

Application Note Series

Switching in Multipoint Testing

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Selection of suitable switching is an extremely important but sometimes under-emphasized function in the process of measurement system design. Switch selection is, in fact, no less critical than the selection of system instrumentation or the design of the test interface.

The objective of any system design is to transfer the accuracies and specified performance of system instrumentation to the Unit Under Test (UUT). These specifications are guaranteed only at the instrument terminals. To complete the test procedure, it may be necessary to insert meters of cable, complex switching, and a unique test interface between the system instrumentation and the UUT. The system designer must deal with errors created by cabling, connections, measurement techniques, and system switching. Add the need to accommodate the designer's worst-case measurement situation, and achievement of the test objective becomes extremely difficult.

This application note describes the use of currently available switching equipment in typical system measurement situations—accommodating or compensating as much as possible for error from various sources. Covered in some detail are system temperature measurements, resistance measurements, high voltage switching, and matrix switching.

System Temperature Measurements

Temperature is often measured in test systems, environmental chambers, automated processes, etc. The fundamental properties being sensed are electrical characteristics, which vary predictably with temperature. Resistance temperature detectors (RTDs), thermistors, and thermocouples are all common sensors suitable for such applications. A detailed discussion of each sensor type can be found in Application Note #401.

The most common temperature sensor in measurement systems is the thermocouple because it is durable, inexpensive, and covers a broad measurement range from about -50°C to 1800°C . In using thermocouples, however, the test engineer is faced with unique problems in dealing with microvolt-level signals. It is difficult to control these levels and to obtain repeatability and accuracy, even in a simple bench setup.

Thermoelectric offset voltages are present in every connection and termination because of the thermoelectric properties of the materials involved. Each connection and switch contact is basically a thermocouple. Thermoelectric offset voltages can

create measurement errors of several degrees; steps must be taken to recognize, control, and minimize these error sources.

In addition, a thermocouple produces an EMF proportional to the difference in temperature from end to end. Therefore, the temperature to be measured cannot be determined unless the temperature is known at the cold junction. For this reason, a temperature reference must be provided.

The reference must be held at or as near as practical to the temperature of the thermocouple cold junction. This is generally accomplished by mounting the terminal connector and the reference device in one thermally conductive block.

The System Solution

There are at least three ways to use thermocouples for multipoint temperature measurements. The method chosen depends on the "acceptable measurement uncertainty."

1. Direct without Compensation.

The method shown in *Figure 1* is simple and can provide adequate accuracy in monitoring high temperatures (typically above 300°C). The computing power of the controller is used to convert the voltage output of the sensor to a temperature value, and to insert a constant reference temperature into the conversion equation. This assumed reference may be valid in well controlled operating environments.

The major error is the difference between the constant temperature assumed for the thermocouple reference and the actual temperature at the terminal block (ΔT_A in *Figure 1*). If the difference is no greater than $\pm 6^{\circ}\text{C}$, the additional error in monitoring temperatures above 300°C is less than 2%. An error of this magnitude may be acceptable in many applications.

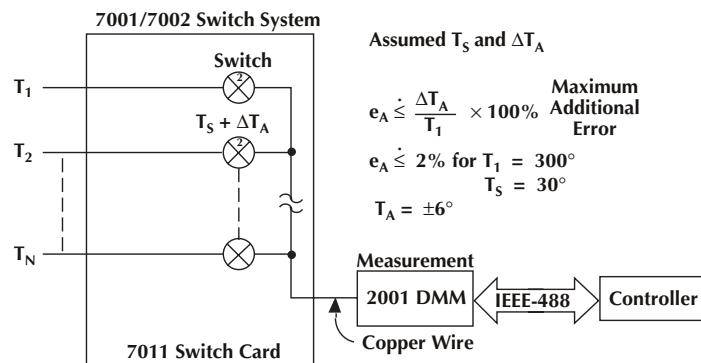


Figure 1: Direct Multipoint Temperature Measurement without Compensation

2. Compensation without Isothermal Block. When better accuracy is required, the temperature must be sensed at the thermocouple reference end. This can be accomplished by mounting a thermistor, RTD or semiconductor temperature sensor near the termination. These reference sensors, unlike thermocouples, provide outputs that represent the temperature at the point of interest, rather than the relative temperature difference between two points.

This method improves accuracy, since there is a temperature detector near the thermocouple termination. The temperature detector allows for fluctuation in the operating environment at the reference end of the thermocouple. There is still a major uncertainty, however, with respect to the temperature difference between the temperature sensor and the thermocouple termination (ΔT_B in **Figure 2**). That temperature difference is uncontrolled and may vary substantially due to the location of convection and radiation heat sources, and also because of heat conducted in electrical traces.

