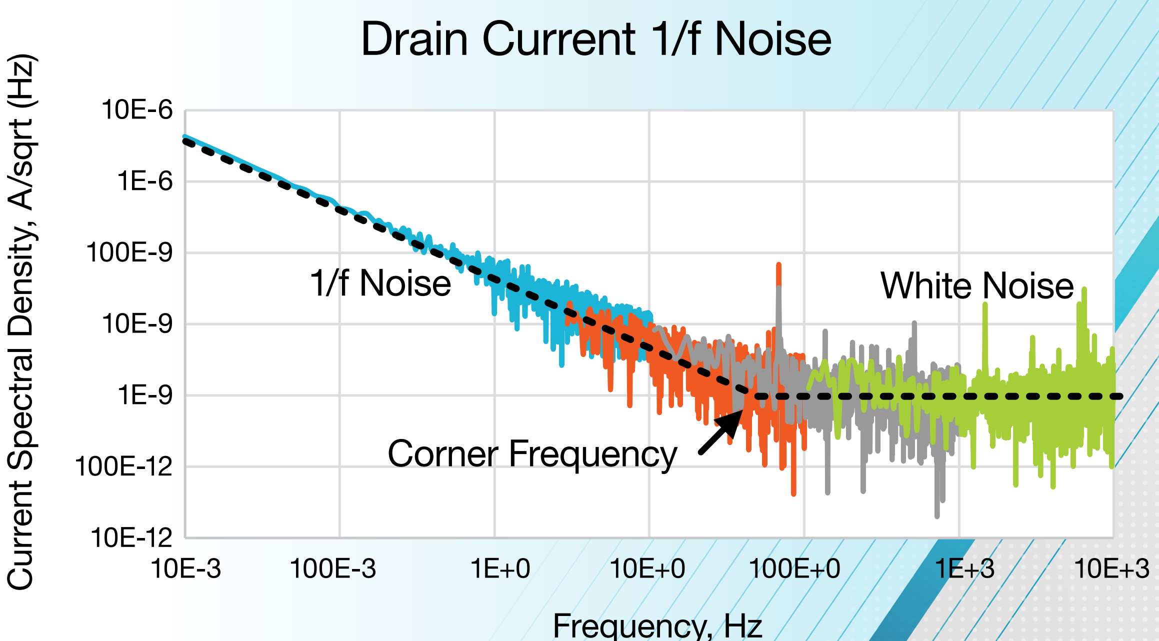
1/f Current Noise Measurements Using the 4200A-SCS Parameter Analyzer

APPLICATION NOTE



Introduction

Electronic devices intrinsically have different types of noise sources including thermal (Johnson) noise, shot noise, white (broadband) noise, and 1/f (flicker) noise. 1/f noise is low-frequency electronic noise where the current (ISD) or power (PSD) spectral density is inversely proportional to the frequency. Many types of components exhibit 1/f noise including semiconductor devices, some types of resistors, 2D materials such as graphene, and even chemical cells. Often the 1/f noise of a device is determined by measuring the current as a function of time and then converting the data into the frequency domain. Fast Fourier Transform (FFT) is a popular method for converting time domain data into frequency domain data.

Noise sources in measurement setups come from different sources, one of them is the measurement instrumentation itself. To extract noise characteristics of the device under test (DUT) instrumentation noise must be smaller than the DUT noise.

Source Measure Units (SMUs) and the Pulse Measure Unit (PMU) are modules for the Keithley 4200A-SCS Parameter Analyzer that measure and source current and voltage in the time domain. The SMU and the PMU can take measurements at a constant rate that can be converted into parameters in the frequency domain using FFT functions that are built-in to the Formulator of the Clarius software. The 4200A-SCS's extensive test library includes example tests with AC parameter computations for generating 1/f noise, current spectral density, and other AC-based measurements.

This application note explains how to make 1/f noise measurements with the 4200A-SCS using both SMUs and the PMU. In particular, the following paragraphs describe 1/f noise basics, determining the noise floor of an instrument by deriving the current spectral density (ISD) on a particular range, measuring the drain current 1/f noise of a MOSFET, configuring 1/f noise measurements on two-terminal devices, and describes the built-in FFT functions.

1/f Noise

Flicker, or 1/f, noise spans over many frequencies, but is often observed at <100 Hz. A typical noise current spectrum of a device is shown in **Figure 1**. For 1/f noise, spectrum density is inversely proportional to the frequency. However, on a log-log scale, the spectral density and frequency appear linearly related. The thermal noise, or white noise, remains constant as a function of frequency. The corner frequency is where the 1/f noise curve intersects the thermal noise on the graph.

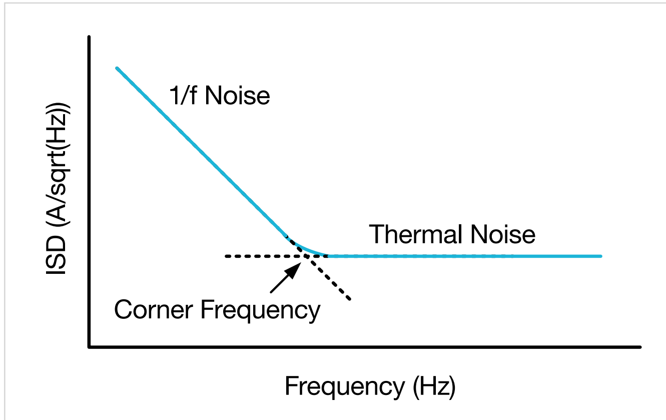


Figure 1. Typical current noise spectrum of a device.

Measuring 1/f Noise of a Device

Even though there are many ways to determine 1/f noise, one method, which uses DC test equipment, is illustrated in **Figure 2.** In this example, voltage is applied to both the gate and drain of a MOSFET, and an ammeter measures the drain current at a given sample rate. The time-based current measurements taken by the ammeter are converted into the current noise spectral density (ISD) and frequency by using FFT computations. Using FFT functions requires that the current and time measurements are evenly spaced apart.

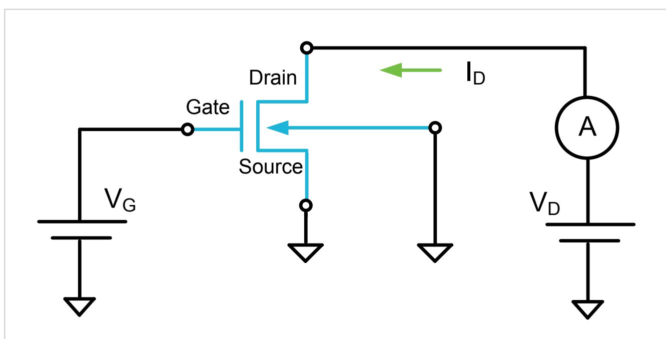


Figure 2. Circuit for measuring 1/f drain current noise of MOSFET.

