Recommendation Report

Measuring Gross Parameters of Signals and Comparing Methods of Measurement Based on Pre-Selected Criteria

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Introduction

Burdell Electronics, a world leader in capacitor manufacturing, enforces a rigorous wear testing process on a small sample of capacitors from each batch. Capacitors are very quickly charged and discharged until electrical or mechanical failure ensues. The rating of the capacitors that are being tested in this evaluation are 5v, 500 µF. These ratings determine the maximum speed the device can charge and discharge, which in this case is approximately 1 kHz. By measuring parameters of the output waveform from the capacitor, it is possible to not only determine when failure occurs, but how the component degraded over time. The parameters that are being observed are the mean and RMS voltages. The waveform produced by an ideal capacitor is known, and by comparing it to the signal produced by a real capacitor, it is possible to track the wear over time. An instrument is needed to measure the mean and RMS voltages that fits the criteria determined for this recommendation. These criteria, in order of importance, are: accuracy, cost effectiveness, precision, feature count, and form factor. The three devices that are analyzed are the Tektronix 3012B oscilloscope, the Agilent 34401A digital multimeter (DMM), and the National Instruments Educational Laboratory Virtual Instrumentation Suite (ELVIS).

To determine the fitness of the measurement instruments of Burdell Electronics, a sample waveform was analyzed by each device. Equation 1 shows the mathematical representation of the waveform that was generated and analyzed.

$$x(t) = 5\frac{e^{-3000t} - e^{-3000*1/1000}}{1 - e^{-3000*1/1000}}$$

Equation 1. Equation of investigated waveform.

This function closely matches the behavior of a 5v, 500 µF capacitor. When plotted, this waveform appears as an exponentially decreasing curve as seen in Figure 1.

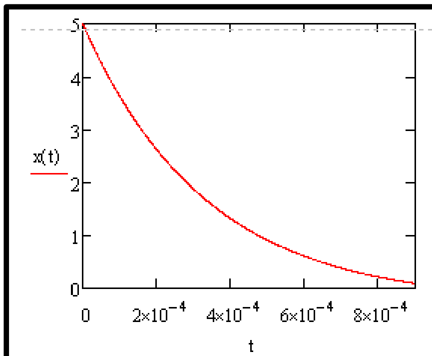


Figure 1. Plot of Equation 1 over an interval taken to be one period.

This waveform was taken to be periodic, with the plot in Figure 1 serving as one period. Because of the discontinuities at each end of the function, it presents a nontrivial case for measuring signal characteristics using standard instrumentation. The function in Figure 1 was first generated Equation 1 using Mathcad. It was then turned into a discrete set of 4000 points. This number was chosen because it approximated the original function to within at least 90% and gave a visually similar plot to the original continuous signal. These points were converted into a waveform file that the ELVIS was capable of reading. The arbitrary waveform generator in the ELVIS was then used to generate a periodic version of the plot in Figure 1. The oscilloscope, multimeter, and the ELVIS were each used to measure the average and RMS voltage of the waveform. The oscilloscope was used to measure the cycle mean and cycle RMS in addition to the average and RMS. An excerpt from the Tektronix 3012B user manual is shown in Figure 2.

	Cycle Mean	The arithmetic mean over the first cycle in the waveform.
	Cycle RMS	The true Root Mean Square voltage over the first cycle in the waveform.
	Mean	The arithmetic mean over the entire waveform.
	RMS	The true Root Mean Square voltage over the entire waveform.

Figure 2. Definitions of each measurement parameter used to compare measurement devices.

The first two rows of Figure 2 give the definition of cycle mean and cycle RMS along with a small image depicting the method used to measure that data point. Figure 2 also gives the definition of the mean and RMS values that the oscilloscope uses. Note that the definition for RMS is a true RMS value. The mathematical definition of the mean value is given in Equation 2.

$$\frac{1}{b-a}\int_a^b f(x)dx$$

Equation 2. Average value of a function.

The mathematical definition of the RMS value is given in Equation 3.

$$\lim_{T\to\infty}\sqrt{\frac{1}{2T}\int_{-T}^{T}[f(t)]^2dt}$$

Equation 3. RMS value of a function.

The definitions of cycle mean and cycle RMS are also calculated with Equations 2 and 3 respectively; however, the interval over which integration is performed is a single cycle.

