Making Fuel Cell ac Impedance Measurements Utilizing Agilent N3300A Series Electronic Loads

Product Note

Agilent electronic loads simplify acquisition of measurement data

Making ac impedance measurements on fuel cells can help identify problems with the fuel cell components and help identify deviations in the fuel cell assembly process. When multiple impedance measurements are made at various frequencies, the results can be plotted across the frequency band resulting in an Electrochemical Impedance Spectroscopy (EIS) measurement. Agilent electronic loads have several features that help to simplify this measurement process. This Product Note discusses a method to make use of the Agilent electronic loads in conjunction with some other readily available equipment to make ac impedance measurements on fuel cells.

Why make ac impedance measurements?

Making ac impedance measurements on fuel cells is important for several reasons. These measurements help identify the kinetic resistances in the fuel cell system, the ohmic resistances in the system (e.g., electrolyte, contact, porous layer resistance), and the transport limitations of the reactant. Fuel cell components affecting the impedance value can include current collectors, porous electrodes, the catalytic layer, and the membrane. The impedance measurements can help identify both problems with the fuel cell components and deviations in the fuel cell assembly process.

Method used for making the fuel cell ac impedance measurements

A method to make an ac impedance measurement on a fuel cell that is producing dc current is to first stimulate the fuel cell with a low level sinusoidal ac current at a particular frequency and then measure both the stimulating ac current and the resultant ac voltage. Measurement instrumentation can be used to acquire the ac voltage and current waveform data. The data can then be read back from the instrumentation to a personal computer, after which any suitable math package can be used to perform a Fast Fourier Transform (FFT) on the data of each waveform. Finally, complex math functions can be used to divide the transformed voltage by the transformed current to obtain the complex impedance (both magnitude and phase). This process can be repeated at any frequency within the capabilities of the equipment being used resulting in a full spectrum of impedance measurements on the fuel cell, or an Electrochemical Impedance Spectroscopy (EIS) measurement.

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Equipment required to make ac impedance measurements on the fuel cell

This ac impedance measurement can be made with an appropriately featured electronic load, a function generator, and a personal computer (PC) loaded with the right software. Optional equipment consists of a boost power supply and/or additional loads with fewer features. See Figure 1 for the equipment setup. Note that this setup can also be used for measuring the fuel cell polarization curve or V-I characteristic.

Electronic load and function generator
A specific example of the method mentioned above would be to use an Agilent N3300A series electronic load to provide three of the necessary functions mentioned in the measurement process.

- First, the load can draw dc current from the fuel cell at the desired operating point.
- Second, the load can facilitate the ac current stimulation by using an external function generator to drive the external programming input on the load.
- Third, the load itself can be used to measure the fuel cell ac current and voltage since it has the ability to digitize the waveforms. This ac waveform data can then be transferred through GPIB from the load to a personal computer (PC) for analysis.

The function generator must have the ability to produce a sine wave and have accurate frequency control in order to ensure accurate FFT results. An excellent choice would be the Agilent 33120A.

Agilent N3300A series electronic loads are uniquely qualified to facilitate this measurement process. The primary features that enable these loads to aid in this measurement process are:

1. **Constant current mode (also has constant voltage and resistance modes)**
   Sets the fuel cell dc current operating point at which the ac measurement will be made. This is the programmed dc setting of the electronic load.

2. **External programming input (also called "analog" programming)**
   By using an externally generated sine wave (for example, from a function generator), this feature provides the ability to superimpose a sinusoidal stimulus signal on the programmed dc setting of the electronic load. The bandwidth of the added signal can be from dc to 10 kHz when operating the load input at or above 3 V (the bandwidth is reduced to 1 kHz below 3 V). Scaling is as follows: 0 to 10 V on the external programming input corresponds to 0 to full scale

current on the load input. Note that the input impedance of the external programming input is about 511 kΩ. Although the voltage on this input can go negative, note that the total load input current cannot go below 0 A since these loads are unipolar. The external programming input is accessed from a connector on the rear of the load.