As shown in **Figure 3**, the two power supplies in the circuit can be replaced by two SMUs (or PMU channels) which can source voltage and measure current and can also be used for determining the I-V characteristics of the MOSFET. In this example, SMU1 is connected to the gate terminal and applies the gate voltage and SMU2 is connected to the drain terminal and forces the drain voltage and measures the resulting drain current.

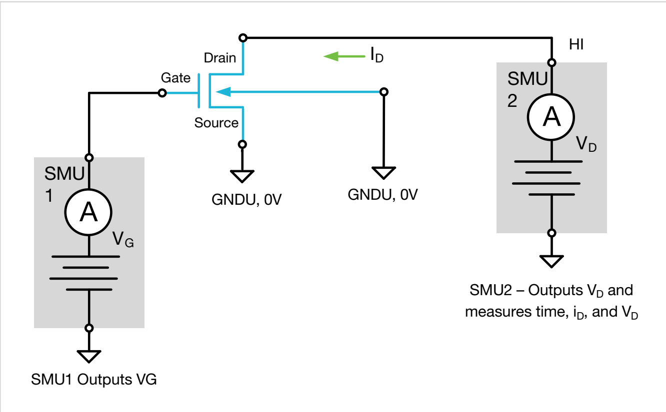


Figure 3. Measuring 1/f drain current noise using two SMUs.

The 4200A's SMUs have 6½-digit resolution and usually have lower DC noise than the PMU. However, the current measurements of the SMU are taken at a slower speed than the PMU and therefore will have lower bandwidth. The PMU can take high-speed current measurements at the expense of noise. The instruments used must have a noise level that is sufficiently less than the expected device noise. This is best determined by deriving the instrument's noise level with an open circuit as described in the next section.

Determining SMU and PMU Noise with an Open Circuit

The instrument noise of the SMU or PMU is derived with an open circuit. To determine their noise, place a metal cap on both the Force Hi and Sense HI terminals and let the instrument warm-up for one hour. If the instrument is connected to a prober, lift the probes before starting the test.

The Clarius software is used to control the instrument in the noise test. The following paragraphs describe how to configure ISD tests in the software for both the SMU and PMU.

SMU Current Spectral Density vs Frequency

The ***SMU Current Spectral Density (smu-isd)*** test in the Clarius Library derives the ISD as a function of the frequency from the current and time measurements taken by an SMU.

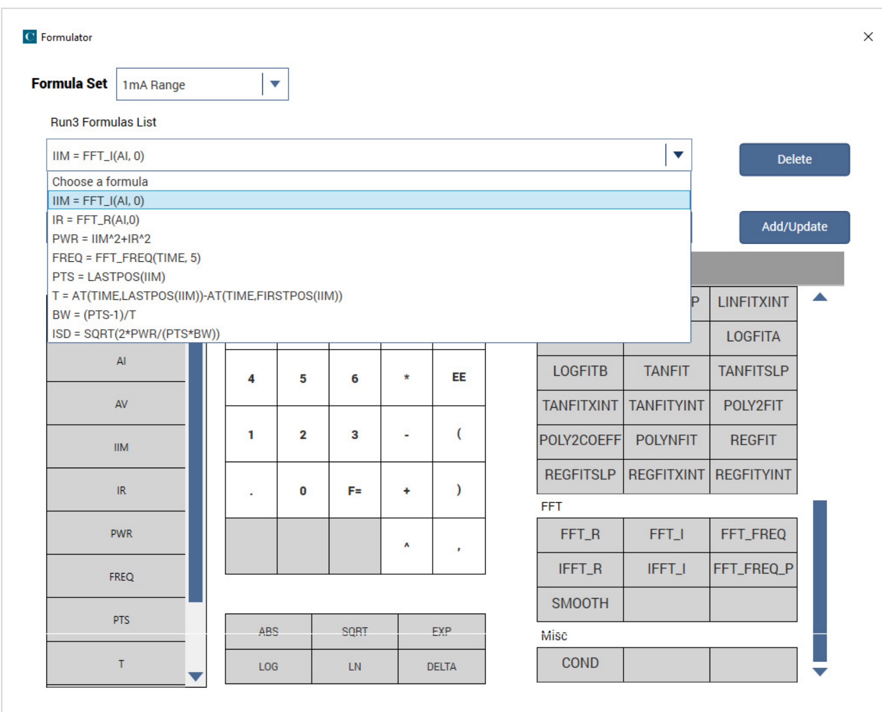


Figure 4. Formulas for the *smu-isd* test.

This test can be added to a project tree by searching for ***smu-isd*** in the Test Library and then adding it to the project tree. This test measures open circuit current on three different current ranges using the Normal speed mode. In the Formulator, FFT equations derive the real and imaginary components of the current, power, frequency, bandwidth, and ISD as shown in the screen capture in **Figure 4**. The specific details of the FFT functions in the Formulator are described in Appendix A.

Because the current is measured with an open circuit, the noise floor of the SMU is determined with this test. The frequency will change depending on the timing settings.

The calculations derive the current noise density which is measured in A/sqrt(Hz). This is not the same as the noise of a single DC measurement which is measured in amps. Expressed in terms of numerical Fast Fourier Transformation, the current spectral density is defined here as:

ISD = sqrt((2*PWR)/(PTS*BW))

where: PWR is the current amplitude squared, or PWR = Im(I)^2 + Re(I)^2

IIM = imaginary component of current Fourier component calculated with FFT

IR = real component of current Fourier component calculated with FFT

BW is the bandwidth of the time sampling

PTS is the number of points, which should be a power of 2

Bandwidth (BW) is defined as 1/dt, where dt is the time step between two measurements, assuming the time step between all measurements is a constant value.

From this test, the power spectral density (PSD) can also be derived by adding the following equation into the Formulator:

PSD = (2*PWR)/(PTS*BW)

Figure 5 shows a graph generated using this test to measure open circuit current noise at 0 V on four different ranges: 100 mA, 1 mA, 1 µA, and 1 nA. Instead of the Normal speed mode used by default in this test, the Custom Speed mode was used. The Custom speed mode enables the user to further define the timing parameters.

