Low-Level AC Current Measurement Performance of the Model 931A Power System Analyzer

The Model 931A Power System Analyzer from Arbiter Systems®, Inc. offers outstanding accuracy and flexibility in measurements on relaying, instrumentation and metering circuits. Its outstanding accuracy, up to 20 times better than competing products, is due to the Model 931A's PowerDSA™ Digital Signal Analysis technology and careful analog circuit design.

The PowerDSA analyzer is based on the Motorola DSP56001 digital signal processor, running proprietary, high-accuracy algorithms that estimate the parameters of periodic waveforms such as sine waves. These parameters, for a sine wave, are frequency, magnitude, and phase. While the design of the PowerDSA analyzer is optimized for outstanding accuracy at the moderate levels of current (40 mA to 20 A) typically encountered in relaying, instrumentation, and metering circuits, there sometimes arises the need to make accurate measurements at lower current levels. The characteristics of the PowerDSA analyzer which suit it so well to measuring higher currents with great accuracy also result in unprecedented low-level performance at currents down to, and below, 1 mA.

Factors Which Affect Low-Current Accuracy

Numerous factors in the design of an instrument such as the Model 931A can affect performance in measuring low-level signals. All of the factors that affect higher-current performance also apply, of course, but several new factors have a particularly significant effect at low levels.

These factors include input section common-mode rejection, channel-to-channel isolation, measurement resolution limits, and algorithm limitations. The first two are a function of analog design considerations. The third is also a function of the analog-to-digital conversion scheme and the resolution of the PowerDSA algorithms. The last is due to the imperfect ability of the PowerDSA algorithms to find a low-level signal without some guidance.

Common-mode rejection (CMR) is the ability of an instrument to reject the effects of voltage on the current input terminals, with respect to instrument common. For the current input, this voltage is the same for both terminals, and arises (for example) when the Model 931A is connected into a CT circuit with substantial burden, or when the current inputs are wired into the ac line circuit to measure line current. The common-mode voltage (so called because the same voltage is present on both terminals) can cause small currents to flow into the measurement circuit input, particularly due to capacitive coupling between the primary winding of the instrument's input current transformer and its secondary winding. These effects can be quite significant; for example, the Model 931A uses an input CT ratio of 1000:1; with a stray capacitance of only 1pF between the primary winding and the output, an equivalent input error of 45 µA will be induced by a 120 Vrms potential on the CT input terminals. When attempting to measure a current of 1 mA with a nominal zero phase angle, this causes a magnitude error of 0.1% and, more important, a phase error of 2.6° (because the error current is 90° out of phase with the signal current). If the nominal phase angle is 90°, there will be no phase error, but now the magnitude error will be 4.5%. The errors can easily be much greater than this, depending on the design of the input CT and the specific voltage and current levels being measured.

Ideally, the current reading is unaffected by common-mode voltage. This goal (infinite common-mode rejection) can be approached in practice but never actually achieved. Doing so, however, requires exceptional care in the design and assembly of the input CT assembly. The input CTs of the Model 931A Power System Analyzer are carefully shielded to maximize CMR, and the input circuitry is assembled on a self-shielded multilayer printed circuit board. This results in a vector error of approximately 2 µA due to a 120 volt common-mode signal. This level of performance guarantees accurate results (less than 1% amplitude and/or 1° phase error) at input signal levels down to a few hundred microamperes.

Channel-to-channel isolation also affects performance at low current levels. The input stage of the Model 931A current section converts the CT output current to a voltage for further processing. At low current levels, this voltage is quite small; for example, at 1 mA input current, it is only 400 µV. Under the conditions described above, with a 120 Vrms voltage signal (1.2 Vrms at the voltage section output), the ratio of these signals is 3000:1 or approximately 70 dB. To maintain reasonable (1%) accuracy at low levels, the channel-to-channel isolation must be at least 100 times or 40 dB better than this, 300,000:1 or 110 dB. Due to the small physical size of the Model 931A, these circuits are in close proximity to each other, and this level of isolation is not trivial to achieve. However, with careful design, this contribution to low-level error has been kept to unmeasurable levels; that is, levels which are masked by other effects and therefore impossible to resolve.

Measurement resolution includes two factors. These are A/D resolution and computational resolution. Both of these factors are minimized in the Model 931A, but by different methods. A/D resolution in the Model 931A is only 12 bits. In the lowest current range, this corresponds to a resolution of about 70 µA per A/D step. It would appear that currents below about 20 µA could not even be detected with this level of resolution; however, in fact this is not the case. Electrical noise, unavoidably present in the measurement circuits, effectively "dithers" the A/D converter, or causes its output to randomly change state over a small number of steps even with no input signal present. This dithering makes it possible for the A/D to resolve signals below its ideal resolution limit, although of course with limited accuracy. Nonetheless, the PowerDSA analyzer is able to make meaningful measurements on signals at around its theoretical quantization limit of 20 µA, due to the effect of this dithering.

