A Traceability Technique for Complex Waveform Generators

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Abstract

Concern about non-linear loads affecting power quality has led to new standards which limit the harmonics that an electrical device can "emit" into the power mains. Accompanying the new standards are a variety of manufacturers producing power meters and power quality analyzers to measure compliance to these standards. However, traceable calibration methods for these meters and analyzers have lagged behind. Traceability of non-sinusoidal waveforms is the primary issue. This paper will present a method to obtain traceability based on summing two precision phase-locked sinusoidal sources. The results of this technique, error analysis, and comparison to the digital sampling method will also be presented.

Introduction

There are many commercially available power analyzers on the market today. Unfortunately there are none with sufficient specified accuracy to support a new precision complex waveform generator (i.e., power meter calibrator) being developed, the Fluke 5520A/PQ. Work done at the NPL in the UK [1], NRC in Canada [2][4], and the Swedish National Testing and Research Institute [3] describe similar calibration methods developed for complex waveforms, based on the digital sampling techniques. This paper will describe another approach. First, a waveform analyzer is characterized by two precision phase-locked sinusoidal sources. This characterized analyzer is then used to verify a two-tone complex waveform generator. Next, an RMS-responding meter is used to link the relative measurements to absolute quantities. Further tests are done to verify that the analyzer is not affected by additional harmonics, or by high slew rate waveforms.

Waveform Analyzer Characterization

The first step for this approach was to find a commercially available complex waveform analyzer with good stability, low noise, high resolution, and a flat frequency response over the bandwidth of interest. The unit chosen was the LEM Norma D6000 Wide Band Power Analyzer System. While this instrument claims phase accuracy sufficient to validate the power meter calibrator, the amplitude accuracy for harmonic measurements falls short of the requirements. To characterize this analyzer's amplitude accuracy, two precision phase-locked sinusoidal sources were resistively summed and the resultant signal applied to the analyzer. See figure 1A. The summing network consisted of two 100kΩ thin film networks adjusted to be of nearly identical value.

Figure 1A. Summed AC Sources

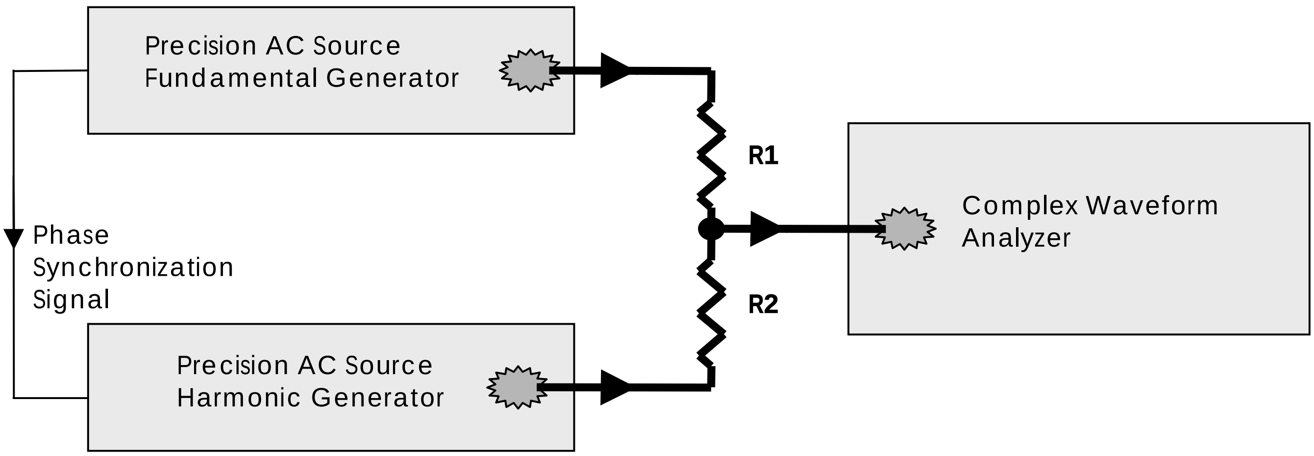
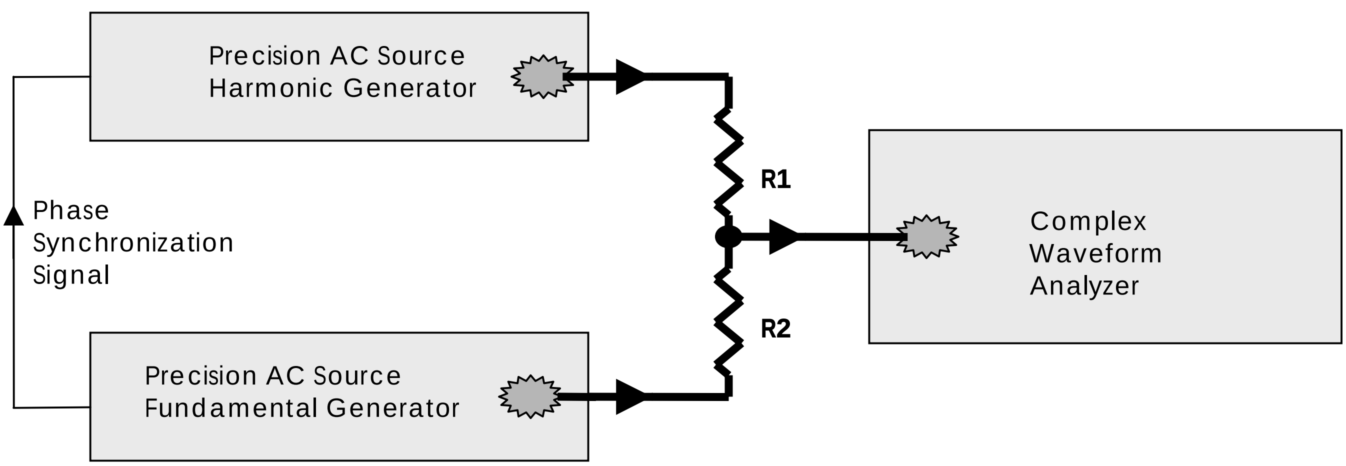


Figure 1B. Summed AC Sources



One source was designated the fundamental frequency generator and set to 50 or 60Hz. The second source, phase synchronized to the first, was the harmonic generator, set at a frequency corresponding to the 2^{nd} through the 63^{rd} harmonic of the fundamental, at an amplitude ranging from 1% to 100% of the fundamental. This configuration determined the gain error of the R1 leg of the summing node for the fundamental, the gain error of the R2 leg of the summing node for the harmonic, combined with the response error of the analyzer. The two sources were then swapped: the fundamental generator became the harmonic generator, and the harmonic generator became the fundamental generator. See figure 1B. This allowed the gain error of the R1/harmonic and R2/fundamental to be determined. The accuracy of the analyzer and summing network is now characterized. Chart 1 shows the results; note the frequency rolloff attributed to the summing network.