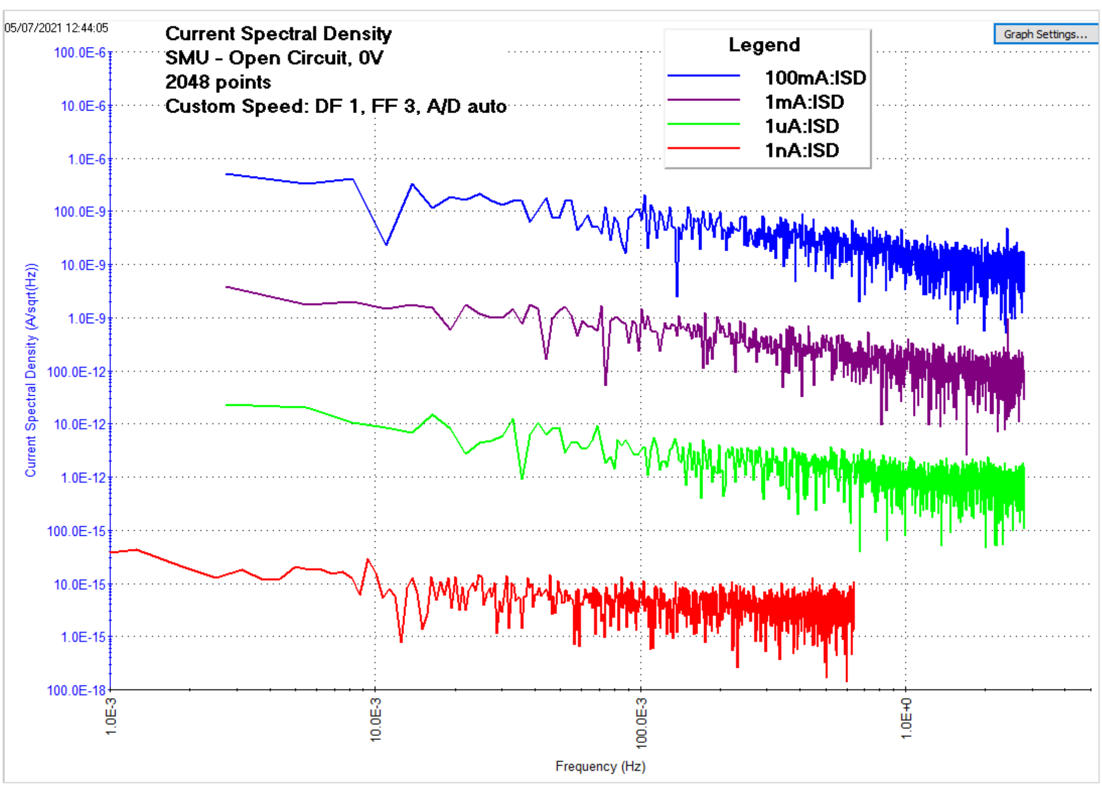


Figure 5. Current spectral density vs frequency of open circuit current data from SMU.

The SMU measurement speed is controlled in the Test Settings Window. By adjusting parameters in the Custom Speed mode, the sampling rate changes which defines the bandwidth. Even though the measurement time cannot be set for SMUs directly, the time, bandwidth and test frequencies can be measured, calculated and returned to the Sheet. By increasing the sampling rate, the noise will stay nearly constant, however the ISD curve will shift either left or right on the Frequency axis depending on if the sampling rate is increased or decreased.

Usually when setting the speed modes, there is a trade-off between the speed and noise of each measurement. The faster the measurement speed, the higher the noise will be. Measurements taken with a slower sample rate would result in smaller bandwidth and lower noise.

The readings in this test were taken on a fixed current range. Using a fixed range, and not Auto Ranging, is important to keep the measurement time constant for each reading which is required for FFT calculations.

The Sampling test mode is used because a constant bias is forced. In this mode, the number of readings must be entered. Even though a large number of readings are desirable when using FFT calculations, it's not practical. In this example, 2048 readings were taken since 2048 is a power of 2. Using the FFTs will automatically reduce the number of readings to the next lowest power of 2. **Table 1** lists the formulas used for the ***smu-isd*** test.

Table 1. Formulas for the *smu-isd* test.

Formula	Description
IIM	Imaginary current array: IIM=FFT_I(AI,0)
IR	Real current array: IR=FFT_R(AI,0)
PWR	Power: PWR=IIM^2 + IR^2
FREQ	Frequency array: FREQ=FFT_FREQ(TIME, 5)
PTS	Total number of points (of FFT calculated data): PTS=LASTPOS(IIM)
T	Total test time (of FFT calculated data): T=AT(TIME, LASTPOS(IIM))-AT(TIME,FIRSTPOS(IIM))
BW	Bandwidth: BW=(PTS-1)/T
ISD	Current spectral density: ISD=SQRT((2*PWR)/(PTS*BW))

PMU Current Spectral Density vs Frequency

Just like the SMU, the ISD of the PMU can also be derived from current and time measurements and FFT calculations. A test, ***pmu-isd***, that calculates the PMU current spectral density with an open circuit can be found in the Test Library and added to a project tree. This test was generated by using the ***PMU_sampleRate*** user module in the ***PMU_freq_time_ulib*** user library. However, the ***PMU_SMU_sampleRate*** user module in the same user library can also be used for this test. With this test, the user can input a voltage bias for both CH1 and CH2, select a current range for CH2, and specify the total test time and sample rate. A screen capture of the Configure view of the ***pmu-isd*** test is shown in **Figure 6**.

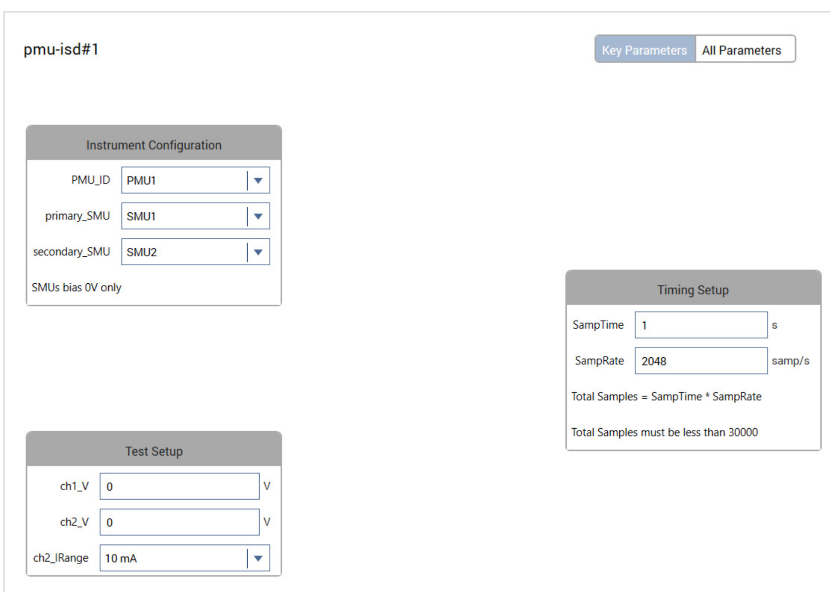


Figure 6. Configure view of the *pmu-isd* test.