After an exhaustive analysis, it was found that the ELVIS was the only instrument with acceptable accuracy along with a reasonable price and form factor. It also has a very wide variety of features. The Tektronix oscilloscope had an error of above 45% in one case and is more expensive. The Agilent DMM, while cheapest, has an error of above 63% in one case. I recommend the ELVIS for measuring capacitor wear testing signals because it is affordable, will complement existing instruments, and is accurate with less than 4% error with a high precision of 4 significant figures.

Analysis/Criteria and Comparison

The criteria that will be compared are accuracy, precision, form factor, available features, and cost to purchase and maintain. Accuracy is the most important criteria because no matter how many features the device has, how small it is, or how cheap it is, it is worthless and should not be purchased because it will not allow the engineer to do his job. The second most important criterion is cost to purchase and maintain. Cost and the other criteria can be traded back and forth until equilibrium is reached. For instance, in some instances, an accurate instrument that is not highly precise is acceptable because it is cheaper, but still does its job correctly. Maintenance costs are important to consider along with initial purchase costs because they can quickly outweigh the initial purchase cost if labor or parts are expensive. In this comparison, the availability of repair parts and the length of the warranty are considered. The third most important criterion is precision. Once cost and accuracy have been decided, the instrument with the best ability to do its job should be selected. The fourth most important criterion is feature count. Many instruments tout lots of new, automatic features that raise the price of the device substantially. Extra features are often useful, but many times their functionality can be replicated by the engineer by hand fairly quickly. The least most important criterion is form factor. It is important to keep in mind the real estate available on the bench, but it is foolish to spend more money on a smaller device just so it will fit in a particular spot. Adding a new shelf or rack is very often much cheaper. In addition, most benchtop gear is now designed to be stacked on top of one another.

To compare accuracy, the percent error was calculated according to equation 4 below.

$$\frac{experimental - theoretical}{theoretical} * 100$$

Equation 4. Formula for calculating percent error.

The accuracy criterion was defined as the extent to which a given measurement agreed with the standard value for that measurement. Cost effectiveness was defined as producing optimum results for the expenditure and was determined using cost, potential maintenance cost, feature count, precision, and accuracy. Precision was defined as the degree to which the exactness of a quantity is expressed and was determined using the number of significant figures that the instrument could resolve. Feature count was simply the numeric total of features and abilities that the device was capable of. Finally, the form factor was simply the physical shape and special dimensions of the device measured in inches, square inches, and pounds. Each criterion with its rank can be found in figure 3.

Importance rank	Criterion	Definition of Criterion	Metric of Comparison
1 (most important)	Accuracy	The extent to which a given measurement agrees with the standard value for that measurement.	Percentage error
2	Cost effectiveness of purchase and maintenance	Producing optimum results for the expenditure.	Cost, potential maintenance cost, feature count, precision, and accuracy.
3	Precision	The degree to which the exactness of a quantity is expressed.	Significant figures.
4	Feature Count	Numeric total of features and abilities that the device is capable of.	Numeric total of features and abilities that the device is capable of.
5 (least important)	Form Factor	The physical shape and special dimensions of the device.	Inches, square inches, and pounds.

Figure 3. Table of criteria, metric of measurement, and importance of each criterion used to reach recommendation.

Accuracy

The raw measurements made with the each device can be seen in Figure 4.

	Tektronix 3012B oscilloscope	Agilent 34401A DMM	ELVIS	Theoretical Values
Output Average	1.81 V	0.51 V	1.451 V	1.405 V
Output RMS	2.81 V	1.30 V	1.961 V	1.949 V
Output Cycle Mean	1.81 V	Not supported	Not supported	1.405 V
Output Cycle RMS	2.80 V	Not supported	Not supported	1.949 V

Figure 4. Results of average, RMS, cycle mean, and cycle RMS of the input wave measured on each device compared to theoretical values.

To determine the accuracy of each device, the theoretical value of the average and RMS voltage were calculated with Mathcad. The errors for each device can be found in the first column of Figure 5.

	Tektronix 3012B oscilloscope	Agilent 34401A DMM	ELVIS
Error for Output Average	28.82%	63.70%	3.27%
Error for Output RMS	44.18%	33.29%	1.26%
Error for Output Cycle Mean	28.82%	N/A	N/A
Error for Output Cycle RMS	43.66%	N/A	N/A

Figure 5. Error of average, RMS, cycle mean, and cycle RMS of the input wave measured on each device.

