Verifying the Wideband Input of an AC Measurement Standard

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Abstract

This paper describes the test method used by the manufacturer of a high accuracy AC Measurement Standard to verify the flatness and gain error of its Wideband input. This input has a 50Ω input impedance and measures voltage from 700 µV to 7 V, 10 Hz to 30 MHz on eight voltage ranges. Discussed first are some issues associated with verifying an instrument with a 50Ω input impedance followed by a description of the method used to verify the AC Measurement Standard. Last is a description of the methods used to calibrate the standards used.

1. Introduction

The AC Measurement Standard described in this paper has a MAIN input and a Wideband Input. The verification of the MAIN input has been described in previous papers [1][2]. This paper describes the method used to verify the Wideband input and also the calibration of the standards used for this verification.

The Wideband input can measure AC Voltage from 700 µV to 7 V, 10 Hz to 30 MHz in eight voltage ranges. The input impedance is a nominal 50Ω and it is calibrated to correctly measure the voltage of a source that has a nominal 50Ω output impedance. Figure 1 shows such a 50Ω source connected to the AC Measurement Standard.

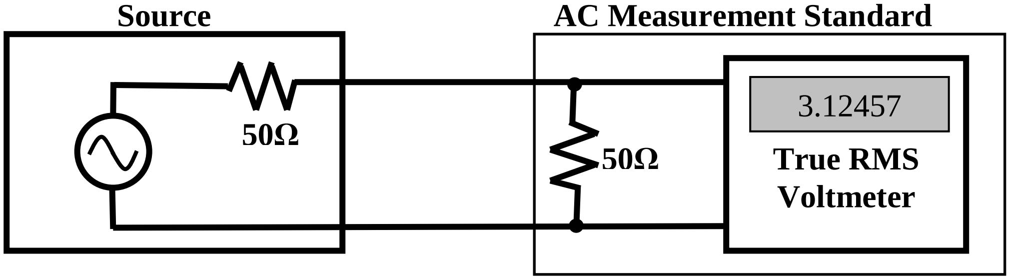

Figure 1. AC Measurement Standard connected to a 50Ω source.

The 50Ω source is modeled as a voltage source with 50Ω impedance in series with the output. The AC Measurement Standard is modeled with an input impedance of 50Ω and a high impedance AC voltmeter to measure the voltage across the 50Ω. As can be seen the output impedance of the source and the input impedance of the AC Measurement Standard form a voltage divider so the voltage at the input to the AC Measurement Standard is highly dependent on these impedances. As a result the source can be calibrated to output the correct voltage only into one impedance and there will be an error for other impedances. The same is true for the AC Measurement Standard. Since these devices are nominally 50Ω, the impedance they are calibrated to work with is exactly 50Ω. In reality the source output impedance is never exactly 50Ω and the input impedance of the AC Measurement Standard is not exactly 50Ω. In fact these impedances can be substantially off 50Ω and change significantly with frequency. But the source whose output impedance is not 50Ω can be calibrated in such a way as to output the correct voltage across 50Ω. The key to doing this is to calibrate it with a very good 50Ω load. Also the AC Measurement Standard can be calibrated so that it reads correctly even though its input impedance is not exactly 50Ω. The key to this is to calibrate it with a very good 50Ω source. Selecting equipment and the right calibration method so as to create a very good 50Ω source and load is the key to the success of the verification of the AC Measurement Standard and the calibration of the standards used to verify it.

2. Gain Error Verification

The method used to verify the AC Measurement Standard to check if it reads correctly in a 50Ω system starts by verifying each range at about mid scale at 1 kHz. This is a two step process with the setup for the first step shown in Figure 2.