Like the SMU Current Spectral Density test, the Formulator has several equations to derive the bandwidth, real and imaginary components of the test current, power, frequency, and the current spectral density. These formulas with descriptions for the ***pmu-isd*** test are listed in **Table 2**. Information on timing, range, number of points and other settings are similar to those described for deriving the SMU Current Spectral Density.

A screen capture showing graphs of the current spectral density vs frequency on the 100 nA, 100 µA and 10 mA ranges of the PMU is shown in **Figure 7.** Because the data was taken with an open circuit, this illustrates the calculated PMU noise on a fixed current range taken at a specified sample rate (SampRate) and total test time (SampTime).

Table 2. Formulas for the PMU spectral density test.

Formula	Description
IIM	Imaginary current array on CH2: IIM=FFT_I(MEASI_CH2,0)
IR	Real current array on CH2: IR=FFT_R(MEASI_CH2,0)
PWR	Power: PWR=IIM^2 + IR^2
FREQ	Frequency array: FREQ=FFT_FREQ(TIMEOUTPUT, 20)
PTS	Total number of points (on FFT calculated data): PTS=LASTPOS(IIM)
T	Total test time (on FFT calculated data): T=AT(TIMEOUTPUT, LASTPOS(IIM))- AT(TIMEOUTPUT, FIRSTPOS(IIM))
BW	Bandwidth: BW=(PTS-1)/T
ISD	Current spectral density: ISD=SQRT(2*PWR/(PTS*BW))

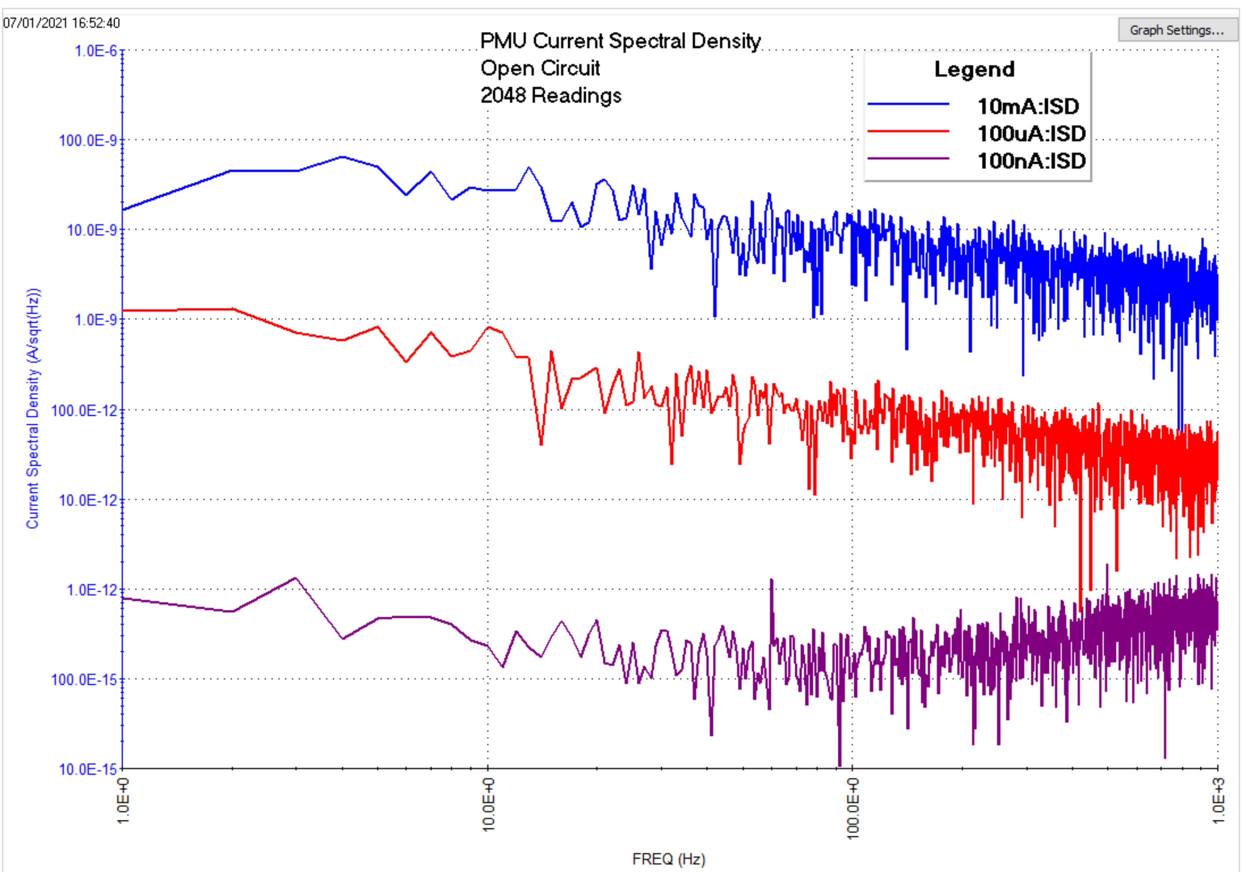


Figure 7. PMU current spectral density.

For the ***pmu-isd*** test, the voltages on CH1 and CH2 were both set to 0 V. In the Configure view, the user inputs the total test time and the sampling rate. The number of points is equal to the sample rate times the total test time. Choose input parameters so that the total number of points is a power of 2 since FFT computations will be performed on the data. For best results, a minimum of 512 and a maximum of 4096 points work best. For the curves generated in the example, a sample time of 1 second and a sample rate of 2048 samples/second were used. These numbers can be adjusted to change the frequency as explained in the next section.

Setting the Minimum and Maximum Test Frequency

When tests are created using either the ***PMU_sampleRate*** or ***PMU_SMU_sampleRate*** user module, the minimum and maximum test frequency can be determined from the total test time and the total number of samples.