All of the values in column one of Figure 4 were obtained using the measure function on the oscilloscope. Because this functionality relies on knowing the correct period of the wave, a fairly large error occurred. The reason for these significant errors is due to the discontinuities in the input waveform. Each time the next period occurs, an asymptote is encountered. The waveform as the Tektronix oscilloscope sees it appears in Figure 6.

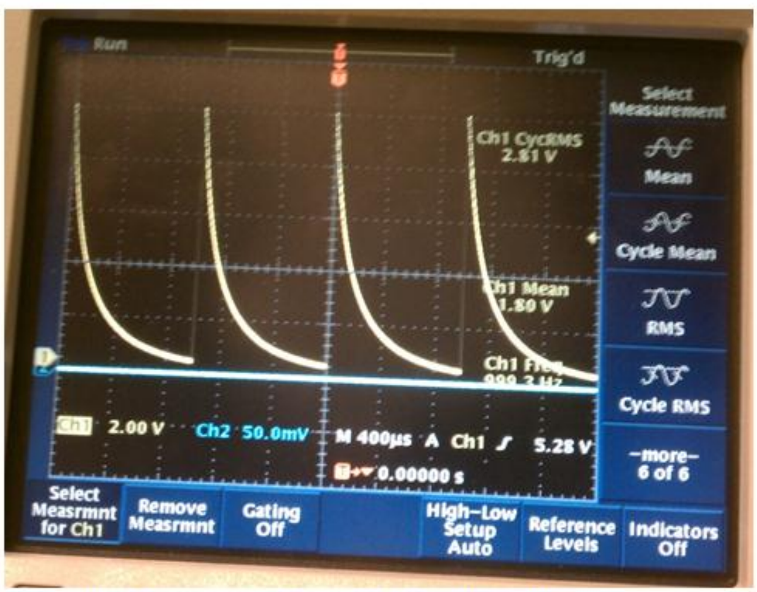


Figure 6. Periodic version of input waveform plot on the Tektronix oscilloscope.

This pulse-train-like behavior makes it very difficult for the oscilloscope to determine the period. In fact, by using the measure function on the oscilloscope and watching the calculated period, it is possible to see the value for the period quickly take on a wide range of values before settling down to the approximate real period as the middle of the wave is encountered. To see this edge corruption effect with the naked eye, the frequency of the wave must be artificially lowered so that the input wave can be seen to scroll across the screen.

The values obtained for the mean and RMS of the input signal by the Agilent DMM are found in column two of Figure 4. This digital multimeter requires a pure sine wave to correctly determine the average value of a signal. Figure 7 depicts an excerpt from the user manual regarding the expected error of several major wave types.

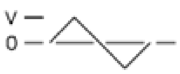
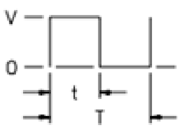
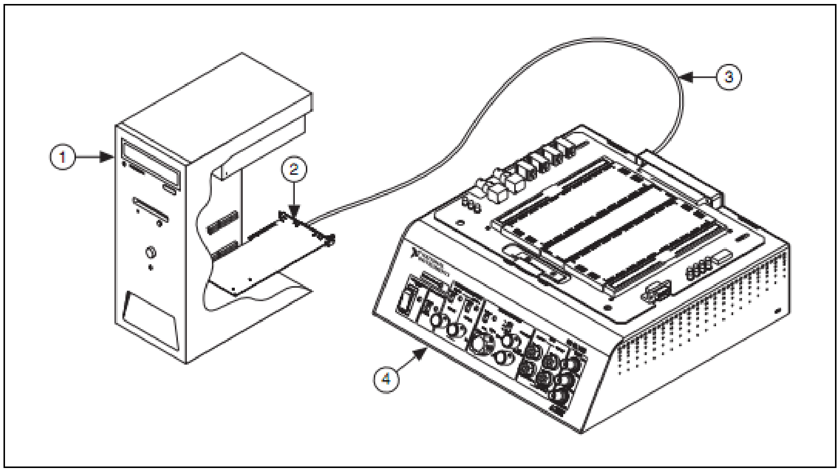
Waveform Shape	Crest Factor (C.F.)	AC RMS	AC+DC RMS	Average Responding Error
	1.414	$\frac{V}{1.414}$	$\frac{V}{1.414}$	Calibrated for 0 error
	1.732	$\frac{V}{1.732}$	$\frac{V}{1.732}$	−3.9%
	$\sqrt{\frac{T}{t}}$	$\frac{V}{C.F.} \times \sqrt{1-\left(\frac{1}{C.F.}\right)^2}$	$\frac{V}{C.F.}$	−46% for C.F. = 4

Figure 7. Method of measurement and expected error for sine, triangle, and square waves for Agilent DMM.