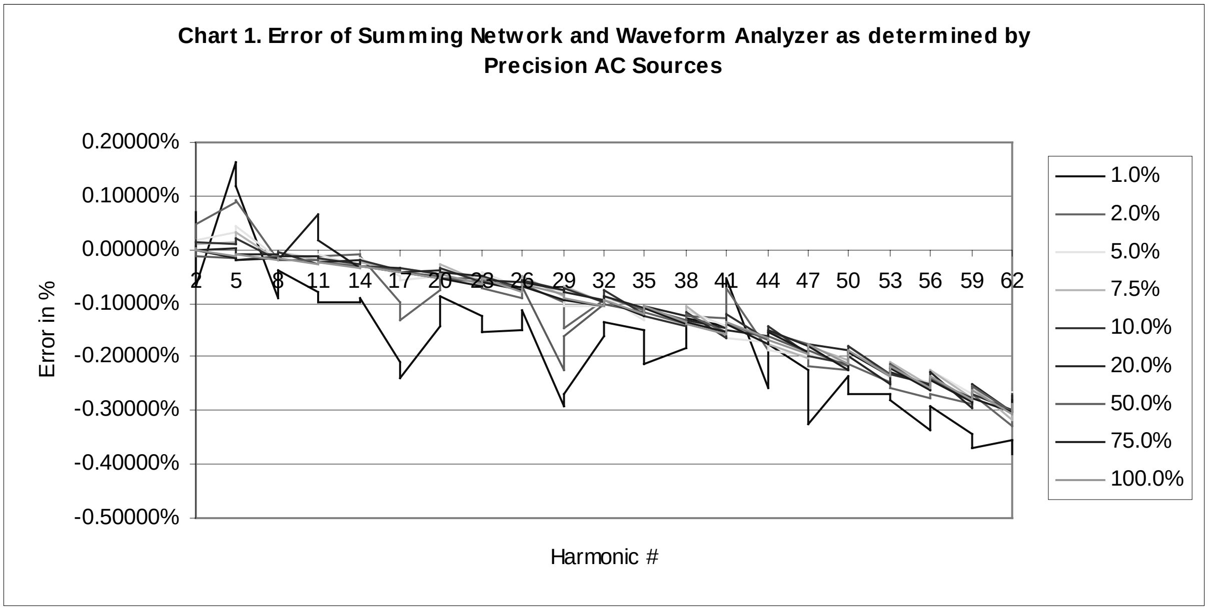
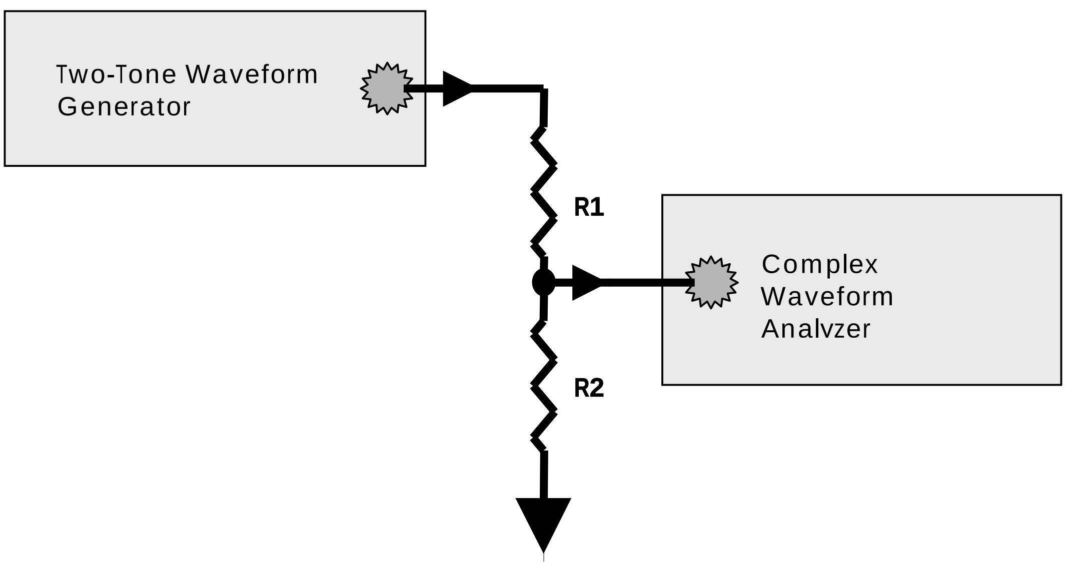


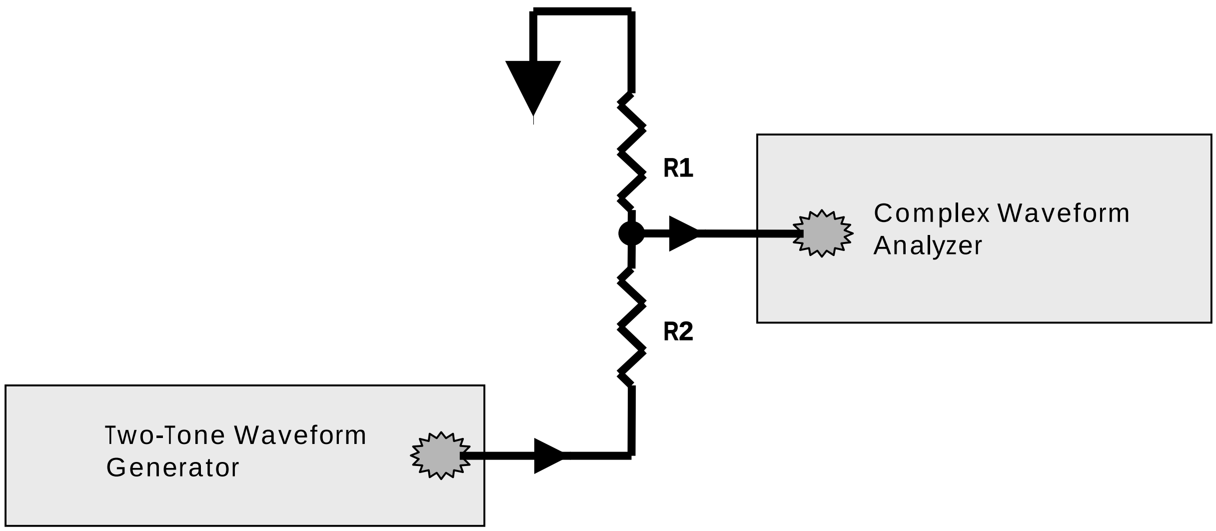
Chart 1. Error of Summing Network and Waveform Analyzer as determined by Precision AC Sources