The minimum test frequency is derived from the inverse of the maximum total test time (SampTime):

$$Freq_{min} = 1/SampTime$$

For example, if the total test time is 100 seconds, then the minimum frequency =

$$Freq_{min} = 1/100 = 10 \text{ mHz}$$

The maximum test frequency is derived from the sample rate or the number of samples per second. According to the Nyquist theorem, the highest frequency that can be obtained from a particular sample rate is found by dividing that sample rate by two. For example, if the sample rate is 1024 samples/second, then the maximum frequency is 512 Hz.

Expanding the Frequency Range by Adjusting the Sample Rate and Test Time

When using the ***PMU_sampleRate*** or ***PMU_SMU_sampleRate*** user modules, multiple test Runs can be used to expand the frequency range on the graph since each test will have its own sample rate. For example, the data graphed in **Figure 8** combines the data of 5 different tests of open circuit measurements taken on the 100 nA PMU range. Each test had 1024 points but were executed with different test times and sample rates. **Table 3** lists the color of each run, total test time, sample rate, and range of test frequency for the graph. By adjusting the timing parameters and checking multiple Runs in Run History, you can expand the frequency range on the graph.

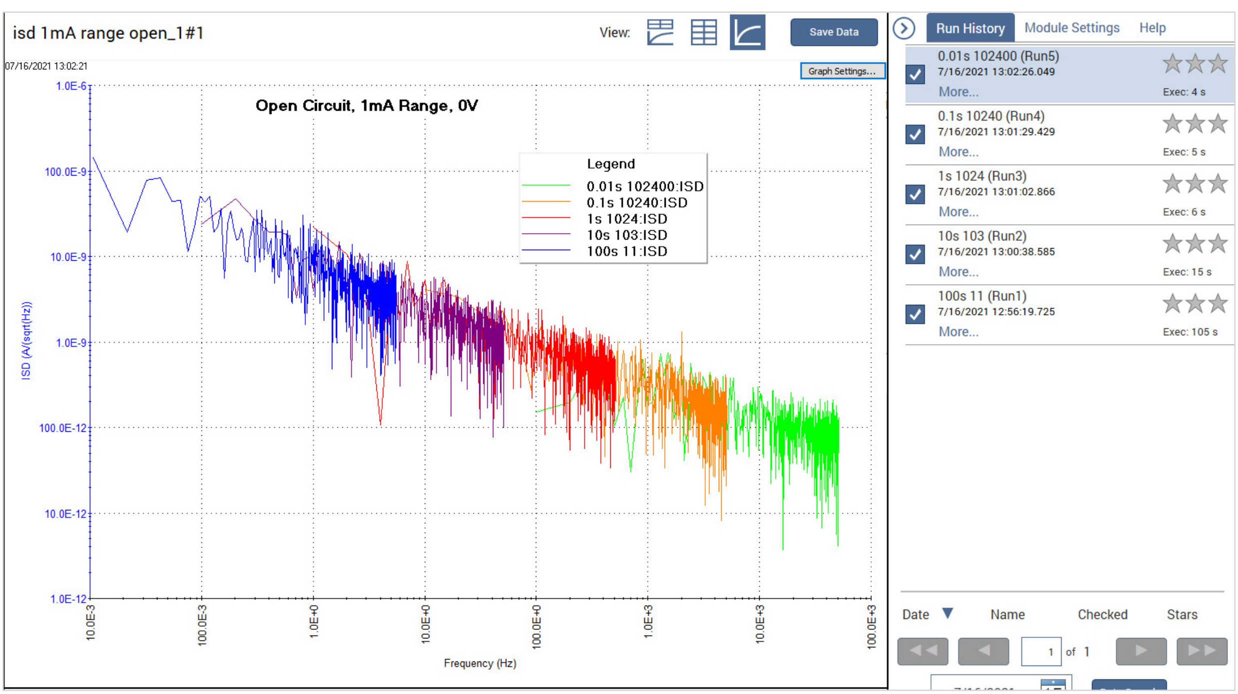


Figure 8. Checking multiple runs to expand frequency on the graph.

Table 3. Timing parameters for graph in Figure 8.

Run #	Graph Color	Total Test Time (s)	Sample Rate (samples/s)	Frequency Range (Hz)
Run 1	Blue	100	11	0.01–5.5
Run 2	Purple	10	103	0.1–51
Run 3	Red	1	1024	1–512
Run 4	Orange	0.1	10240	10–5120
Run 5	Green	0.01	102400	100–51200

Determining 1/f Noise of the Drain Current of a MOSFET

The Clarius library includes a test that determines the 1/f noise of the drain current of a MOSFET. This test, ***mosfet-isd***, uses the SMU to bias the gate and a PMU to bias the drain and measures the resulting drain current. The voltage source of the SMU will have lower noise than the PMU, but the PMU can measure current faster than the SMU. Keep in mind that any noise on the gate will be amplified and measured by the ammeter connected to the drain.

A circuit diagram for using the ***mosfet-isd*** test is shown in **Figure 9**. An SMU is connected to the gate and a PMU is connected to the drain. The source and bulk terminals are connected to the GNDU which outputs 0 V.

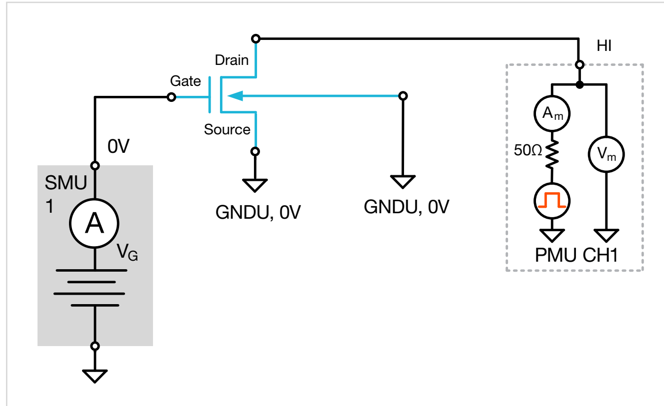


Figure 9. Applying gate voltage with an SMU and measuring drain current with a PMU.

To enable these measurements, the ***mosfet-isd*** test can be copied from the Test Library into a project tree. This test was created using the ***PMU_SMU_sampRate*** user module in the ***PMU_freq_time_ulib*** user library. The configure view of this test is shown in **Figure 10**. In this test, the user sets the PMU channel, SMU number, PMU and SMU voltage outputs, the PMU current range, the total test time, and the sampling rate.