Symmetrical waves are able to be analyzed with an error of under 4%. This is not the case for nonsymmetrical waves because of reasons similar to those of the oscilloscope. The multimeter tries to acquire the period but often isn't able to because of large discontinuities. Additionally, nonsymmetrical waveforms contain DC voltages which are rejected by AC coupled measurements. The Agilent DMM does, however, employ true RMS, meaning that it can accurately determine the RMS value of a waveform, even if it is not a sine wave. There is a caveat though: the crest factor of the wave must be small. There is no public documentation on what the exact crest factor limit is, however the user manual states that waveforms with large discontinuities can expect an error of around 46%. Notice that this instrument does not support measuring cycle mean and cycle RMS.

Data acquired by the ELVIS is found in column 3 of Figure 4. The error can be found in column 3 of Figure 5. The ELVIS had very low error compared to the other instruments because of its principal of operation. The ELVIS uses a 68 pin M series Data Acquisition (DAQ) device that interfaces with a PC to read and analyze data from transducers on the benchtop workstation. This setup allows the ELVIS to look at the entire set of data and apply more intensive processing than the DMM and oscilloscope because it can leverage the use of the attached PC. By looking at a continuous stream of data points acquired by the transducers, the ELVIS can reconstruct the wave as it is actually sensed and then do math on it without having to trade off accuracy for speed (since the Agilent DMM and Tektronix oscilloscope both rely on embedded processors to analyze data). There are no restrictions on wave types or shapes that the ELVIS is able to accurately analyze. Data was not available on expected device error percentages from the manufacturer. Like the multimeter, however, it is not capable of measuring cycle RMS or the cycle mean. Figure 8 shows the typical setup of the ELVIS and how the workstation is connected to the PC via a PCI card.



1 Desktop Computer
2 68-Pin M Series DAQ Device
3 Shielded Cable to M Series Device
4 NI ELVIS Benchtop Workstation

Figure 8. Desktop configuration for ELVIS workstation depicting the PCI interface.

Precision

The Tektronix 3012B oscilloscope is capable of displaying 3 significant figures for average and RMS values. The Agilent 34401A multimeter has the highest precision at 6.5 significant figures for these values. The ELVIS can display four significant figures for average and RMS values. Only the oscilloscope can measure cycle mean and cycle RMS, and it is capable of displaying 3 significant figures for these data points.

Form Factor

The form factor of the device, including its size and ease of operation are important since bench space is scarce with all of the other instruments at each workstation at Burdell Electronics. A table of the dimensions, weight, and the footprint of each device is in Figure 9.

	Length (inches)	Width (inches)	Height (inches)	Footprint (inches^2)	Weight (lbs)
Tektronix 3012B	5.9	14.8	6.9	87.32	7
Agilent 34401A	14.72	10.02	4.08	147.49	8
ELVIS (workstation only)	11.02	13.5	2.99	148.77	9

Figure 9. Comparison of spatial dimensions and weight of each device.

The Tektronix 3012B digital oscilloscope is 14.8 inches wide, 6.9 inches high and 5.9 inches deep. It weighs 7 pounds. The oscilloscope form factor can be seen in Figure 10.

Figure 10. Tektronix 3012B digital oscilloscope.

The oscilloscope is an average sized benchtop instrument with a footprint of 87.32 square inches. It is also able to be stacked on top of other instruments. To operate, only a single power cable on the back along with a probe cable for each channel on the front is needed.

The Agilent 34401A DMM is 10.02 inches wide, 4.08 inches high, and 14.72 inches long. It weighs 8 pounds and can be seen in Figure 11.