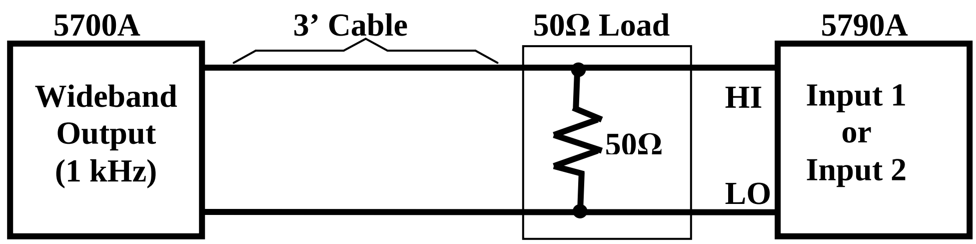

Figure 2. First step of verifying the gain error, characterizing the source.

The source for all the steps of verifying the AC Measurement Standard is the wideband output of a meter calibrator. The output impedance of this calibrator is not close enough to 50Ω to use it as is so it must first be characterized into a good 50Ω load. This load is made up special for this test. It consists of a number of metal film resistors in parallel and trimmed to be very close to 50Ω. At such a low frequency, 1 kHz, the reactance of metal film resistors is so small that it is not difficult to build such a load. The voltage across the load can be read with any AC Voltmeter that has adequate uncertainties down to 1 mV. If the input impedance of the voltmeter is too low it can load the 50Ω. If this occurs then a correction can be applied to the results to correct for this. A good choice for a meter is the MAIN input of a Fluke 5790A. Its input impedance on all the ranges that are used, except one, is >10 MΩ so it has an insignificant loading of the 50Ω. On the one range where the loading is significant, a correction can be applied.

The source is characterized at eight voltage levels, one for each range of the AC Measurement Standard. This is from 3.2 V for the 7 V range down to 1 mV for the 2.2 mV range. Once the source is characterized, it can then be used to measure an AC Measurement Standard under test. The source is stable and repeatable enough that it doesn't have to be characterized every time it is used. It appears that characterizing it every 30 days is adequate. Figure 3 shows the setup for connecting the source to the unit under test. The same 3' cable that was used during the characterization is used here. The source is set to the same voltages as it was when it was characterized and a reading is taken from the unit under test. The difference between each of these readings and the corresponding reading of the AC Voltmeter in the first step is the error in the unit under test for that range.

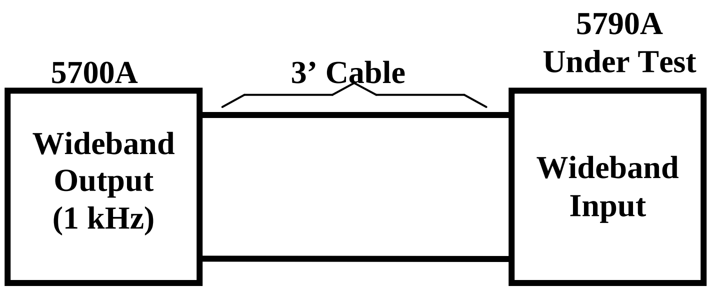

Figure 3. Second step of verifying an AC Measurement Standard at 1 kHz.

There is some error in this process due to the output impedance of the source and the input impedance of the AC Measurement Standard under test not being 50Ω. Measurements of the output impedance of the source showed that it could be significantly off 50Ω at 1 kHz but is predominately resistive so it can be modeled as a resistor. The input impedance of the AC Measurement Standard is close to 50Ω and is also resistive. Equation (1) gives the error, in µV/V, in the gain verification due these impedances not being 50Ω.

$$Error_{(uV/V)} = 10^6 \left[\frac{2*50(Z_{OUT} + Z_{IN})}{(50 + Z_{OUT})(50 + Z_{IN})} - 1 \right] \qquad (1)$$

This equation shows that if either impedance is exactly 50Ω there is no error in the process and if one of the impedances is near 50Ω then the error in the process is small even if the other impedance is significantly off 50Ω.