3. **Synchronized input V and I waveform digitization**
   Precise synchronization of the acquisition of the V and I waveforms is a necessary condition for the FFT analysis to work properly. Agilent N3300A series electronic loads digitize their input voltage and input current waveforms virtually simultaneously. Acquisition of the data is precisely timed due to the highly accurate crystal used in the digitization process. The sample rate is user controlled and ranges from 10 µs to 0.032 s. It can be incremented by 10 µs increments. The number of data points acquired for the waveforms can be set between 1 and 4096.

4. **Remote voltage sense**
   This feature enables the user to connect the load's voltage measurement sensing inputs exactly to the points of interest on the fuel cell for accurate voltage measurements. Note that up to a 5 V
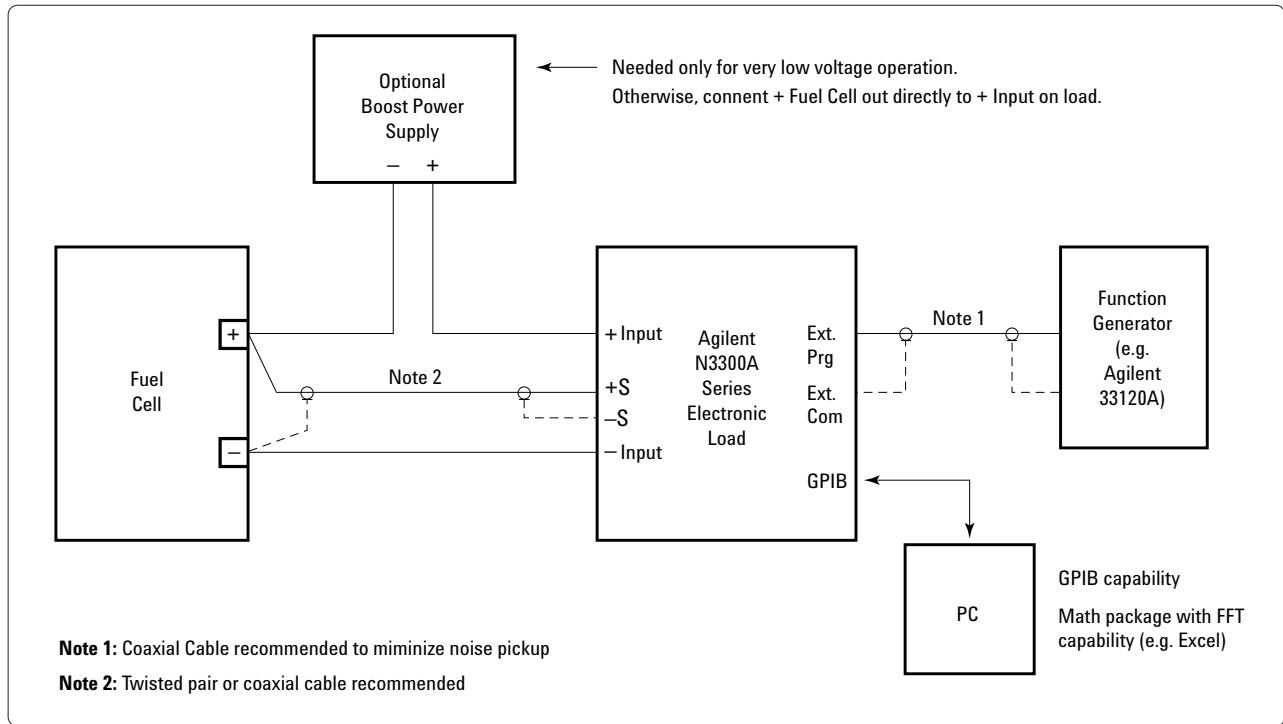
Figure 1. Equipment Set-up

difference is allowed between the sense terminals and the load input terminals. Also note that there is a push-button local/remote sense switch on the back of each load module; for remote voltage sensing, this switch must be in the "out" position or "RMT" position.