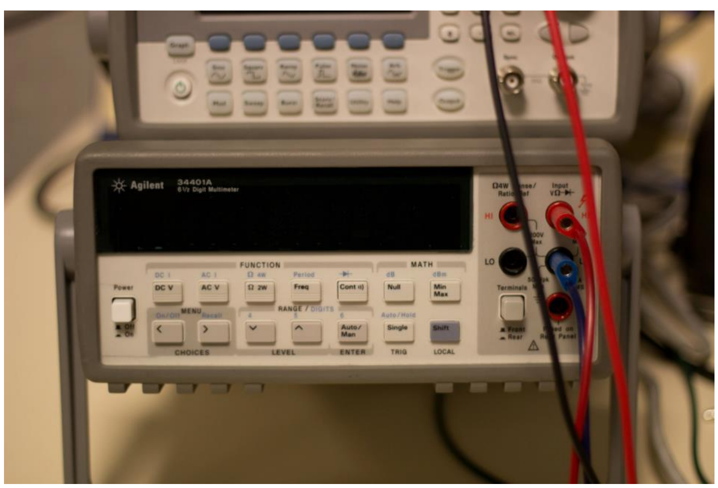


Figure 11. Agilent 34401A digital multimeter.

The DMM has a larger footprint than the oscilloscope at 147.49 square inches. However, this instrument is designed to be stacked between other similar sized instruments (as can be seen in Figure 11). Operation requires a single power cord in the back, although test cables can also be attached to the back. There are also test cable ports on the front.

The ELVIS is the largest of the three instruments, requiring a computer and benchtop workstation. The workstation can be seen in Figure 12.

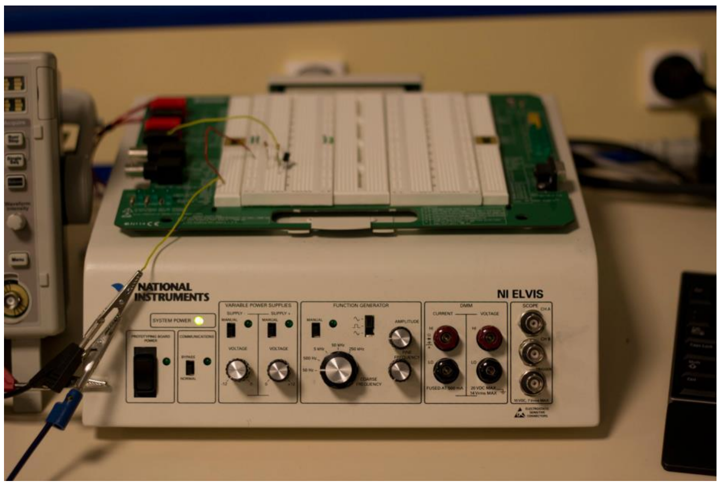


Figure 12. ELVIS benchtop workstation.

The ELVIS PC interface that allows for the control of elements on the workstation via a PCI bus can be seen in Figure 13.

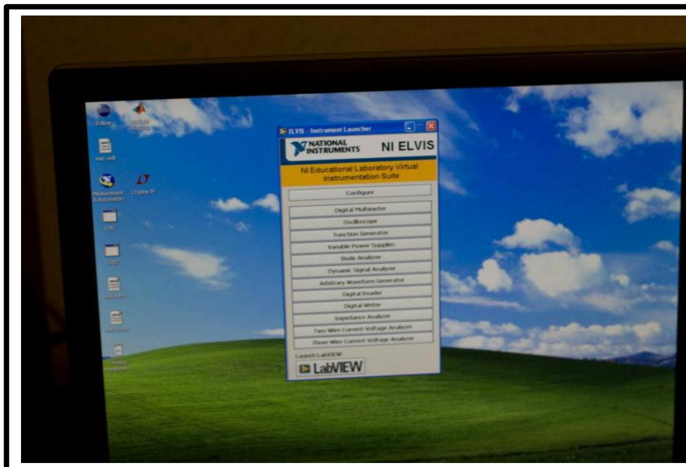


Figure 13. ELVIS PC software interface.

The ELVIS benchtop workstation is 13.50 inches wide, 2.99 inches high and 11.02 inches long for a footprint of 148.77 square inches. It weighs 9 pounds. Unlike the other instruments, the ELVIS workstation cannot have anything stacked on top of it, and its dimensions are not conducive to stacking it on top of anything either. Additionally, a PC, keyboard, mouse, and monitor are required to use any of the analysis tools that the device is capable of. Overall, the ELVIS has the largest footprint because of the need for a separate PC. Power and data cables must be routed from the back of the device and test leads are connected on the front panel.