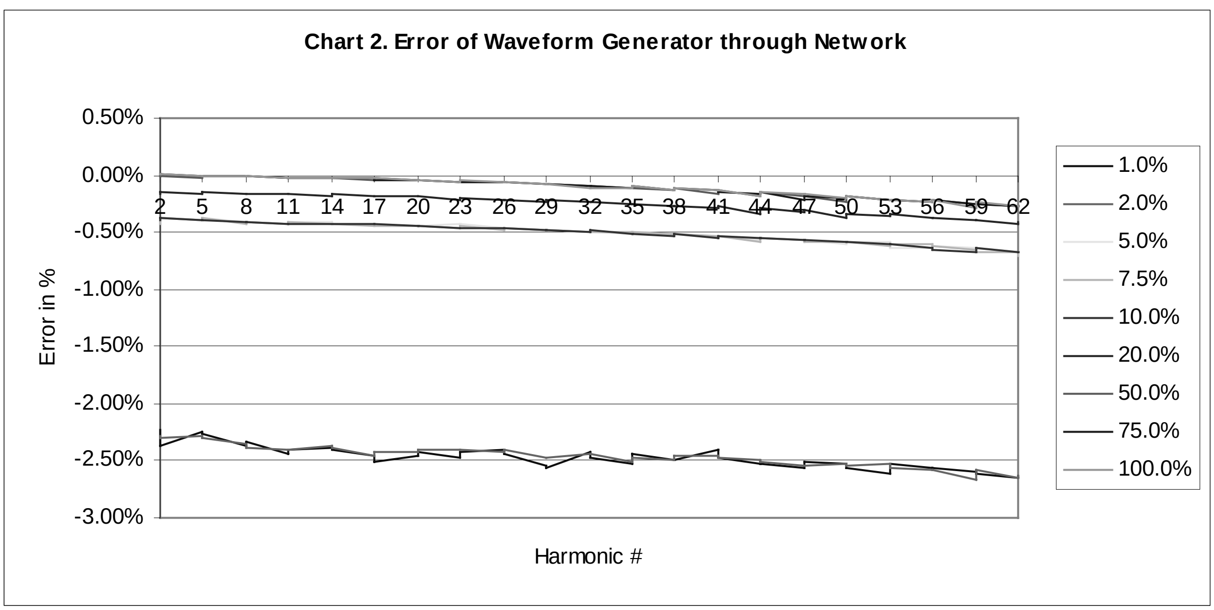
Figure 2A. Two-Tone AC Waveform



The second step replaces the two sinusoidal sources with a two-tone waveform generator. See figure 2A. The generator is set to a level that yields the same RMS value as the summed signals above. The waveform generator applies the same two-tone signals at all of the points previously characterized. In this case, both the fundamental and the harmonic are across the same leg of the summing node, R1. The gain error of the fundamental, determined in configuration 1A above, is applied to the fundamental, and the gain error of the harmonic component across R1, determined in configuration 1B above, is applied to the harmonic. The two-tone generator is then applied to the other leg of the summing node (figure 2B), and the R2 gain errors are applied. The relative amplitude accuracy of the two-tone fundamental and harmonic is now determined, since the error of the analyzer/network has been determined. Chart 2 plots the data for this test; notice the error of the two-tone generator at low harmonic amplitudes, as well as the rolloff of the network. Chart 3 plots the difference, effectively canceling the combined error of the analyzer and the network. This chart shows the error of the waveform generator as measured by the analyzer.

Figure 2B. Two-Tone AC Waveform





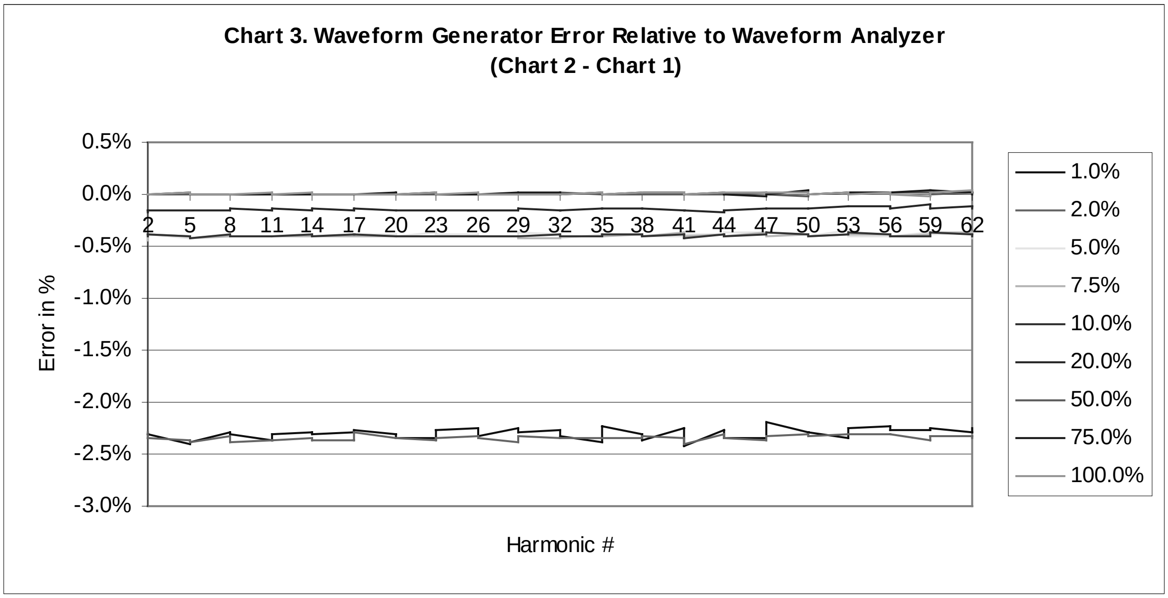
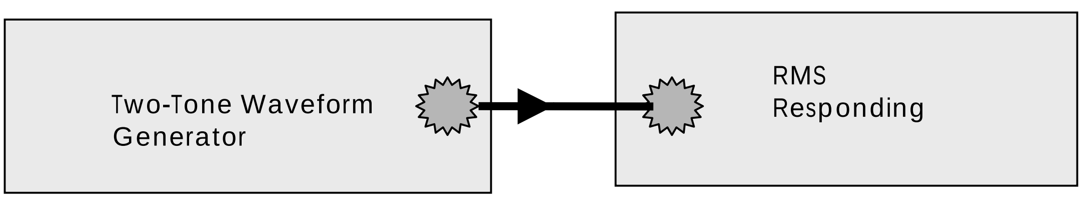


Chart 3. Waveform Generator Error Relative to Waveform Analyzer (Chart 2 - Chart 1)

Next, the absolute accuracy of the waveform analyzer needs to be determined. The two-tone generator signal is applied directly to an RMS responding detector (figure 3). The detector used determines the fundamental frequency of the signal applied, and applies flatness corrections at this frequency only. Since the applied signal contains components higher than the fundamental, these components will be corrected only to the extent of the fundamental. Fortunately, over the bandwidth of interest, the corrections are small relative to the accuracies required. The absolute RMS accuracy of the generator is now known.