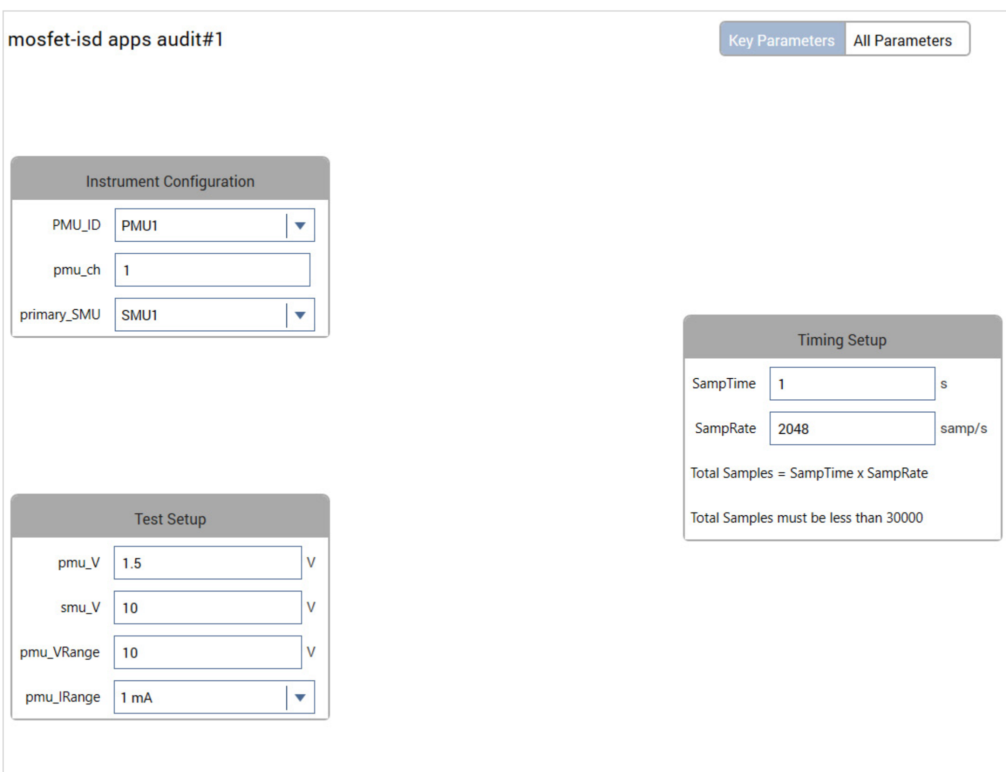


Figure 10. Configure view of the *mosfet-isd* test.

In this test, both the SMU and PMU output a constant voltage while the PMU measures a current at the configured sampling rate for the specified time-period. The resulting current and time are returned to the Sheet and equations in the Formulator convert the time-based measurements into frequency-based measurements using FFT equations. In particular, the current spectral density (ISD) and frequency are calculated. The results of measuring the drain current noise on a MOSFET are shown in **Figure 11**.

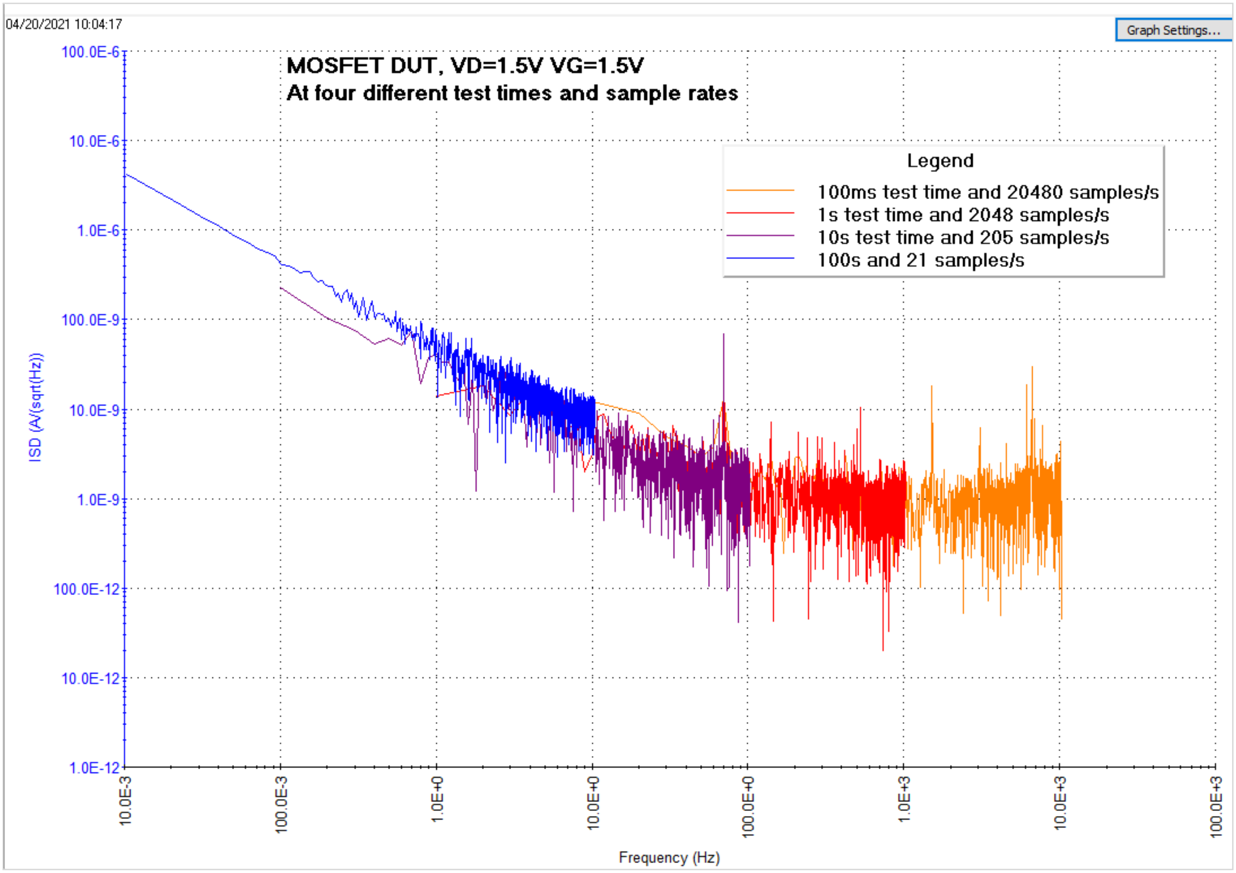


Figure 11. MOSFET drain current ISD vs frequency.