5. Low voltage operation
Agilent loads can draw current all the way down to 0 volts on their inputs. The amount of current they can draw is linearly derated from full rated current at 2 V on the input terminals down to 0 A at 0 V on the input terminals. Stacked fuel cells are typically more than 2 V, however, single fuel cells

typically operate below 1 V. Therefore, if more current capability than is available at this voltage is required from the load, it is possible to put a power supply in series with the fuel cell in order to boost the total load input voltage[1]. Remote voltage sensing can still be done at the fuel cell (see note regarding remote voltage sense above). To meet a higher current demand at lower voltages, it is also possible to use a load that is rated for a higher current since this load will be able to draw more current at lower voltages even without a boost supply. Note that the bandwidth of the load input is 10 kHz at and above 3 V, and 1 kHz below 3 V.

6. Parallel operation
If more current is required from the fuel cell than one load module can handle, Agilent loads can be placed in parallel in order to increase the total current capability. Only one of the paralleled loads would need to be used for the ac imped-ance measurement as the others would simply be used to draw extra dc current. In fact, an Agilent load could be placed in parallel with another vendor's load to facilitate the ac impedance measurement described here assuming that the parallel load is not impacted by the effect of the ac stimulus.

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[1]   See Agilent Product Note "Agilent Zero Volt Electronic Load" at www.agilent.com/find/loads
     for more information about operating electronic loads at low voltages.

The process for making the ac impedance measurement

Personal computer

To communicate with common test equipment, the PC would require GPIB capability (RS-232 could be used, but is much slower). Additionally, the PC would require a math package capable of FFT analysis. Microsoft Excel® with the Fourier Analysis tool loaded (from Analysis ToolPak Add-Ins) can be used for this purpose. Excel can also be used to acquire the measured waveform data directly from the load by utilizing the built-in Visual Basic® programming capability. The electronic load VXI*plug&play* driver must also be installed in order to communicate with the load via GPIB.

Optional equipment

Other optional equipment would include a boost power supply (needed only when testing fuel cells below 2 V if more current capability than is available at the test voltage is required from the load) and additional loads (to draw more dc current from the fuel cell).

First, it will be useful to review the overall measurement method. Refer again to Figure 1 for the equipment setup.

Overall measurement method

1. With the fuel cell connected to the load, set the dc operating point

2. Set the 33120A function generator to the frequency at which an impedance measurement will be made, and for a sine wave output at an appropriate magnitude

3. Digitize the fuel cell voltage and current waveforms with the load

4. Read the digitized waveform data from the load to the PC

5. Perform an FFT on both the voltage and current waveform data

6. Divide the FFT voltage data by the FFT current data to get the complex impedance

7. In the complex FFT impedance data, look up the resultant measured impedance at the desired frequency

8. Repeat steps 2 through 7 at all frequencies of interest to obtain an EIS plot

Implementation of the majority of these eight steps is straightforward. The only exception is the selection of a setting for the function generator test frequency (step 2) since it is affected by some important factors related to FFT data analysis that need to be considered before making this measurement.

Before discussing these important factors and the selection of the test frequency setting, a few definitions relating to the measurements and FFT analysis are in order. These are as follows:

N = number of samples taken (set with load)

t_s = sample time = time between samples (set with load)

f_s = sample frequency = $1/t_s$ (= $N*f_{bin}$; indirectly set by load t_s)

t_w = sample window = total time during which samples are taken = $N*t_s$ (indirectly set by load N and t_s)

f_{bin} = bin frequency = $1/t_w$ = $1/(N*t_s)$ = f_s/N (indirectly set by load N and t_s)

f_{tst} = test frequency = frequency at which test is run (set with function generator). f_{tst} can be any integer multiple of f_{bin} between f_{tstmin} and f_{tstmax}

$f_{tstmin} =$ minimum test frequency = lowest frequency at which test can be run = f_{bin}

$f_{tstmax} =$ maximum test frequency = highest frequency at which test can be run = $f_{bin}*(N/2) = 1/(2*t_s) = f_s/2$