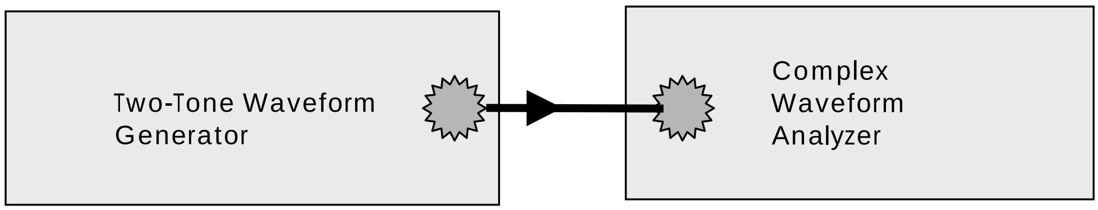
Figure 3. Absolute AC Measurement



Finally, the two-tone generator signal is applied directly to the analyzer (figure 4). Again, the generator applies the same two-tone signals at all of the points previously characterized. Chart 4 plots the RMS error of the analyzer relative to the RMS detector. This chart indicates that the analyzer error ranges from -0.02% to -0.035%. When these corrections are applied, the absolute RMS, fundamental, and harmonic accuracies of the two-tone signal from the generator are known, and the analyzer is characterized for a two-tone signal.

This completes the characterization of the analyzer for a 2-tone signal. Further evaluation of the analyzer is required to insure that its ability to measure a single harmonic is not compromised by the presence of additional harmonics. Also, since complex waveforms, depending on harmonic and phase content, can contain fast rise times, the analyzer needs to be evaluated for slew rate limiting.

Figure 4. Waveform Analyzer Characterization



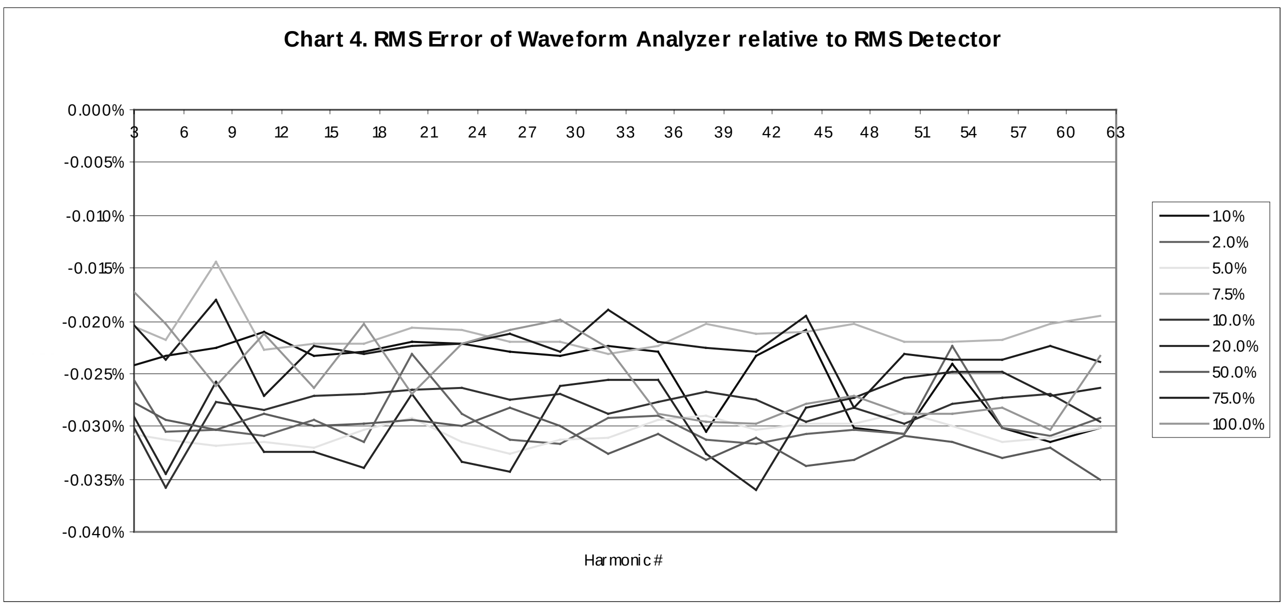
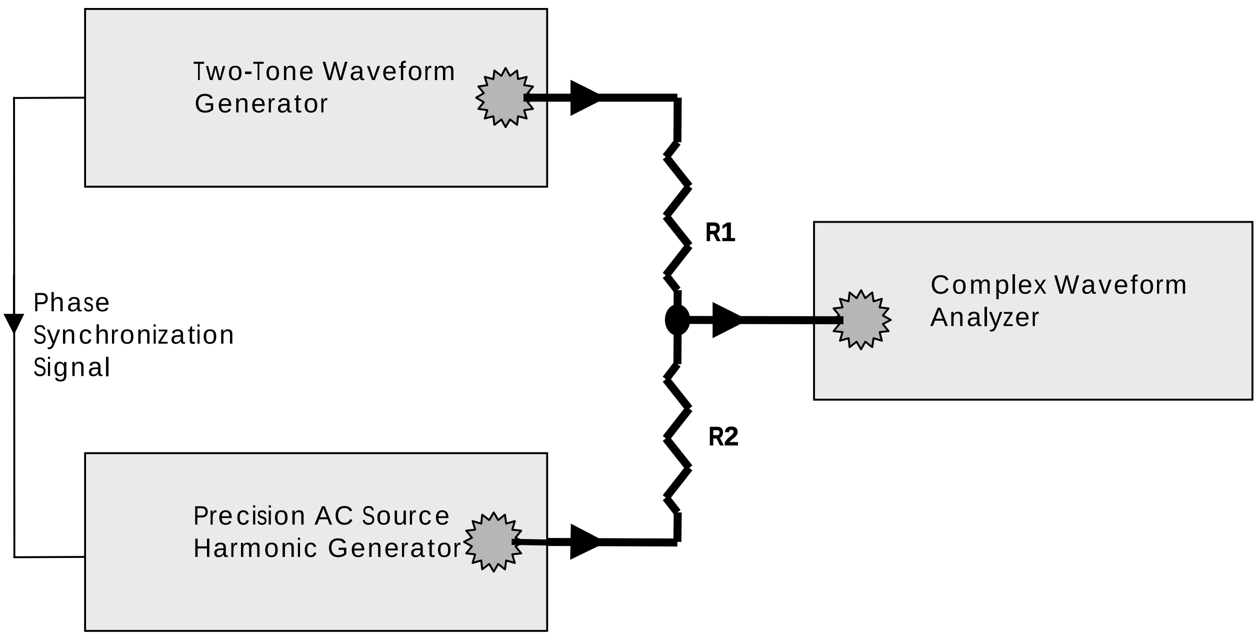