For the first step where the source is characterized into a very good load, the error is insignificant because the load is so close to 50Ω. For the second step where the source is connected to the AC Measurement Standard under test, the error is not as small but still insignificant compared to other measurement errors. Following is an example of this using actual impedances for the source and the AC Measurement Standard at 3.2 V.

$$Error_{(\mu V/V)} = 10^6 \left[\frac{2*50(51+50.2)}{(50+51)(50+50.2)} - 1 \right] = -20(\mu V/V)$$

The gain test is a measurement of the absolute error of each range at one frequency, 1 kHz, but the AC Measurement Standard is specified for absolute uncertainty from 10 Hz to 500 kHz. To determine the absolute error over this range of frequencies, the flatness of each range relative to 1 kHz is measured and combined with the gain error to get the absolute error. Since the AC Measurement Standard is also specified for flatness from 10 Hz to 30 MHz, this flatness test covers that whole range.

3. Flatness Error Verification

The flatness test determines the variation in the AC Measurement Standard reading with frequency relative to 1 kHz . This is done at about the mid scale of each range. If a range is flat then it reads the same at all frequencies as it read at 1 kHz with the same input voltage.

The first step of the flatness test is to characterize the source for flatness and the setup for this is shown in Figure 4. Here the standard is an EL 1100, which is a 3 V, 50Ω, Thermal Voltage Converter (TVC) which has been characterized for flatness. It is connected to the end of the three foot cable. The output of the EL 1100 is measured with a DMM.

The plane of reference for the calibration of the EL 1100 is its input connector so that makes the plane of reference for this characterization at the end of the cable. The input impedance of the EL 1100 is close to 50Ω but more importantly since this is a flatness test, its impedance changes very little with frequency.

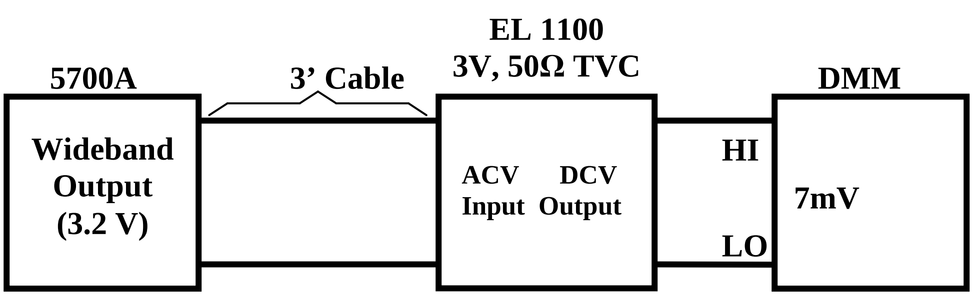

Figure 4. First step of the flatness test, characterize the source for flatness.

The EL 1100 is characterized for its AC/AC Difference relative to 1 kHz. That means that for a positive AC/AC Difference more AC Voltage at the test frequency is needed than at 1 kHz for the same output. To be compatible with this definition, the characterization of the source is done in two steps. The first of these steps determines how much the output of the source needs to be shifted at the test frequency so the output of the EL 1100 is close to the same it is at 1 kHz. The second step is then done with this new setting. The results of these measurements is the determination of a setting for the source which will flatten its output. For each frequency this setting is determined by the use of Equation 2.

$$5700A_{Setting} = 5700A_{Out}\left[1-\left(\left(\frac{V_2 - V_1}{V_1 * 1.7}\right)10^6 + EL1100_{ACACDiff}\right)10^{-6}\right] \qquad (2)$$

$5700A_{Setting}$ - 5700A Setting to Flatten the Output Voltage (V)
$5700A_{Out}$ - 5700A Setting to get nearly the same output from the EL1100 at the test frequency as at 1 kHz (V)
V_1 - The EL 1100 Output Voltage at 1 kHz (V)
V_2 - The EL 1100 Output Voltage at the Test Frequency (V)
$EL1100_{ACACDiff}$ - The AC/AC Difference of the EL 1100 (µV/V)

In equation 2, the shift in the EL 1100 output is divided by 1.7 because the EL 1100 is a square law device which means that its output voltage changes approximately with the square of the input voltage. At 3.2 V, where this characterization is done, it varies with the 1.7 power of the input.

The next step is to use the characterized source to determine the flatness errors for the 7 V range of the AC Measurement Standard under test. The AC Measurement Standard is connected in place of the EL 1100 as shown in Figure 5. This makes the plane of reference for the measurement at the AC Measurement Standard input connector.

