the measured voltage is greater than $0.75V_{max}$ and less than $1.15V_{max}$ [7]. The preceding constraints seem to work for cells and modules with a 40% fill factor to a 95% fill factor [119].

This allows the measured current to be corrected for intensity fluctuations to a constant intensity value. It is best to measure the incident irradiance with a reference cell at each current–voltage point and to use separate meters for the same sampling interval. A less accurate method is to measure the current and voltage sequentially with the same meter and only measure the intensity once. This method assumes that there are no temporal fluctuations in the simulated or natural light intensity during the measurement period and that the voltage is constant. This may not be the case if the bias rate or capacitance is large or if there are transients in the device [29, 119]. One commercial I–V system averages 40 voltage readings and then 40 current readings to obtain a single I–V point. This approach causes problems if the voltage and current are not in equilibrium because of too large a bias rate or other transient phenomena. A better approach would be to take 40 pairs of current and voltage points and then average the voltage and current because this relaxes the assumption that the current and voltage at a given load setting are random with time.

Useful additions that are rarely found in commercial I–V equipment include checking for valid contacts and limiting the maximum current through the device. To prevent damage to PV cells, the resistance between the current and voltage contacts should be measured with manual or automatic measurements prior to the I–V measurement. If the sample is too small for Kelvin contacts, then the current at zero voltage should be monitored while making contact with the cell. Most commercial systems are polarity-dependent because bipolar power supplies or loads are much more expensive. The current near zero volts is obtained by a low-voltage load of opposite polarity. This feature can damage cells and modules with a low reverse-bias breakdown such as amorphous silicon or GaAs if a diode is not placed in parallel with the sample to prevent a reverse-bias voltage from being applied. The polarity can easily be determined from the sign on the voltage near zero current or the sign on the current near zero voltage. This keeps the operator from worrying about which connection is positive and prevents excess bias voltages from accidentally being applied by automatically choosing a safe range for the maximum forward and reverse bias.

Commercial I–V systems developed for the semiconductor industry by Hewlett Packard/Agilent Technologies Inc., Keithley Instruments Inc., and others are readily available. These units can be operated manually or with a computer with a wide range of features and capabilities including bipolar operation. The primary problem with units designed for transistor and diode analysis is the cost and limited maximum current. This limitation is only a problem for groups that need to perform I–V measurements at biases over ~100 V and ~5 A. These generic I–V systems require software to download the data, save it, and calculate relevant PV parameters. There is also a variety of manufacturers of PV test equipment for I–V measurements including Daystar Inc., Spire Inc., Spectrolab Inc., Pasan Beval S.A., Wacom Electric Co. Ltd, and numerous other small companies. Commercial I–V measurement software is typically designed for industrial applications and lacks the capability to detect bias rate artifacts by changing the bias direction, or variable bias, or load slew rate. Commercial software also has a fixed format for saving the data and plotting the results that may be difficult or impossible for the user to modify.