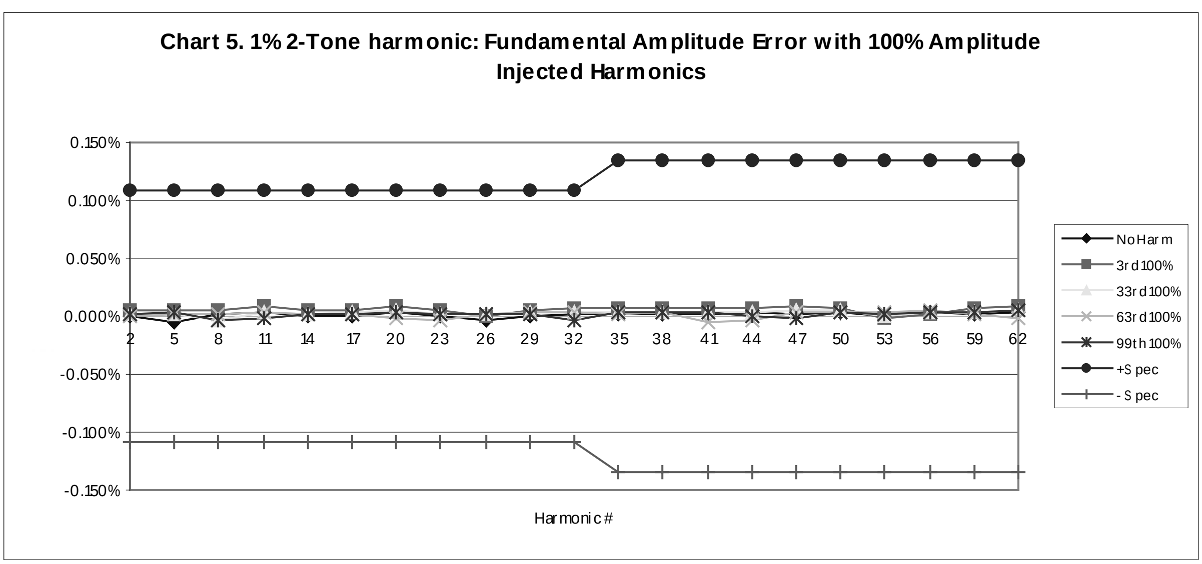
Chart 4. RMS Error of Waveform Analyzer relative to RMS Detector

Multiple harmonics

The tests described up to this point determine that a summed two-tone signal can characterize the performance of a complex waveform analyzer. The next step is to prove that the analyzer’s ability to measure a fundamental and an individual harmonic, both amplitude and phase, are not affected by additional harmonics introduced on the waveform. To do this, the summing network used for the two-tone validation is used to inject an additional harmonic synchronized with the fundamental of the complex waveform generator. See figure 5. While the RMS value is understandably increased, the fundamental and the harmonic should be unaffected by the additional harmonic. Initially a two-tone waveform from the generator was applied to the analyzer, with a third signal applied from the other leg of the summing network. The frequency of the injected harmonic ranged from 180 Hz (3^{rd} harmonic) to 5.94 kHz (99^{th} harmonic); the amplitude ranged from 1% to 100% of the fundamental. The results of these tests show conclusively that the effect of this injected harmonic on the analyzer's amplitude measurement ability is negligible relative to the specs. Chart 5 plots the fundamental amplitude error and chart 6 shows the harmonic amplitude error. It was found that the analyzer's phase accuracy for very low level amplitudes is affected by the presence of adjacent harmonics of high amplitude. In chart 7, note that the 1% 2^{nd} harmonic phase is 0.5 degrees in error with a 3^{rd} harmonic at 100%, and the 1% 32^{nd} and 35^{th} harmonic are more than a degree in error in the presence of a 100%, 33^{rd} harmonic. These same points at 5% amplitude indicate an immunity to the injected harmonic (chart 8). On these charts, the specification of the generator is shown for reference.

Figure 5. Summing Additional Harmonics





The next step is to generate a multi-tone waveform and inject an additional harmonic. For this test, a 15-tone square wave and the 25-tone NRC7030 waveform [4] were used. Again, the introduction of an additional waveform did not affect the analyzer's ability to accurately report the fundamental and harmonic amplitudes, or the phase of the harmonics relative to the fundamental. For the 15-tone square wave, a harmonic equal to 100% of the fundamental was introduced as a 4th, 33rd, 63rd, and 99th harmonic relative to the fundamental. The amplitude error for the resultant square wave is shown in chart 9, and the phase error is shown in chart 10. Again, the spec of the generator is shown for reference.

Chart 6. 1% 2-Tone Harmonic: Harmonic Amplitude Error with 100% Amplitude Harmonics Injected

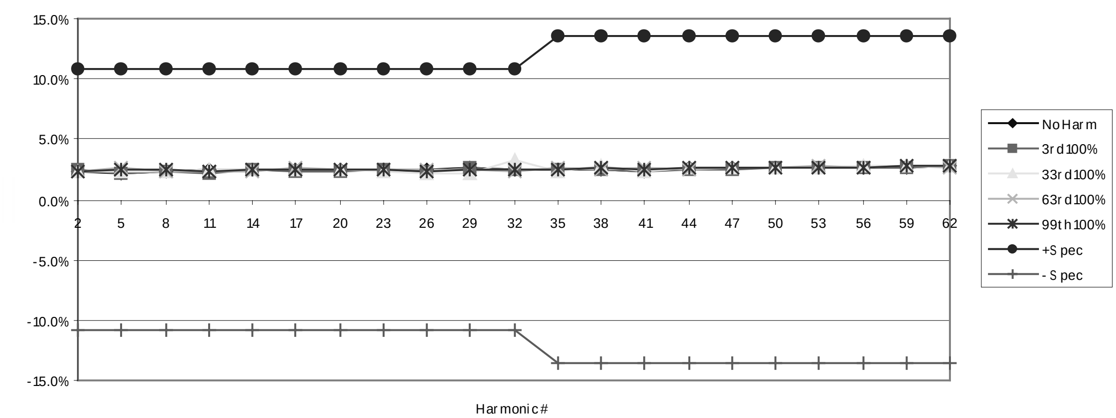
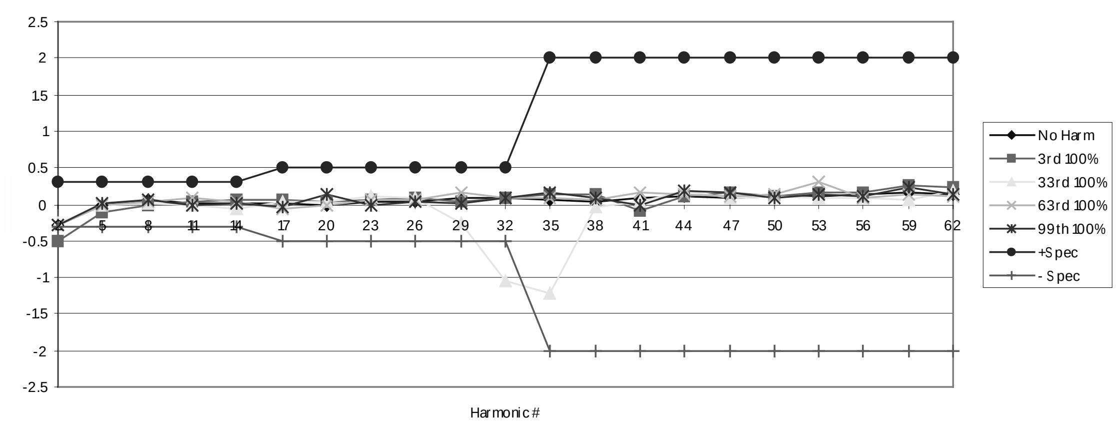