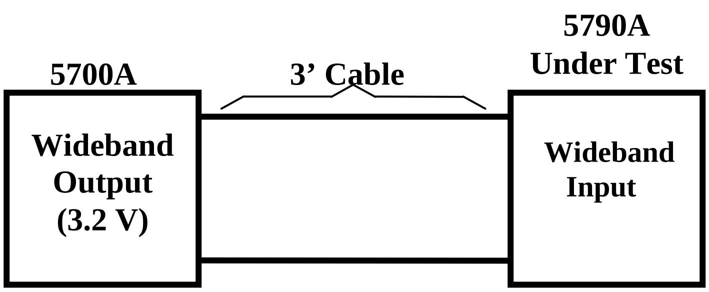

Figure 5. Second step of the flatness test, measure the flatness error of the 5790A under test at 3.2 V on the 7 V range.

For each test frequency the source is set to 1 kHz and a reading taken from the AC Measurement Standard and then the Source is set to the test frequency and appropriate level for a flat output and another reading taken from the AC Measurement Standard. The error in the flatness is determined according to equation 3.

$$5790A_{Error} = \left(\frac{V_2 - V_1}{V_1}\right)10^6 \qquad (3)$$

$5790A_{Error}$ - Flatness Error of the 5790A Under Test (µV/V)
V_1 - The 5790A Reading at 1 kHz (V)
V_2 - The 5790A Reading at the Test Frequency (V)

This completes the test of the 7 V Range. Next the 2.2 V Range is tested. To do this range a characterized 10 dB attenuator is added at the input to the AC Measurement Standard to reduce the voltage to about 1 V as shown in Figure 6. The attenuator was characterized for flatness with a 50Ω source and load.

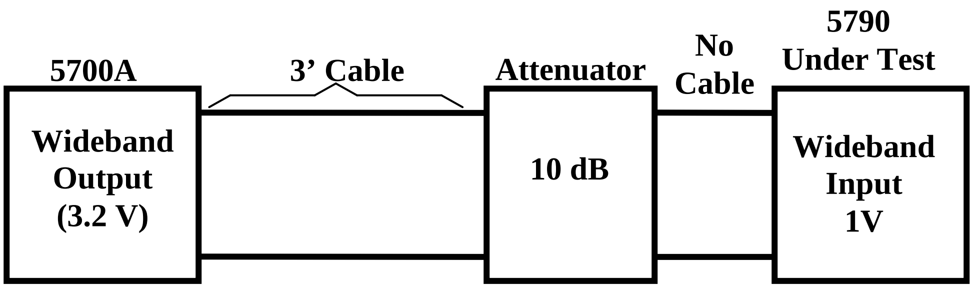

Figure 6. Third step of the flatness test, measure the flatness error of the AC Measurement Standard under test at 1 V on the 2.2 V range

For each test frequency the source is set to 1 kHz and a reading taken from the AC Measurement Standard and then the source is set to the test frequency and appropriate level and another reading taken from the AC Measurement Standard. The error in the flatness is determined according to equation 4.

$$5790A_{Error} = \left(\frac{V_2 - V_1}{V_1} \right) 10^6 + Atten_{Correction} \quad (4)$$

$5790A_{Error}$	- Flatness Error of the 5790A Under Test (µV/V)
V_1	- The 5790A Reading at 1 kHz (V)
V_2	- The 5790A Reading at the Test Frequency (V)
$Atten_{Correction}$	- Attenuator Correction for the Test Frequency (µV/V)

For the next range, the 700 mV Range, a characterized 20 dB attenuator is used in place of the 10 dB. This reduces the voltage to about 320 mV. The same procedure and equation is used as just described for the 2.2 V Range.

To test the next range, the 220 mV Range, the 10 dB and 20 dB attenuators are both used to reduce the voltage to about 100 mV. The same procedure is used except for the attenuator correction used in equation 4 is the sum of the 10 dB correction and the 20 dB correction.