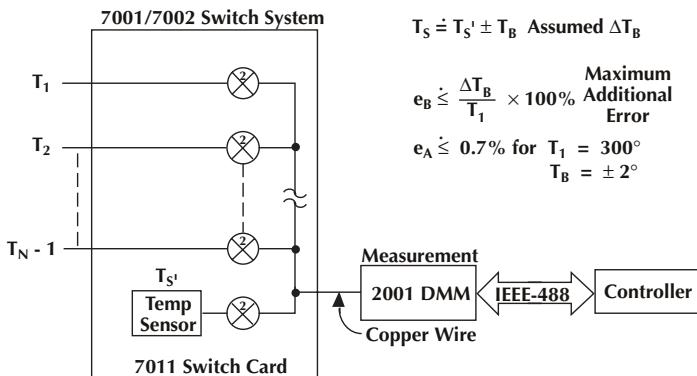


Figure 2: Multipoint Temperature Measurement without Isothermal Block

Note that with this method, the DMM must be switched to the resistance mode to monitor the value of the reference sensor. Also, the controller must be programmed with the characteristic equations to convert signals from both the thermocouple sensor and the reference sensor.

3. Compensation with Isothermal Block. Using an isothermal block (**Figure 3**) ensures that the temperatures at the thermocouple terminations differ by no more than a fraction of a degree from the reference sensor temperature. This arrangement reduces the number and magnitude of system uncertainties and provides the best measurement accuracy.

In a typical application as presented in **Figure 4**, the DMM reads the thermocouple and reference voltages; the DMM then converts voltages to temperature values. The Model 2001 DMM HI/LO limits can be set to control the Digital I/O and therefore control the heater. This same system may be extended to control or monitor up to 78 temperature points. Those channels not dedicated to thermocouple sensors can be used to monitor other signals and system test points. **Figure 5** illustrates a typical reference and thermocouple measurement configuration.

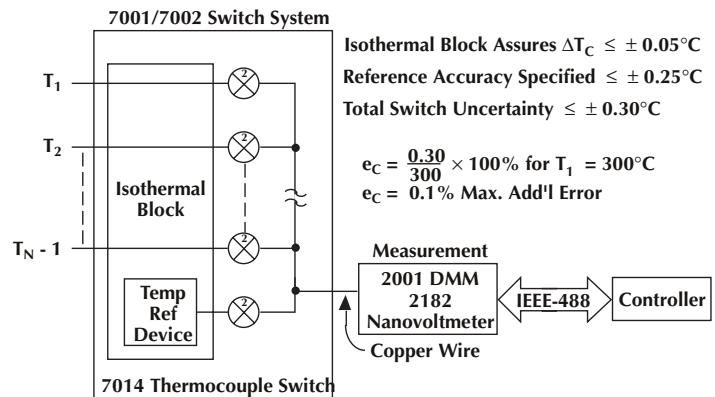


Figure 3: Multipoint Temperature Measurement with Isothermal Block

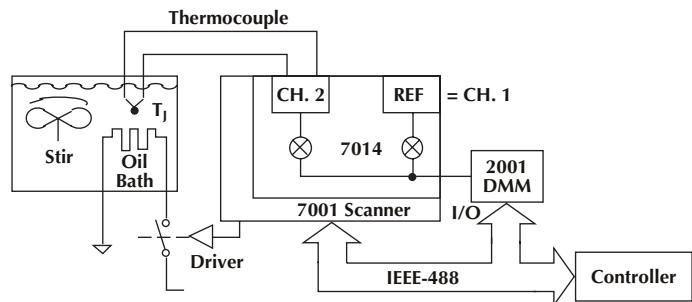


Figure 4: Automatic Control of Oil Bath Temperature

Summary of Thermocouple System Uncertainties

System Uncertainty	Design Considerations
1. Thermoelectric Offset Voltages	<ul style="list-style-type: none"> Select conducting materials with low thermal characteristics. Clean copper wire is very good. Match thermal characteristics of materials brought together in any connection. Shield connections from all heat sources (radiation, conduction, convection). Maintain gas-tight connections. Metal oxides typically have much higher EMFs. Select quality low thermal switching.
2. Reference Temperature	<ul style="list-style-type: none"> Accuracy of the reference temperature sensor is directly related to the degree of system error. Isothermal block construction minimizes errors created by differences between the measured reference temperature and the temperature at thermocouple terminations.
3. Measurement Instrument	<ul style="list-style-type: none"> Stability, sensitivity, and accuracy of the instrument directly affect measurement accuracy.
4. Thermal Curve Conformity	<ul style="list-style-type: none"> Thermocouples that have undergone thermal shocks, mechanical stress, and aging can exhibit errors approaching $\pm 2^\circ\text{C}$ from standard tables and curves.