Chart 7. 1% 2-Tone Harmonic Phase Error with 100% Amplitude Injected Harmonic



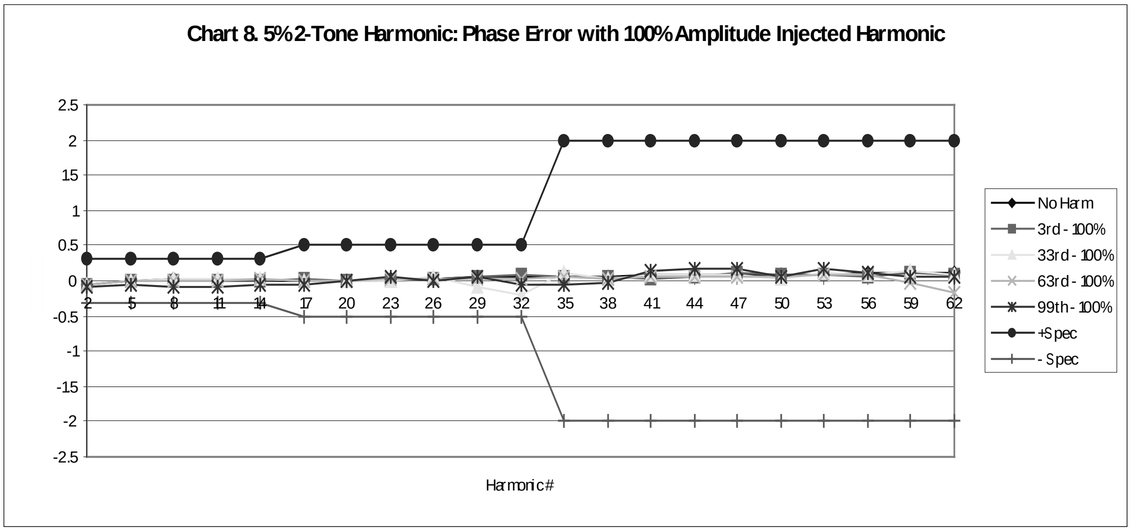


Chart 8. 5% 2-Tone Harmonic: Phase Error with 100% Amplitude Injected Harmonic
2.5
2
15
1
0.5
0
-0.5
-1
-15
-2
-2.5
2 5 8 11 14 17 20 23 26 29 32 35 38 41 44 47 50 53 56 59 62
Harmonic #
No Harm
3rd - 100%
33rd - 100%
63rd - 100%
99th - 100%
+Spec
- Spec

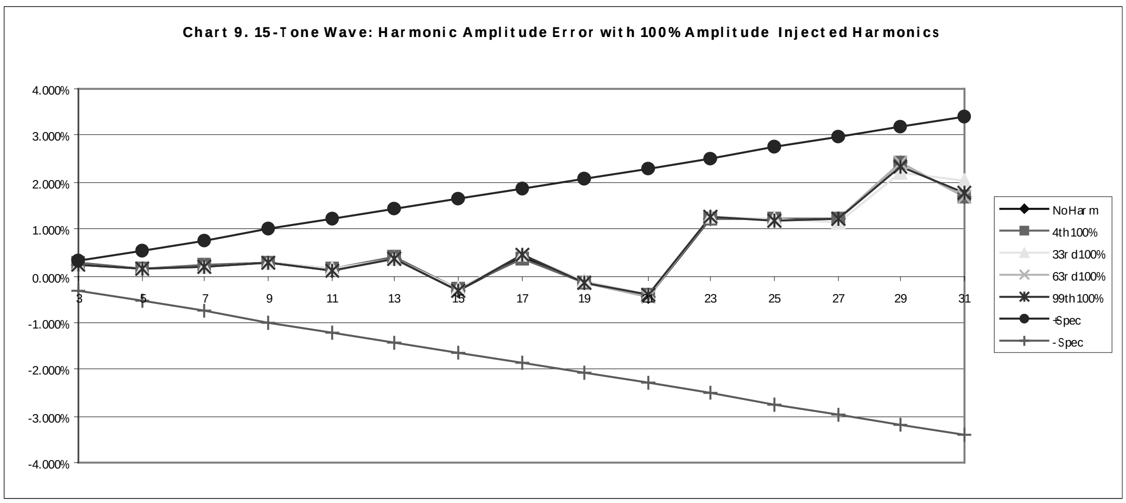


Chart 9. 15-Tone Wave: Harmonic Amplitude Error with 100% Amplitude Injected Harmonics
4.000%
3.000%
2.000%
1.000%
0.000%
-1.000%
-2.000%
-3.000%
-4.000%
3 5 7 9 11 13 15 17 19 21 23 25 27 29 31
No Harm
4th 100%
33rd 100%
63rd 100%
99th 100%
+Spec
- Spec