The important factors to consider related to FFT data analysis are as follows:

Important factors to consider when using this method

a) The FFT requires N to be an integer power of 2. Therefore, the load must be set to capture waveform data with a number of points (N) that is an integer power of 2, namely 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024, 2048, or 4096 (note that the number of samples that can be taken with the load is from 1 to 4096).

b) Discrete sample times (t_s) are available from the load resulting in discrete sample frequencies (f_s). As mentioned earlier, the load sample rate can be adjusted between 10 µs and 0.032 s in 10 µs increments.

c) f_{tst}, the test frequency, must be an integer multiple of f_{bin}, the bin frequency. Otherwise, spectral leakage will occur causing inaccuracies in the results of the FFT calculation.

d) The Excel FFT function acting upon N points in a waveform array returns an array consisting of a dc value followed by N sets of complex numbers representing ac magnitude and phase values. After the dc value, the first N/2 ac values in the FFT array are the significant results that are then repeated as a mirror image in the second N/2 values.

e) The dc value returned by the Excel FFT function must be scaled[1] by dividing by N.

f) The ac values returned by the Excel FFT function must be scaled[1] by dividing by N/2 and represent the peak of the sinusoid (divide by √2 to get rms values for the magnitudes).

Now, a sample procedure to obtain a valid setting of the test frequency for step 2 of the overall measurement method above can be discussed:

Sample procedure to obtain setting for the test frequency[2]
(for step 2 of overall measurement method)

1. Select the desired test frequency (= f_{des}). Note that the actual test frequency, f_{tst}, could end up being slightly different than f_{des} due to the discrete sample frequencies available from the load.

2. Select N

3. Multiply f_{des} by N

4. Take the reciprocal of the result to get the desired sample time

5. Round this result to the nearest 10 µs due to the quantized load sample rates

6. Take the reciprocal of the result

7. Divide the result by N to get f_{tst}, the actual test frequency, to be programmed in the function generator (using this procedure, this frequency also happens to be f_{bin}, the bin frequency)

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[1] Note that a package other than Excel in which an FFT operates may scale the FFT returned values differently than Excel

[2] See Appendix A for a further discussion regarding the selection of a test frequency

ac impedance measurement example

To demonstrate the overall measurement method of ac impedance measurements with a real example, a known test impedance was inserted in series with the output of a power supply. See Figure 2. The previously described method was used to measure the total series impedance, which was determined nearly entirely by the test impedance since the output impedance of the power supply at the test frequency is much lower than the test impedance itself. The test impedance chosen was 0.49 Ω in series with 796 µH, and the desired test frequency was 50 Hz. dc settings for the power supply voltage and load current were arbitrarily chosen to be 5 V and 2 A, respectively.

Applying the sample procedure steps above in this example to first determine the actual test frequency results in the following:

1. f_{des} = 50 Hz
2. N = 256 (set on load)
3. f_{des}*N = 50*256 = 12800 Hz
4. 1/12800 = 78.125 µs
5. Round 78.125 µs to 80 µs (= t_s; set on load)
6. 1/80 µs = 12500 Hz (= f_s)
7. 12500/256 = 48.828125 Hz (= f_{tst} = actual test frequency. Set on function generator. Also equals f_{bin} for this method.)
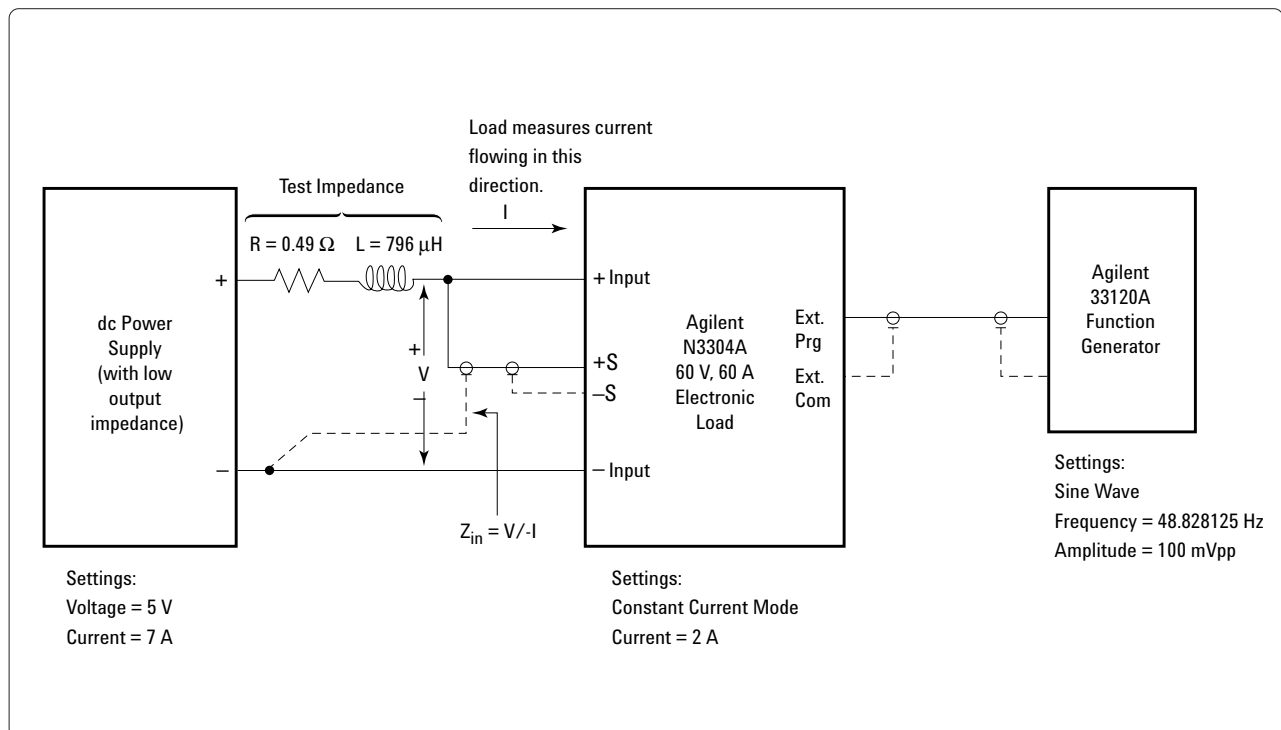