Computational resolution is kept from being a significant factor due to the 24-bit resolution of the DSP56001 processor. For example, the 20 µA signal just described which represents one quantizing level of the input A/D represents over 3000 quantizing levels at the DSP processor. Due to roundoff and other mathematical precision limitations, it is important to have substantially more resolution in the DSP processor than the A/D for optimum results. In the Model 931A PowerDSA, computational resolution does not place a significant limit on performance.

Algorithmic limitations affect not the ability of the PowerDSA analyzer to measure a small signal, but its ability to find this signal in the first place. The PowerDSA parametric estimation algorithms begin with an estimate of frequency that is made by counting zero crossings of the channel 1 signal. This initial estimate does not need to be extremely accurate, but it must be close enough that the signal passes through digital filters subsequently used to reject noise, harmonics and unwanted signals. When the signal level gets too small, the zero crossings cannot be accurately determined. This occurs at a signal level of approximately 1% of range, which is about 1 mA for the Model 931A's lowest current range. Below this level, the Model 931A will not display measurement results, with one exception.

This exception is that if the channel 1 signal is greater than 30% of the lowest range (approximately 27 mA for current or 1.1 V for voltage), the channel 2 result will be measured and displayed, based on the channel 1 frequency as an initial estimate. The accuracy of this measurement depends on the current level. The sections which follows describe the performance to be expected in this mode.

Measured Performance

The performance of the Model 931A was first measured at low current levels by using a stable voltage source to drive one of the voltage inputs, and using a resistor to generate a small current from the voltage (by Ohm's law), which was applied to one of the current inputs. This resistor was as large as 1 megohm, making possible measurements down into the microampere range.

Amplitude Measurement Results

Amplitude measurements were within 1% of nominal at currents of 300 µA or greater. Accuracy degraded quickly below this level, being 6% in error (reading high) at 150 µA. Since the resistors used to generate the currents measured had 1% accuracy themselves, it was difficult to measure accuracy better than this level, although (by comparison to an accurate DVM) the following were estimated: at 1 mA, the error was approximately 0.5% and at 10 mA, approximately 0.05%.

Phase Angle Measurement Results

Many times at low currents, phase angle is of more interest than amplitude. The following phase angle accuracy was determined, again using a resistor and a voltage source: At 15 µA (the lowest level tested), performance was dominated by noise, giving a standard deviation around 5°. At 100 µA, the measurements were again noise-dominated, but with a reduced standard deviation around 1°; at 300 µA, standard deviation decreased to 0.3°. At 1 mA, the noise was greatly reduced and the standard deviation was approximately 0.1°. At 10 mA, the standard deviation was less than 0.05° and appeared to be due to other factors than input signal level.

No significant bias errors (errors in the mean equal to or greater than the standard deviation) were seen with the input common-mode voltage at zero volts. Bias errors, due to imperfect CMR, could be seen at low currents with high input voltages, for example, at currents of 150 and 300 µA, with voltages of 150 and 300 Vrms, using a 1 megohm resistor, bias errors of plus or minus 1° could be observed, depending on the polarity of the common-mode voltage. With currents of 1 mA or more, and voltages of up to 150 Vrms, bias errors due to CMR were generally less than 0.1°.

Current-to-Current Phase Angle Measurements

Measurements of phase angle between two currents are possible with the Model 931A. Both currents must be above approximately 1.3 mA to ensure proper operation of the PowerDSA algorithms, or alternatively one current may be 30 mA or more and the other may then be as small as a few microamperes.

Measuring the same current with two different channels gave the following results: at 1.3 mA (lower limit), the magnitudes were within 0.5% and the standard deviation of phase angle less than 0.03°; no bias error in phase angle was measured at this current or any higher level. At 5 mA, magnitudes were within 0.1% and phase angles within 0.01°. At 10 mA, magnitudes were within 0.05% and phase angle was usually displayed as 0.00.

Measuring different currents on the two channels, a reference current (channel 1) of 30 mA was used, and various values of current were measured with channel 2. At 30 µA, standard deviation was approximately 10°. At 200 µA, standard deviation dropped to 1.5°; at 1.5 mA, it was 0.15°. At 6 mA, standard deviation was approximately 0.03 degree. At no current level was any significant bias error observed.

Conclusion

The Arbiter Systems, Inc. Model 931A Power System Analyzer not only performs with state-of-the-art accuracy inside its specified limits for current measurement, but due to careful design, delivers outstanding accuracy at lower levels with performance of around 0.5% and 0.1° typical at current levels of 1 mA, with proportionally smaller errors with increasing current. For phase angle measurements, the Model 931A is usable with currents as low as 15 µA, although substantial noise degrades measurement usefulness at such low levels.