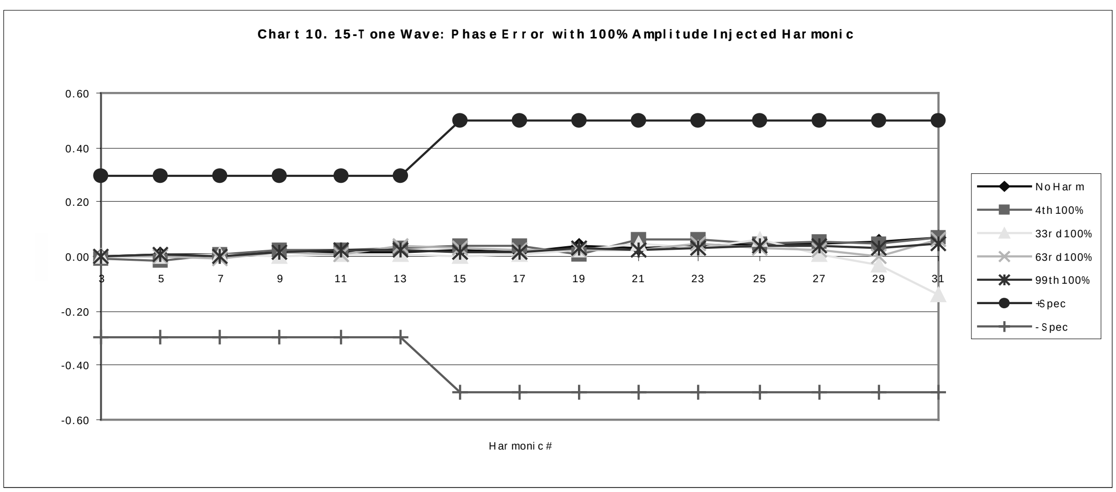
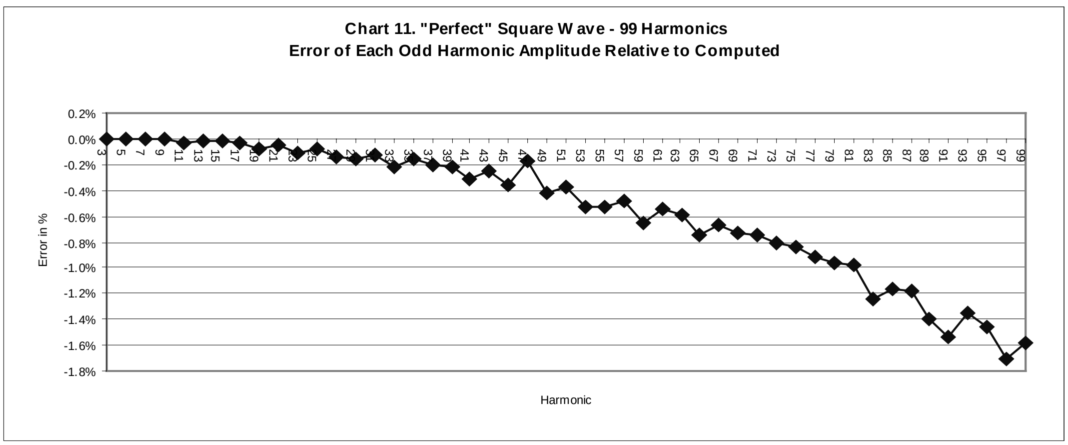
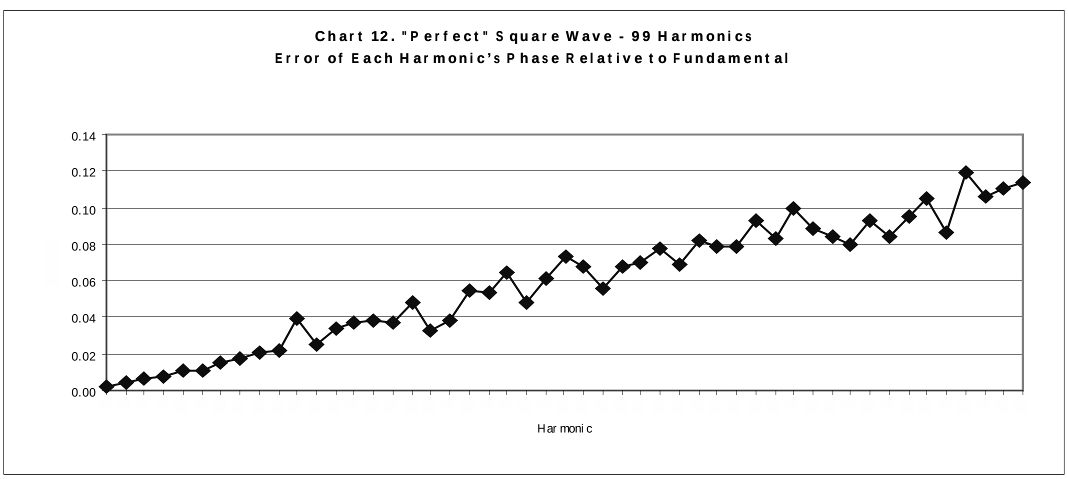


Chart 10. 15-Tone Wave: Phase Error with 100% Amplitude Injected Harmonic
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
3 5 7 9 11 13 15 17 19 21 23 25 27 29 31
Harmonic #
No Harm
4th 100%
33rd 100%
63rd 100%
99th 100%
+Spec
- Spec

Slew Rate

A final evaluation of the complex waveform analyzer is to apply a "perfect" square wave to see if it is affected by high slew rate signals. A 60Hz square wave, with a maximum overshoot of 2% and aberrations less than 0.5%, is applied directly to the analyzer for this test. To prove immunity to high slew rate inputs, the analyzer should report an accurate RMS value of the waveform, and should report the odd harmonic amplitudes as the product of the inverse of the harmonic number (i.e., 3rd harmonic: 0.333, 5th harmonic: 0.20, etc.) times the fundamental amplitude. As with the previous tests, the RMS value of the applied square wave is determined by an RMS responding detector. This error was found to be consistent with the waveform analyzer accuracy errors already discussed. The harmonic amplitude and phase errors are shown in charts 11 and 12, respectively. These graphs indicate that at the 99th harmonic (1% of the fundamental amplitude) the relative amplitude error is less than 2% and the phase error is less than 0.15 degrees.





Error Analysis

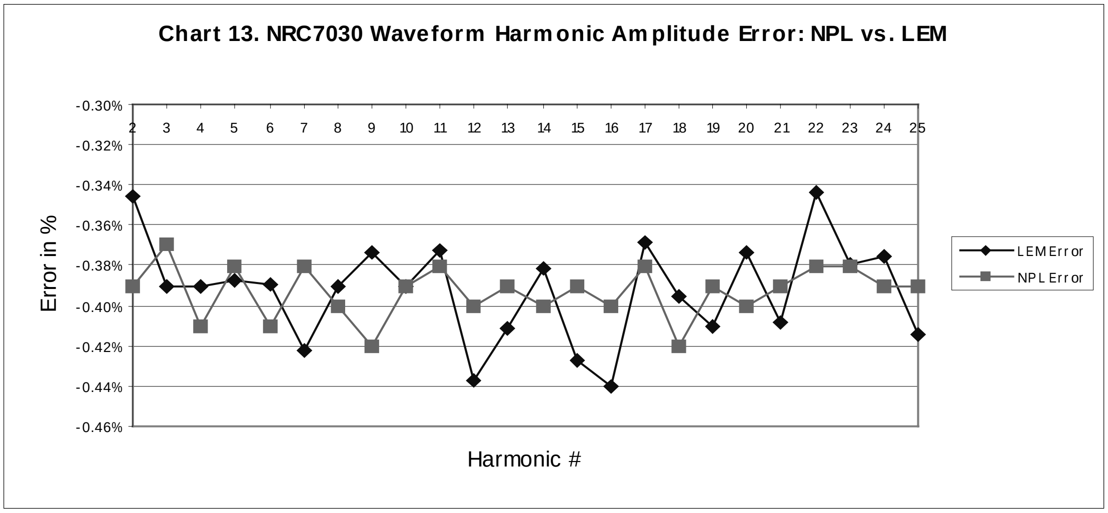
It is beyond the scope of this paper to provide a detailed error analysis for the multitude of measurements discussed in the analyzer characterization. A few of the substantial error sources are presented here.