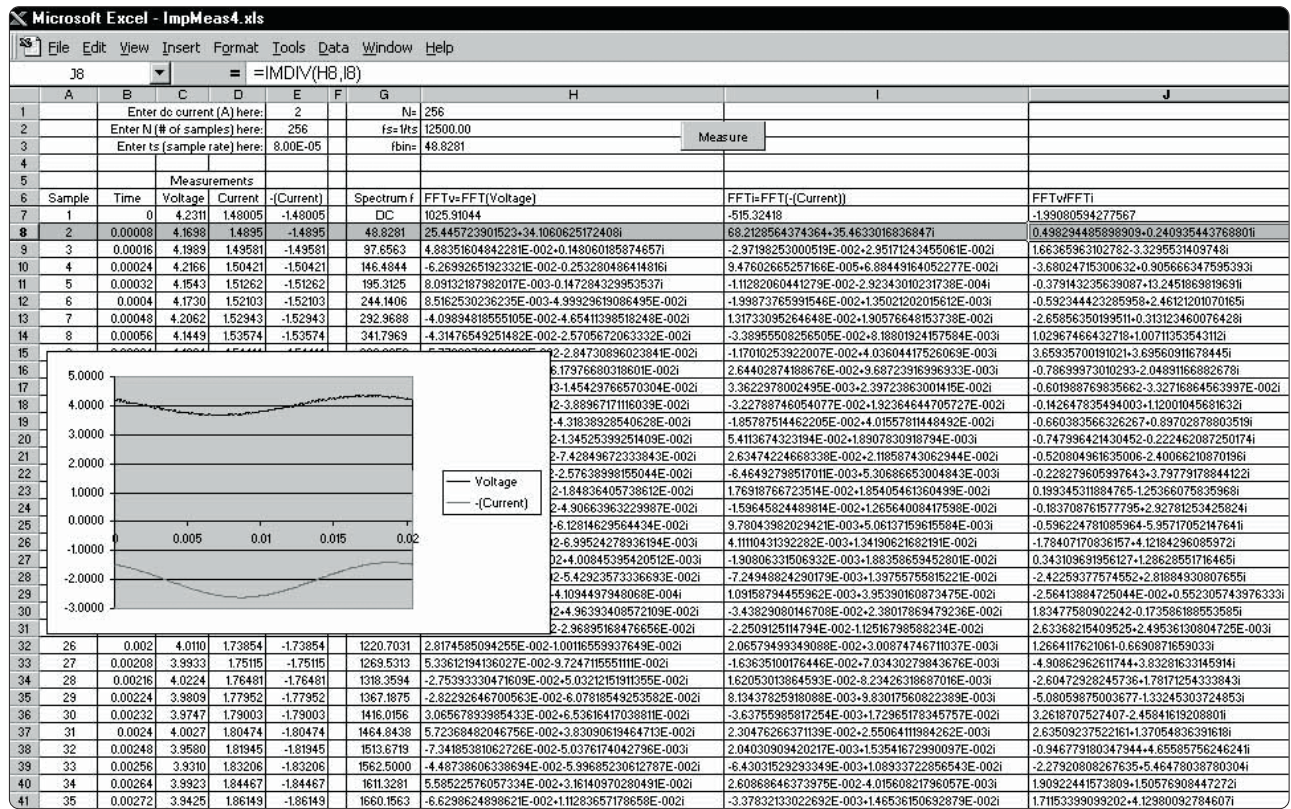**Figure 2.** Example Impedance Measurement Test Set-up

Figure 3. Excel Spreadsheet Showing Load Waveform Measurements and FFT Calculations

With the test frequency set on the 33120A, an arbitrary magnitude for the sine wave output was chosen to be 100 mV peak-to-peak. Note that the 33120A function generator and many other function generators are designed with a 50 ohm output impedance and are expecting to drive 50 ohms. Since the external programming input on the load is significantly higher than 50 ohms, the actual output voltage of the 33120A will be twice the programmed value, or 200 mV peak-to-peak.

A Visual Basic program in an Excel spreadsheet was used to control the load and make the waveform measurements utilizing VXI*plug&play* commands. In the program, a triggered measurement on the load using N and t_s from above was configured and executed resulting in the load digitizing the voltage and current (with AgtN330X_configureTriggered Measurement and AgtN330X_trigger commands). Then, the digitized voltage and current waveform data was read back to the PC (with AgtN330X_fetchArray commands).

Figure 3 shows part of the Excel spreadsheet displaying the measured results from the load for the known test impedance and the subsequent FFT calculations. Columns C and D were populated with the actual voltage and current data points (256 for each) read back from the load. Note that the load measures current flowing *into* its positive input terminal, which is equal to the current flowing *out of* the test impedance (or fuel cell). To make the ac impedance measurement, the current flowing *into* the test impedance (or fuel cell) is the needed current, which is

simply equal to the reverse of the load current (refer again to Figure 2). Therefore, column E is equal to –(Current). The measured Voltage and –(Current) from the load are plotted in the graph.

Next, the FFT function (from Tools, Data Analysis, Fourier Analysis) was used on the 256 point Voltage and –(Current) data arrays to produce the FFT_v and FFT_i arrays in columns H and I, respectively. Finally, column J shows the complex division of the voltage by the current (IMDIV function) to arrive at the measured complex impedance. Only row 8 is of significance since it shows the measured impedance at the actual test frequency of 48.828125 Hz.