As an alternative, SMUs can be used to bias the gate and measure the drain current as shown in the configuration in **Figure 12**. The Source and Bulk terminals are connected to the GNDU. Depending on the timing settings and current range, the bandwidth can be in the range of approximately 1 mHz to <50 Hz. The SMUs have 6½-digit resolution. This test can be easily generated using a new ITM to configure the SMUs and adding FFT formulas to convert the current measurements into the frequency domain.

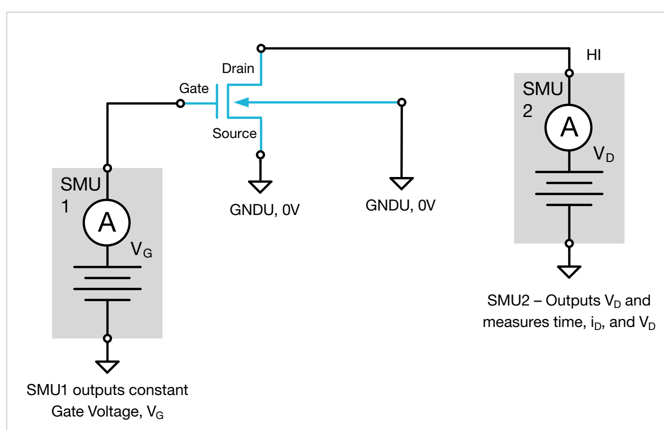


Figure 12. Connecting two SMUs to the gate and drain of a MOSFET.

As an alternative for higher bandwidth, two PMU channels can be used to measure the 1/f drain current noise as illustrated in the example in **Figure 13**. PMU CH1 applies a voltage bias to the gate and PMU CH2 applies the drain voltage and measures the drain current and time. The source and bulk terminals are connected to the GNDU or two SMUs forcing 0 V. For this example, use the ***pmu-isd*** test as previously described.

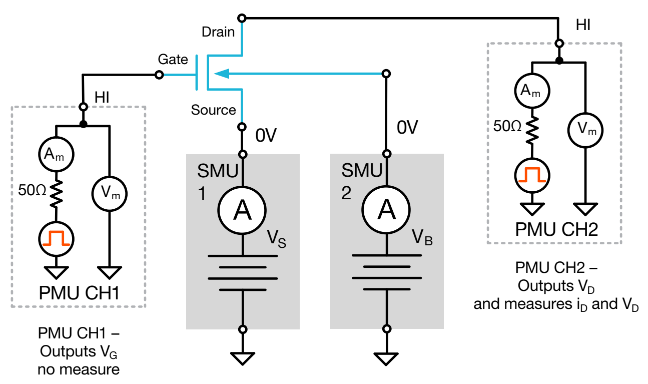


Figure 13. Using two PMU channels to source Gate voltage and measure Drain current and time.

Configuring 1/f Noise Measurements on Two-Terminal Devices

The 1/f noise can also be derived on two-terminal devices. The following paragraphs explain how to configure these measurements on a diode.

Only one SMU is needed to test a two-terminal device as shown in **Figure 14**. In this example, the SMU is connected to the anode of the diode and the ground unit (GNDU) is connected to the cathode. The SMU biases the diode and measures the resulting current and time. To derive the ISD, the ***smu-isd*** test from the library can be used.

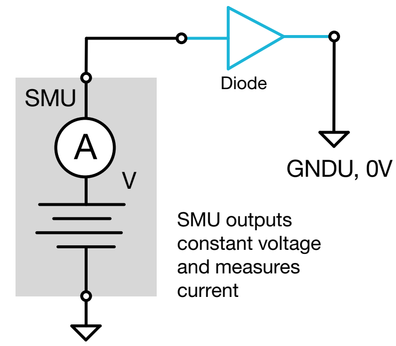


Figure 14. Using a single SMU to source a constant voltage and measure the DC current and time.

Another method is to use an SMU to apply a voltage and the PMU to measure the resulting current. In this case, the voltage source of the SMU will have lower noise than the PMU, but the PMU can measure current faster than the SMU so it can obtain higher frequencies.

In the example in **Figure 15**, the SMU is connected to the anode of the diode and supplies a voltage. PMU CH1 is connected to the cathode and measures the resulting current and time. To use this configuration, create a new Custom Test (UTM). In the Configure view, select the ***PMU_SMU_sampleRate*** user module in the ***PMU_freq_time_ulib*** user library.

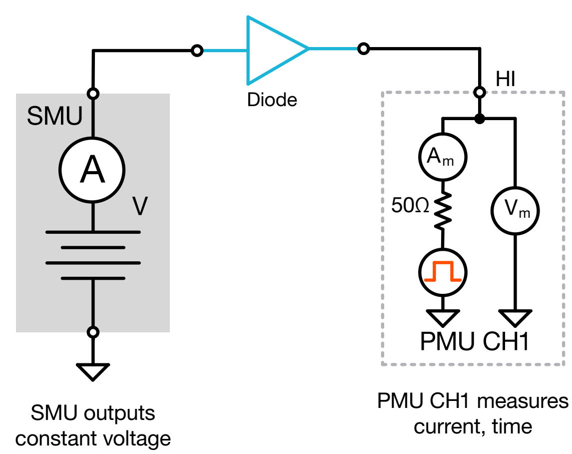


Figure 15. Biasing and measuring diode current with an SMU and PMU.

Finally, the third method uses two PMU channels to source voltage and measure current. This method has the highest bandwidth but also has the highest amount of noise. **Figure 16** shows two PMU channels connected to either side of a diode. PMU CH1 forces a constant voltage and PMU CH2 measures the resulting current and time. The pmu-isd test in the Library can be used to implement this configuration.

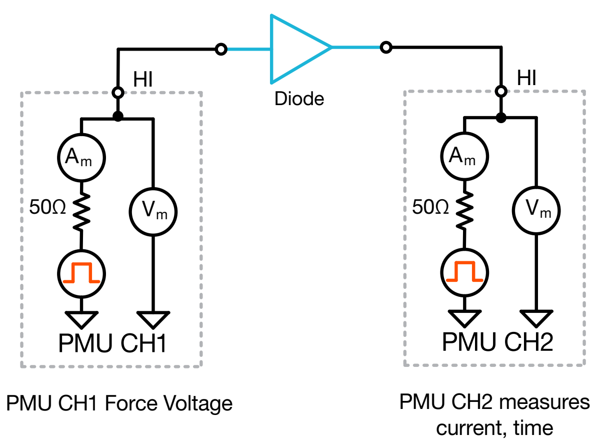


Figure 16. Using two PMU channels to measure diode current.