<u>Feature Count</u>

The oscilloscope, DMM, and the ELVIS all have more features than were tested in this experiment. These additional features need to be considered when discussing intent to purchase. The Tektronix 3012B additional features can be seen in Figure 14.

Channels	2
Bandwidth	100 MHz
Sampling Speed	1.25 GS/s
Time base range	10 ns to 10 s/div
Maximum input	300 V (with 10x probe)
GPIB?	Yes
Triggering modes	9
Automatic measurements	Mean, RMS, cycle mean, cycle RMS, period, frequency, width, rise and fall time, duty cycle, overshoot, high and low, max and min, peak-to-peak, amplitude, burst width, delay, phase, area, cycle area

Figure 14. Feature list of Tektronix 3012B oscilloscope.

The oscilloscope has two channels with a total of 100 MHz of bandwidth and a sampling speed of 1.25 GS/s. It has a time base range of 10 ns to 10 s/div and a maximum input voltage of 300 V with a 10x probe. It has the ability to connect to an external PC over GPIB and has 9 different trigger modes. Along with automatically measuring mean, RMS, cycle mean, and cycle RMS, it can measure period, frequency, width, rise time, fall time, duty cycle, overshoot, high, low, max, min, peak-to-peak, amplitude, burst width, delay, phase, area, and cycle area.

The Agilent multimeter performance statistics are found in Figure 15.

Maximum voltage	1000 V
Resolution	6.5 digits
DC Voltage accuracy	0.0015%
AC Voltage accuracy	0.06%
GPIB?	Yes, but only at 1000 Hz
Supported measurements	DC voltage, true RMS AC voltage, resistance, DC current, true RMS AC current, frequency, period, continuity, diodes

Figure 15. Feature list of Agilent 34401A digital multimeter.

The 34401A can measure up to 1000 V at 6.5 digits of resolution. It has 0.0015% basic DC V accuracy and 0.06% basic AC V accuracy. It supports GPIB like the oscilloscope, but can only output at 1000 Hz. Aside from measuring DC voltage and true RMS AC voltage, it can measure resistance, DC current, true RMS AC current, frequency, period, continuity, and diodes.

The ELVIS incorporates many standard benchtop instruments into a single package. Details of its features are found in Figure 16.

DC Voltage range	20 V
AC Voltage range (RMS)	14 V
DC Voltage accuracy	0.3%
AC Voltage accuracy	0.3%
Oscilloscope bandwidth	50 kHz
Oscilloscope channels	2
Oscilloscope sampling speed	500 KS/s
Supported functions	Arbitrary waveform generator, Bode analyzer, digital bus reader and writer, digital multimeter, dynamic signal analyzer, function generator, impedance analyzer, oscilloscope, two and three wire voltage current analyzer, and variable power supplies
GPIB?	No, but data acquisition is supported via LabVIEW

Figure 16. Feature list of ELVIS.

It features an arbitrary waveform generator, Bode analyzer, digital bus reader and writer, digital multimeter, dynamic signal analyzer, function generator, impedance analyzer, oscilloscope, two and three wire voltage current analyzer, and variable power supplies. It also has higher level functions and integration with LabVIEW that can be used in analysis. The built in digital multimeter can measure capacitance, continuity, current, diodes, inductance, resistance, and voltage. Compared to the Agilent multimeter, it has 0.3% accuracy over an input range of 20 V DC. Likewise, it has a 0.3% accuracy over an input range of 14 V AC. The oscilloscope has a bandwidth of 50kHz, compared to the Tektronix 3012B's 100 MHz. The ELVIS oscilloscope has two channels that can each capture 500 KS/s, compared to the Tektronix's 1.2 GS/s.

<u>Cost effectiveness of purchase and maintenance</u>
A table of the cost, warranty information, and spare parts availability of each device is found in Figure 17.

	Cost (dollars)	Warranty period	Parts availability
Tektronix 3012B	3000	3 years	Easy to find
Agilent 34401A	900	1 year	Easy to find
ELVIS	2000	1 year	Hard to find

Figure 17. Comparison of cost effectiveness criteria of each device.

