA result.

$$VA = Voltage \times Current$$

### **Multi-Phase VA Measurements**

All forms, AC+DC, AC only, DC only, single harmonic, or harmonic range, of multi-phase VA results are obtained using the same equation. In each case, the Watts and VAR results used are those obtained with the phase selection and bandwidth specified for the VA result. Note that  $VA_{DC}$  is the same as  $Watts_{DC}$  by definition.

$$VA = \sqrt{Watts^2 + VAR^2}$$

### **Power Factor Measurements**

All forms, single phase, multi-phase, AC+DC, AC only, single harmonic, or harmonic range, of Power Factor results are obtained using the same equation. In each case, the Watts and VAR results used are those obtained with the phase selection and bandwidth specified for the Power Factor result.

$$PF = \frac{Watts}{\sqrt{Watts^2 + VAR^2}}$$

### **DPF (Dissipation Power Factor) Measurements**

By definition, DPF is the same as the Power Factor at the fundamental harmonic.

### **Effective Phase Angle Measurements**

All forms, single phase, multi-phase, AC+DC, AC only, single harmonic, or harmonic range, of Effective Phase Angle results are obtained using the same equation. In each case, the PF result is obtained with the phase selection and bandwidth specified for the Effective Phase Angle result.

$$EPA = \cos^{-1}(PF)$$

### **Multi-Phase and/or Harmonic Lead/Lag Indications**

These are taken from the polarity of the resultant VAR calculation using the required phase combination and bandwidth. If VAR is positive then the Power Factor is leading by definition.

## Derived Load Measurements

### Load Impedance

All forms, AC+DC, AC only, DC only, single harmonic, or harmonic range, of load impedance results are obtained using the same equation. In each case, the Volts and Current results used are those obtained with the bandwidth specified for the impedance result.

$$Z = \frac{V}{A}$$

### Load Series Resistance

All forms, AC+DC, AC only, DC only, single harmonic, or harmonic range, of load series resistance results are obtained using the same equation. In each case, the Watts and Current results used are those obtained with the bandwidth specified for the series resistance result.

$$R_{series} = \frac{W}{A^2}$$

### Load Series Reactance

All forms, AC+DC, AC only, DC only, single harmonic, or harmonic range, of load series reactance results are obtained using the same equation. In each case, the VAR and Current results used are those obtained with the bandwidth specified for the series reactance result.

$$X_{series} = -\frac{VAR}{A^2}$$

### Load Series Inductance

All forms, AC+DC, AC only, DC only, single harmonic, or harmonic range, of load series inductance results are obtained using the same equation. In each case, the  $X_{SERIES}$  result used is obtained with the bandwidth specified for the series inductance result.  $F$  is the synchronization frequency (in Hz).

$$L = \frac{X_{series}}{2 \times p \times F} \text{ in Henries}$$

### Load Parallel Resistance

All forms, AC+DC, AC only, DC only, single harmonic, or harmonic range, of load parallel resistance results are obtained using the same equation. In each case, the  $Z$  and  $R_{\text{SERIES}}$  results used are those obtained with the bandwidth specified for the parallel resistance result.

$$R_{\text{parallel}} = \frac{Z^2}{R_{\text{series}}}$$

### Load Parallel Capacitance

All forms, AC+DC, AC only, DC only, single harmonic, or harmonic range, of load parallel capacitance results are obtained using the same equation. In each case, the  $X_{\text{SERIES}}$  and  $Z$  results used are those obtained with the bandwidth specified for the series capacitance result.  $F$  is the synchronization frequency (in Hz).

$$C_{\text{parallel}} = \frac{-X_{\text{series}}}{2 \times p \times F \times Z^2} \text{ in Farads}$$

## Inrush Results

All inrush results are computed in the same manner. Each result maintains the maximum value of the respective standard measurement result. When the user clears the inrush results, then all inrush results are flagged as invalid, and will be all updated to the next available measurement results.

In the 255x, 256x and 257x families the inrush voltage and current peak values are not computed in this manner. These are computed separately from the normal measurement result peak values on a sample-by-sample basis, and are set to the next available sample when cleared. These families compute to non-peak inrush measurement results in the normal manner.

## Accumulated or Integrated Results

In the 2500, 2503, 2503H and 2503AH families these results are called accumulated results. In the 255x, 256x and 257x families these are called integrated results. In all cases, all results data are calculated in the same manner.



At regular intervals (typically 1ms) while integrating, each respective measurement result is multiplied by the incremental time (in Hours) since the last interval and added to the integrated result. In all families, special mathematics routines are used with extreme precision (more than 80 bits in all families) to ensure that accuracy is maintained over long integration periods. The total integration time is also maintained. By dividing the relevant integrated result by the total integration time, integrated average results are made available.

Some products also have accumulated peak results available. These are evaluated at the same time intervals as the normal integrated results, but it is the maximum value of the respective measurement result that is maintained.

When integrated results are cleared, normal results are set to zero, and peak results are flagged for update to the next available measurement result.

The 2503AH family also has DC charge and discharge results available. These are updated at the above stated intervals, with either the charge accumulator, or the discharge accumulator, being updated, dependent on the polarity of the measurement result.