The expected measured ac impedance of 0.49 Ω (R) in series with 796 µH (L) at 48.828125 Hz (f) is 0.49 + j0.2442 (= R + j2πfL). The actual measured ac impedance result appears as 0.49829 + 0.24094i in cell J8 and correlates very well with the expected value.

This process can be automated and repeated at various frequencies to produce multiple ac impedance measurements that can then be plotted along a frequency axis to produce a full spectrum of impedance measurements. When performed on a fuel cell, the final result will be an EIS measurement.

Note that to properly evaluate the magnitudes of the individual FFT_v and FFT_i results in columns H and I, as noted earlier, it is necessary to scale the results by dividing the dc result by N and the ac results by N/2. The impedance in column J need not be scaled since when dividing FFT_v by FFT_i, the scaling factors cancel each other. As an example of the scaling, cell H7 shows the FFT transformed dc voltage as 1025.9 that needs to be scaled by dividing by N. 1025.9/256 = 4.01 V. This is the dc voltage at the load sense terminals, and the value is reasonable since the power supply was set to 5 V, had 2 A of dc current flowing through 0.49 Ω of resistance, dropping about 1 V from the 5 V. Similarly, the FFT transformed dc current is –515.324 which scales to –515.324/256 = -2.01 A, the expected current.

A more interesting calculation can be performed to substantiate the magnitude of the value in cell I8. This is the ac current resulting from the 48.828125 Hz sine wave superimposed on top of the 2 A dc load current via the function generator and load external programming input. With the function generator set at 100 mV peak-to-peak, it supplies double that voltage when terminated in a resistance much higher than 50 Ω, as is the case here. Therefore, the function generator is providing

Summary

a 100 mV peak sine wave. The Agilent N3304A load used is a 60 A full scale current load, so the 100 mV peak sine wave will produce an expected 600 mA peak sine wave in the current (load scaling on this input was discussed earlier). The FFT_i result at 48.828125 Hz is shown in cell I8 as 68.213 + 35.463i, which represents a peak magnitude of 76.88 [$= \sqrt{(68.213^2 + 35.463^2)}$] to be scaled by dividing by N/2 (= 256/2 = 128) resulting in 0.6 A, as expected. The FFT_v result can be similarly justified using the complex FFT_i result times the test impedance.

Making ac impedance measurements on fuel cells by utilizing Agilent N3300A series electronic loads can eliminate the need for other more costly equipment. Combined with a function generator, and a PC with GPIB capability and an FFT analysis package, the Agilent load provides the key stimulus and measurement functions necessary to make ac impedance measurements. Excel is a convenient package that can provide the necessary automation with GPIB control and Visual Basic programming, in addition to providing the required FFT capability. These software and hardware tools can easily be combined and utilized to make measurements across the frequency band resulting in a cost-effective solution for producing Electrochemical Impedance Spectroscopy measurements for fuel cell testing.

Appendix A

An alternate procedure for obtaining the setting of the test frequency
As part of the ac impedance measurement method described here, it is necessary to select a test frequency, f_{tst}, at which to perform the FFT. In order to avoid inaccuracies in the results of the FFT calculation due to spectral leakage, f_{tst} must be an integer multiple of f_{bin}, the bin frequency. This can be expressed as:

$f_{tst} = n*f_{bin}$ where n is an integer.

Since $f_{bin} = 1/(N*t_s)$,

$f_{tst} = n*f_{bin} = n/(N*t_s)$
(Equation 1)

The selection of f_{tst} (set on the function generator), N (set on the load), and t_s (also set on the load) must be such that Equation 1 is satisfied.

Since both N and t_s can be selected with parameters on the load, there are many combinations of N and t_s that will yield the same (or similar) f_{tst}. This is illustrated in Table 1 showing the minimum and maximum values for f_{tst} (f_{tstmin} and f_{tstmax}) for a variety of N and t_s selections on the load. Recall that t_s can be set on the load to any value between 10 µs and 0.032 s (32000 µs), but the settings are quantized in 10 µs increments. Also recall that N must be an

integer power of 2. Note that f_{tstmin} is dependent on both N and t_s, while f_{tstmax} is dependent only on t_s. Also note that the values displayed in Table 1 are rounded to 4 decimal places for ease of viewing.