The rest of the ranges are tested the same way using more characterized 20 dB attenuators. So for the lowest range, the 2.2 mV range, one 10 dB and three 20 dB attenuators are used to get 1 mV.

This concludes the verification of the AC Measurement Standard.

4. Measurement Uncertainty Considerations

The uncertainty of the verification of an AC Measurement Standard Wideband input depends on a number of factors. The uncertainty of the calibration of the standards used, the EL 1100 and attenuators, are the largest uncertainty components. But there are some other sources of uncertainty that need to be considered.

A source of uncertainty that can be small if care is taken but can easily be large if care is not taken is the repeatability and stability of the source and its connection to the standards and the AC Measurement Standard under test. The source is connected through a three foot cable with Type N male connectors on each end. It is important that a good quality cable in good condition be used. During the development of the verification method, different types of cables were tested. Looked at was the effect of flexing the cable, the line loss and characteristic impedance and the repeatability of the connectors. Using an RG8/U size cable with a Zo of 50Ω and stainless steal connectors gave the best results but it was also found that the cable made of RG58C/U that comes with the Wideband option of the source, worked well enough if in good condition. Whatever cable is used, it should be tested first for repeatability of results before being put into service. Also whenever the cable is connected it should be tightened securely.

The repeatability of the source should also be tested. This can be done by characterizing it repeatedly over a period of time. It was found that most sources would repeat well enough and were stable enough that they could be used for this verification and only needed to be characterized every 30 days.

Another important consideration for the source is its output impedance or in other words how well it is matched to 50Ω. Equation 1 showed that if a source and load are connected and one of them is very close to 50Ω then the other one can be off 50Ω a ways and still have a low uncertainty. In the case of the flatness test, the EL 1100 is close to 50Ω and very flat with frequency so the source can be off 50Ω by several ohms and still have an acceptable uncertainty. When the source is connected to the AC Measurement Standard to verify its 7 V range the mismatch error is larger because the 5790A is not as well matched to 50Ω or as flat as the EL 1100. For this reason the output impedance of the source needs to be measured over the frequency range of the test. If measured at the end of the cable it should be within a few Ohms of 50Ω. A sample of units were measured and some of them were far enough off as to add significantly to the uncertainty at 20 MHz and above.

5. Characterization of the Standards

The real key to the success of the flatness verification is the use of standards that are well characterized and have input impedances that are close to 50Ω and most importantly have impedances that change very little with frequency. The EL 1100 and the particular attenuators picked for this verification meet this requirement. The way in which these standards are characterized is also very important. They must be characterized with a good 50Ω source and load when determining their flatness. The way this is done for the EL 1100 will be explained first.

5.1 EL 1100 Characterization

The EL 1100, 3 V, TVC is characterized using a three step process. The setup for the first step is shown in Figure 7.

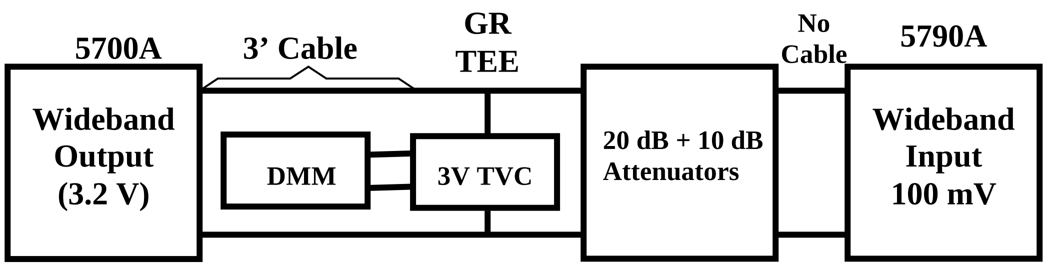

Figure 7. First step, measuring the flatness of an 5790A at 100 mV

The source, 3 V TVC and the attenuators make up a 50Ω source of known flatness with an output impedance that is close to 50Ω and changes very little with frequency. The 3 V TVC has a nominal input impedance of 600Ω and is used to level the voltage at its input which is at the center of the GR TEE. This effectively creates a zero source impedance at that point. The 30 dB of attenuation between that point and the input to the 5790A insures that the 5790A sees an impedance that is close to 50Ω and changes very little with frequency. The attenuators are hand picked to have a minimum change in impedance with frequency.