The cost of the Tektronix 3012B oscilloscope is $3000. The cost of ELVIS is $2000, but this does not include the cost of the PC that is needed to actually use the device. The cost of the Agilent 34401A is $900. Tektronix provides a 3 year warranty for electrical or manufacturing failures. National Instruments provides a one year warranty against manufacturing failures, and Agilent also proves a one year warranty. In the event that an in-house repair of any instruments is necessary, parts are readily available for the Tektronix 3012B and Agilent 34401A, however parts for the ELVIS benchtop workstation are difficult to find.

Conclusions

The ELVIS is the most accurate instrument by a significant margin, with the highest percent error of any measurement of 3.27%. The ELVIS's built in oscilloscope can see waveforms, but not waves as fast or detailed as the Tektronix 3012B can. The Tektronix oscilloscope can capture waveforms at 1.25 GS/s while the ELVIS oscilloscope can only capture at 500 KS/s. The lowest percent error of any measurement taken with the Tektronix oscilloscope was 28.82%, which is unacceptably high. The Agilent 34401A DMM also suffers from poor accuracy with the lowest percent error of any measurement being 33.29%.

The Tektronix oscilloscope has a precision of three significant figures. This is sufficient for the kinds of measurements conducted at Burdell Electronics. The Agilent multimeter has the largest precision at 6.5 digits. The ELVIS can measure the same parameters that the Agilent 34401A can measure, but only with 4 significant figures.

The oscilloscope has a high feature count with many useful automatic measurements built in including mean, RMS, cycle mean, cycle RMS, period, frequency, width, rise and fall time, duty cycle, overshoot, high and low, max and min, peak-to-peak, amplitude, burst width, delay, phase, area, and cycle area. The ELVIS offers more features than the Tektronix oscilloscope, including an arbitrary waveform generator, Bode analyzer, digital bus reader and writer, digital multimeter, dynamic signal analyzer, function generator, impedance analyzer, oscilloscope, two and three wire voltage current analyzer, and variable power supplies. The Agilent 34401A has a small feature count compared to the ELVIS and Tektronix oscilloscope, but is still capable of measuring DC voltage, true RMS AC voltage, resistance, DC current, true RMS AC current, frequency, period, continuity, and diodes.

The oscilloscope has the smallest footprint, and even though it is not stackable, it still only takes up 87.32 square inches of countertop. The Agilent 34401A has the second smallest footprint at 147.49 square inches plus the ability to stack. The large 148.77 square inch footprint of the ELVIS (not including the footprint of the PC) may initially seem detrimental, but engineers at Burdell Electronics already have a PC at their lab benches. They also normally have a breadboard for prototyping. By using the existing computer as the host for the ELVIS and replacing the breadboard with the ELVIS workstation (which has a breadboard built in), very little additional space is taken up.

The Tektronix oscilloscope has a three year warranty, the longest of any device, and is easy to find parts for. It costs $3000. The ELVIS has a one year warranty and a price of $2000, making cheaper than the oscilloscope, but not the DMM. Additionally, parts are difficult to find for the ELVIS. The Agilent 34401A costs $900 and comes with a one year warranty. Given that parts are easy to find, this device is expected to have a maintenance cost that is lower than the ELVIS and a slightly higher than the Tektronix oscilloscope.

Recommendation

While the Tektronix 3012B oscilloscope offers a small form factor, it lacks the ability to accurately determine the given wave characteristics. A large percent error coupled with a high price tag of $3000 means that this oscilloscope would not be the best choice for this application because of its poor cost efficiency.

The Agilent 34401A digital multimeter is small, cheap, and precise. Despite the Agilent DMM's low price of $900, accuracy is the most important criterion. The DMM's extremely poor accuracy means it is also not suitable for use in this application.

The ELVIS was able to achieve the highest accuracy with a 3.27% error for the mean and 1.26% error for RMS. It is also cheaper than the Tektronix oscilloscope by $1000. Because the ELVIS would replace the existing breadboard the engineers at Burdell Electronics use and because they already have a PC at their workbenches, only a small amount of additional space would be used. Investing in the ELVIS will allow the engineers at Burdell Electronics to put our capacitors through rigorous testing and obtain meaningful data to ensure a reliable product. I recommend the ELVIS for measuring capacitor wear testing signals because it is affordable, will complement existing instruments, and is accurate with less than 4% error with a high precision of 4 significant figures.