As an example showing that there are multiple combinations of N and t_s that will yield the same (or similar) f_{tst}, it is possible to test at f_{tst} = 39.0625 Hz with N = 128 and t_s = 200 µs, or with N = 256 and t_s = 100 µs, as can be seen in Table 1.

f_{tst} can be any value between f_{tstmin} and f_{tstmax} that meets the requirements of Equation 1.

| ts (µs) | \multicolumn{8}{c}{Table shows f_{tstmin} = f_{bin} = 1/(N*t_s) (Hz)} | ts (µs) | f_{tstmax} = f_s/2 = 1/(2*t_s) (Hz) |

ts (µs)	32	64	128	256	512	1024	2048	4096	ts (µs)	f_{tstmax} = f_s/2 = 1/(2*t_s) (Hz)
10	3125.0000	1562.5000	781.2500	390.6250	195.3125	97.6563	48.8281	24.4141	10	50000
20	1562.5000	781.2500	390.6250	195.3125	97.6563	48.8281	24.4141	12.2070	20	25000
50	625.0000	312.5000	156.2500	78.1250	39.0625	19.5313	9.7656	4.8828	50	10000
100	312.5000	156.2500	78.1250	39.0625	19.5313	9.7656	4.8828	2.4414	100	5000
200	156.2500	78.1250	39.0625	19.5313	9.7656	4.8828	2.4414	1.2207	200	2500
500	62.5000	31.2500	15.6250	7.8125	3.9063	1.9531	0.9766	0.4883	500	1000
1000	31.2500	15.6250	7.8125	3.9063	1.9531	0.9766	0.4883	0.2441	1000	500
2000	15.6250	7.8125	3.9063	1.9531	0.9766	0.4883	0.2441	0.1221	2000	250
5000	6.2500	3.1250	1.5625	0.7813	0.3906	0.1953	0.0977	0.0488	5000	100
10000	3.1250	1.5625	0.7813	0.3906	0.1953	0.0977	0.0488	0.0244	10000	50
20000	1.5625	0.7813	0.3906	0.1953	0.0977	0.0488	0.0244	0.0122	20000	25
32000	0.9766	0.4883	0.2441	0.1221	0.0610	0.0305	0.0153	0.0076	32000	15.625

Table 1. Minimunm and Maximum Test Frequencies for a Selection of t_s and N Values

To illustrate this point, note that for N = 1024 and t_s = 1000 μs, the minimum test frequency that can be used is 0.9765625 Hz (f_{tstmin}), which is f_{bin}. The maximum test frequency for this selection of t_s is 500 Hz (f_{tstmax}). From Equation 1, with this selection of N and t_s, other valid f_{tst} values are 2*0.9765625 Hz = 1.953125, or 51*0.9765625 Hz = 49.804687 Hz, or 205*0.9765625 Hz = 200.19531 Hz or any integer multiple of f_{bin} that yields a result no greater than f_{tstmax} for this setting of t_s which is 500 Hz.

For a given value of n, the resultant magnitude and phase information of the FFT is contained in the nth ac value of the FFT data array.

Another way of viewing the application of an FFT to a sinusoidal waveform
Obtain a sinusoidal waveform array by taking N samples every t_s seconds. If the frequency of the waveform meets the requirement $n/(N*t_s)$, where n is a positive integer less than or equal to N/2, the magnitude and phase of the waveform can easily be obtained by performing an FFT on the waveform array. (An alternate way of stating the requirement is that a positive integer number of cycles of the waveform must fall within the total sample time of $N*t_s$, as long as not more than N/2 cycles fall within the total sample time.)

Since the FFT acting on an array returns an array consisting of a dc value followed by N/2 ac values, the magnitude and phase information of the sinusoidal waveform will be contained in the nth ac element of the array.

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