The first step determines the flatness of the 5790A at 100 mV, 10 Hz to 30 MHz. Figure 8 shows the setup for the second step.

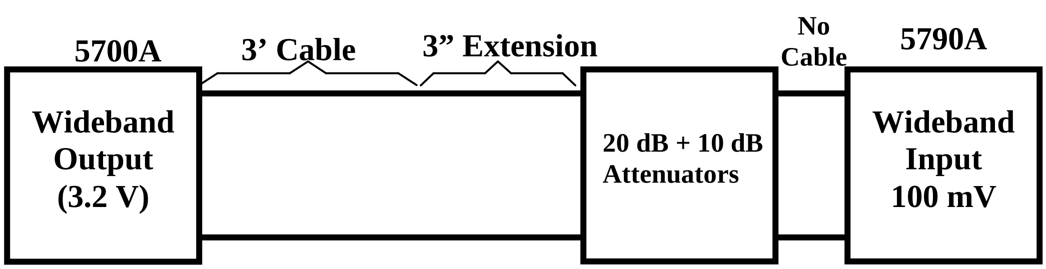

Figure 8. Second step, leveling the output of a 50Ω source at the end of the cable

It is the same as the first step with the 3 V TVC and GR TEE removed. A short section of transmission line in the form of a 3" extension is placed between the end of the 3 foot cable and input of the attenuator to replace the missing TEE. This is so that the plane of reference for the measurement, which was at the center of the TEE for the first step, is now at the end of the cable for the second step. This step determines the setting for the source so that the voltage at the end of the cable is flat over the whole frequency range relative to 1 kHz. Again the attenuators insure that the source see an impedance near 50Ω and doesn't change much with frequency.

Figure 9 shows the setup for the third step. This step determines the flatness of the EL 1100 which has a nominal 50Ω input impedance.

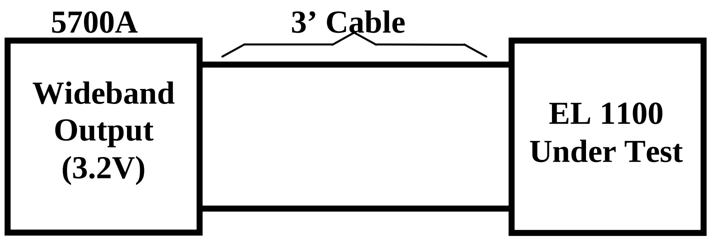

Figure 9. Third step, measuring the flatness of EL 1100, 3 V, 50Ω, TVC

In the second step the source was leveled at the end of the cable so this step determines the flatness of the TVC right at its input connector. The input impedance of the TVC is close to 50Ω and has a small change with frequency. The response of this TVC is very stable so it is characterized once a year.

5.2. Attenuator Characterization

Characterizing an attenuator determines its flatness or in other words its change in loss relative to 1 kHz and is measured in µV/V. It is measured using a 50Ω source and load. It is very important that the attenuators used have input and output impedances that are close to 50Ω and most importantly that the impedances changes very little with frequency. The attenuators used were chosen because they meet this criteria very well.

Measuring the flatness of a 10 dB attenuator is a two step process. Figure 10 shows the setup for the first step.