Conclusion

Both the PMU and SMU can be used to make 1/f noise measurements on devices depending on the required noise levels and frequency. The user can verify the noise floor of a particular test configuration using an open circuit and the provided library tests. The build-in tests and FFT functions are used to convert the time domain measurements into the frequency domain. This enables the user to get important test results much faster since the data no longer needs to be downloaded and analyzed in a separate tool.

Appendix A

FFT Related Functions in the Clarius Formulator

The Clarius software has a built-in Formulator that enables the user to make calculations on test data and on the results of other Formulator calculations. The Formulator provides a variety of computational functions, common mathematical operators, and common constants. Beginning with the Clarius V1.9 release, FFT formulas have been added to the Formulator. A screen capture of the Formulator with the FFT functions is shown in **Figure 17**.

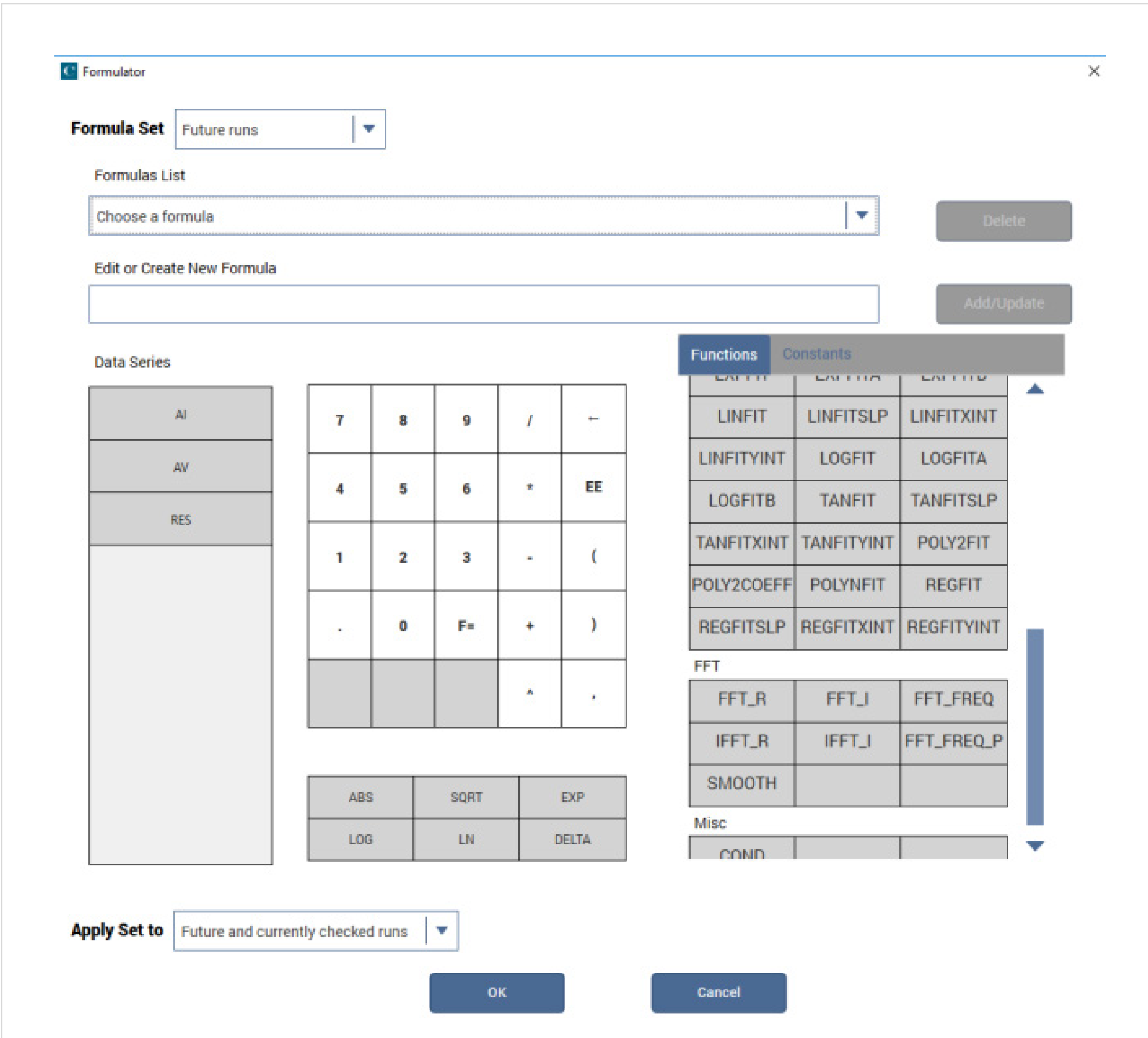


Figure 17. FFT functions in the Formulator in the Clarius software.

The built-in FFT functions and their descriptions are listed in **Table 4**. These equations can perform an FFT or an inverse FFT on real and imaginary input arrays and then output the real or imaginary components. Two of the formulas return an array of frequencies from an input time array. A smooth function uses digital filtering on an input array by zeroing out high frequency components.

Table 4. FFT formulas and descriptions.

Formula	Description
FFT_R(Real, Imag)	Performs an FFT on the provided real and imaginary input arrays and then outputs the real components of the calculated FFT.
FFT_I(Real, Imag)	Performs an FFT on the provided real and imaginary input arrays and then outputs the imaginary components of the calculated FFT.
IFFT_R(Real, Imag)	Performs an inverse FFT on the provided input arrays and then returns the real parts scaled by 1/N where N is the number of samples.
IFFT_I(Real, Imag)	Performs an inverse FFT on the provided input arrays and then returns the imaginary parts scaled by 1/N where N is the number of samples.
FFT_FREQ(Time, Tolerance)	From an input time array, returns an array of frequencies that correspond to the frequencies of the FFT output
FFT_FREQ_P(Time, Tolerance)	From an input time array, returns an array of positive only frequencies that correspond to the frequencies of the FFT output
Smooth(X, Percent)	Performs digital filtering on an input array by zeroing out high frequency components.

When using the FFT formulas, its best to take data in evenly spaced time intervals. When converting a time array into an array of frequencies, the FFT_FREQ function enables the user to enter a tolerance parameter to determine if the consecutively spaced time data is evenly spaced. If the delta, expressed in percentage, between two points in the input time array is greater than the tolerance value, #REF will be returned to the Sheet.

The output size of the calculated real and imaginary data arrays will be a power of 2. As a result, the ideal number of acquired data points should be a power of 2 such as 64, 128, 256, 512, 1024, etc. If the number of data points is not a power of two, the returned number of points will be reduced to the next lowest power of two.

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