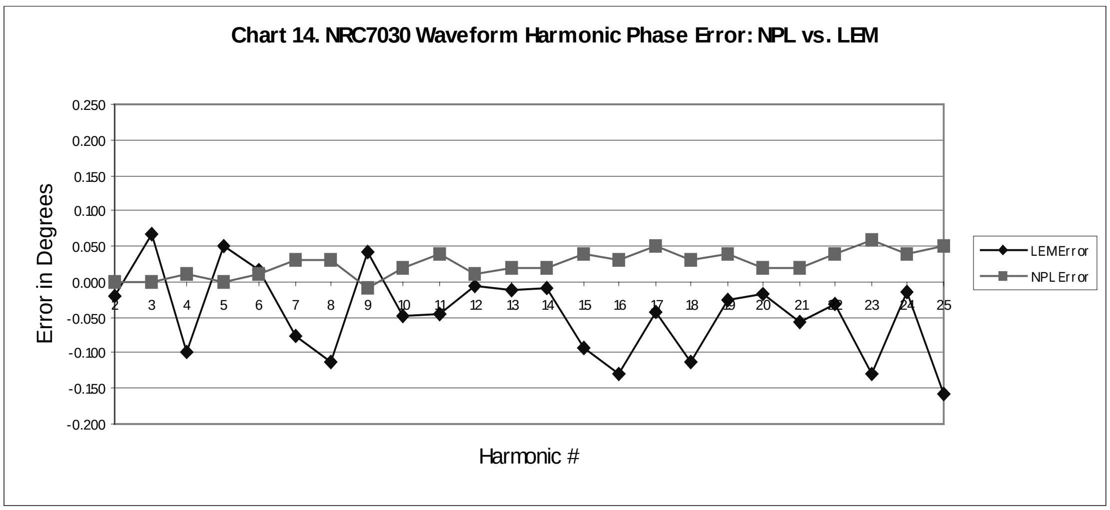
Fundamental and Harmonic Amplitude:
The precision sinusoidal sources used here are Fluke 5520A calibrators with an accuracy specification of less than 200 ppm at the amplitudes and frequencies generated for the analyzer characterization. The RMS detector, a Fluke 5790A, specifies an absolute accuracy of 25 ppm at a single frequency and bandwidth corrections are less than 10 ppm to 5kHz. The stability and repeatability of the analyzer's measurements of fundamental and harmonic amplitude varied with the percent amplitude of the harmonic relative to the fundamental, the frequency of the harmonic, and the number of harmonics present on a particular waveform. With lower frequency, higher amplitude harmonics, the fundamental varied less than 10 ppm, and the harmonic varied less than 30 ppm. As the frequency of the harmonic increased, the fundamental variation remained constant but the harmonic amplitude variation increased exponentially, with the 63rd exhibiting up to a 200 ppm standard deviation. The tightest generator spec for the fundamental and lower frequency, higher amplitude harmonics is 0.1%, permitting a Test Uncertainty Ratio (TUR) of better than 4:1 for both. Long term stability, temperature coefficient, loading effect, and tertiary error sources were not found to be significant when RSS'd with these primary sources.

Harmonic Phase (relative to Fundamental):
The LEM Norma specifies phase as +/-(0.1 degrees + 0.05 degrees per kHz). Tests performed indicate the stability and repeatability is less than 0.01 degrees for harmonics less than the 20th (1.2 kHz @ 60 Hz), less than 0.05 degrees for harmonics less than the 40th (2.4 kHz) and less than 0.1 degree up to the 63rd (3.780 kHz). The waveform generator's best spec of 0.3 degrees (up to 900 Hz) is the area of the lowest TUR, with the analyzer specifying 0.145 degrees, for a TUR of 2:1. In the 900 Hz to 2 kHz band, the worst case TUR (at 2 kHz) for the 0.5 degree spec of the generator is 2.5:1. For higher frequencies, the TURs are all in excess of 6:1.

Comparison To NPL

Evaluation of Fluke's complex waveform generator by other labs is work in process. As of this writing, the National Physical Laboratory in the UK, using methods described in reference [1], has reported its findings on a prototype generator [5], but the generator has not yet been returned to our lab for comparison. However, comparison between the NPL data and another prototype generator reveal encouraging results. Chart 13 plots the harmonic amplitude error of the NRC7030 waveform as found at NPL and as measured with the LEM Norma D6000. Chart 14 plots the phase error for the same waveform.





Conclusion

This paper has presented a method to obtain traceable measurements of a complex waveform. Data was presented showing that a complex waveform analyzer can be characterized with precision AC signals summed to form a two-tone signal. The errors of the summing network and the analyzer were accounted for, yielding absolute measurements of the RMS, fundamental, and harmonic components of the waveform. Further testing demonstrated that the analyzer's measurements were immune to additional harmonics and high slew rate inputs. A first order error analysis of the measurements was then discussed, and data showing correlation to alternate measurement methods was provided.

References

[1] Wright, Paul, *"Calibration of Power Frequency Harmonics Analyzers as used in Conjunction with EN61000-3-2"*, 2000 NCSL Workshop and Symposium, Session 10-B

[2] Arseneau, Rejean; Filipski, P. S.; Zelle, John, *"Portable and Stable Source of AC Voltage, Current, and Power"*, IEEE Transactions on Instrumentation and Measurement, Vol. 44, No. 2, April 1995

[3] Svensson, Stefan, Rydler, Karl-Erik, *"A Measuring System for the Calibration of Power Analyzers"*, IEEE Transactions on Instrumentation and Measurement, Vol. 44, No. 2, April 1995

[4] The NRC7030 waveform is based on *"A Calibration System for Evaluating the Performance of Harmonic Power Analyzers"* and *"An Efficient Test Method for Harmonic Measurement Equipment"* by Rejean Arseneau and Dr. Peter Filipski of the National Research Council of Canada (NRC) Institute for National Measurement Standards, Ottawa, Ontario, Canada

[5] National Physical Laboratory, Report of Calibration Reference ED.17/01/012/EtD 258.057, Issued 22nd February 2001