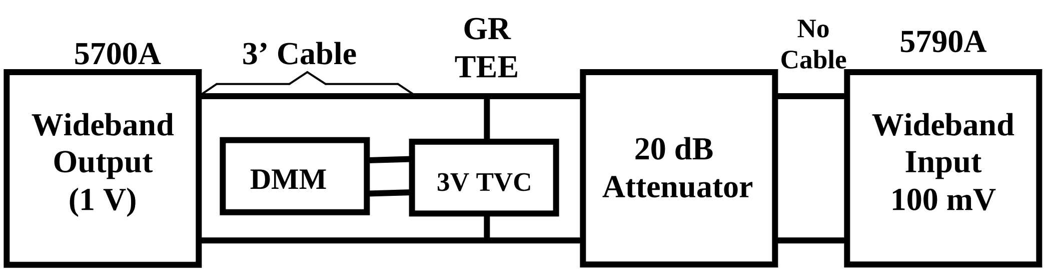

Figure 10, First step, characterization of a 10 dB attenuator

This setup is the same as the setup in the first step of the measurement of the flatness of the EL 1100 except 20 dB of attenuation is used instead of 30 dB between the 3V TVC and the 5790A. The source is set to 1V and the flatness of the 5790A is determined but no corrections are used for the 3 V TVC.

Figure 11 shows the setup for the second step.

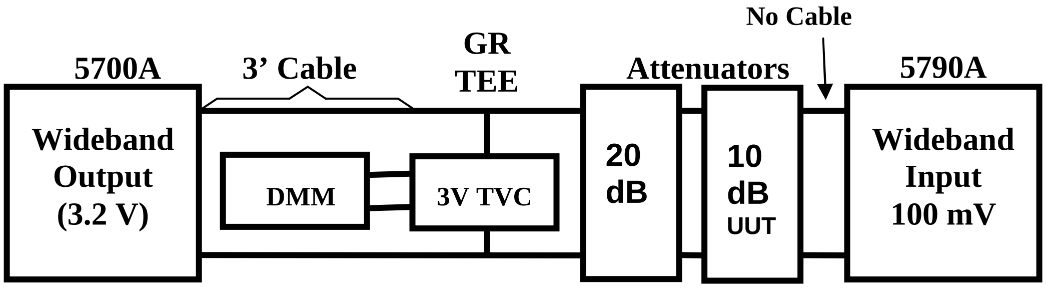

Figure 11. Second step, characterization of a 10 dB attenuator

The 10 dB attenuator under test is inserted between the 20 dB attenuator and the 5790A. The source is set to 3.2 V which is a 10 dB increase over the 1 V used before. This gets the voltage at the input of the 5790A to the same level as for the first step, 100 mV. Again the flatness of the 5790A is measured with no corrections being applied to the 3 V TVC. The difference in the flatness of the 5790A between the two steps is equal to the change in loss of the attenuator under test. This is true because the flatness of the 3 V TVC doesn't change with voltage and the 5790A is at the same voltage in both steps so any change in the measured flatness is due to the attenuator under test.

Test were run to insure that the flatness of the 3 V TVC didn't change between 1 V and 3.2 V. The results of this test showed that there was only a difference at 10 Hz and 20 Hz. At these frequencies a correction is applied to the results to correct for the change in flatness with level.

The measurement of a 20 dB attenuator is also a two step process with the setup for the first step being the same as shown in Figure 11 with two differences. One difference is that the source is set to 1 V which makes the input to the AC Voltmeter about 32 mV. The other difference is that instead of the 10 dB attenuator under test, a well characterized 10 dB attenuator is used. The flatness of the 5790A is measured with no corrections being applied for the 3 V TVC. For the second step, the 10 dB attenuator is removed and the 20 dB attenuator under test is inserted. The source is set to 3.2 V and the flatness of the 5790A determined. The flatness of the 20 dB attenuator is the difference of the flatness of the 5790A between the two steps and the flatness of the 10 dB attenuator.

6. Conclusion

A method for the verification of the calibration of the Wideband input of an AC Measurement Standard was presented. First was given an explanation of how the AC Measurement Standard is calibrated using a 50Ω source which dictates that it be verified with a 50Ω source. No real world source is exactly 50Ω so a description is given of how to characterize a source so that it can be used with satisfactory uncertainties. Next the use of attenuators with the source is described to verify the ranges below the top range. Finally a description of the characterization of the EL 1100 and attenuators was given.

References

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2. N. Faulkner, "A New Method for the Calibration of the mV Ranges of an AC Measurement Standard", NCSLI Workshop & Symposium, Salt Lake City, Utah, July 2004. Available on the Fluke web site: www.fluke.com.