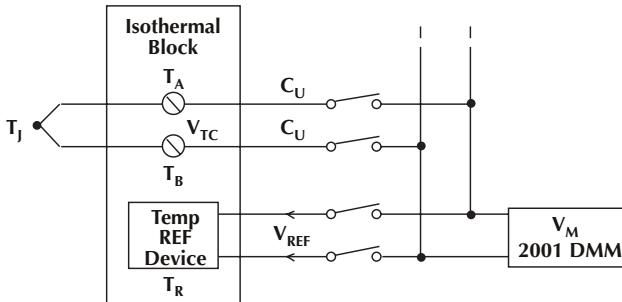


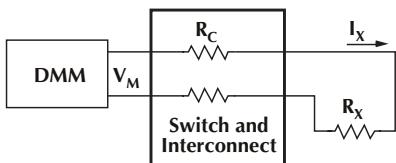
Figure 5: Typical Reference and Thermocouple Measurement Configuration

Resistance Measurements

Applications for resistance measurements in systems are numerous. They range from network and device testing to the testing of backplanes and interconnects, as well as the use of platinum resistance temperature detectors (PtRTDs) or thermistors.

Four-wire resistance measurements are used most often in system applications to overcome errors introduced by cabling and switch contact resistances. These effects are especially bothersome in the measurement of resistance values at $1\text{k}\Omega$ and below. One ohm of cable and contact resistance in a conventional 2-wire circuit adds a 0.1% error to the $1\text{k}\Omega$ measurement.

The effect of this cable and contact resistance (R_C) is shown in **Figure 6**. The DMM outputs a current, I_X , which develops a meter voltage, V_M , proportional to the sum of the unknown resistance and the series connection resistance R_C . The value of R_C could be measured separately by replacing R_X with a short; R_X is then determined by subtracting R_C from the two-wire measured value. While this may be practical for a manual test, system testing uses a wide range of signal channels, relays, and cabling. Each measurement path would require a separate characterization of R_C , an impossible and unnecessary task.

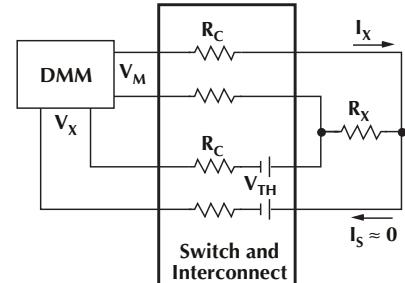


$$V_M = (R_C + R_X) I_X \quad \% \text{ Error} = \frac{R_C}{R_X} \times 100\%$$

Figure 6: Two-Wire Resistance Measurement

A four-wire resistance measurement, often called a Kelvin measurement, is most common in system environments as a means of avoiding series resistance errors. See **Figure 7**.

Ignoring for the moment the voltage (V_{TH}) in **Figure 7**, a current, I_X , is still generated by the DMM from the Ω source terminals. A separate voltage sensing circuit uses the characteristic



$$V_X = I_S R_C + I_X R_X + V_{TH}$$

$$V_X \approx I_X R_X + V_{TH}$$

$$\% \text{ Error} = \frac{V_{TH}}{I_X R_X} \times 100\%$$

Figure 7: Four-Wire Resistance Measurement

high input impedance of the voltmeter. The sense current, I_S , is the input current of the voltmeter, and for all practical purposes can be considered to be zero. Therefore, no voltage attributable to I_S is developed in the sense circuit, and voltage, V_X , is proportional exclusively to the unknown resistance.

In precision measurements or very low resistance measurements, there are additional considerations. For example, make a measurement of a 1Ω resistance with 0.1% accuracy. Use a 5½-digit DMM on the lowest range (200Ω full scale) and a source current, I_X , of 10mA. The result would be:

$$V_X = 10\text{mV} + V_{TH}$$

from the equation in **Figure 7**. Now assume that the thermoelectric offset voltage, V_{TH} , is $30\mu\text{V}$. This condition results in an additional measurement error of 0.3%. For low resistances, as in thermistor temperature measurements, the system designer must determine—in addition to the accuracy of the DMM—the acceptable measurement uncertainty, and select appropriate low voltage switching and interconnect circuitry. Applications involving thermistors require low source current to minimize self heating. The Model 2001 has high resolution and low source current to minimize this source of error.

A good, low thermal design can achieve thermoelectric offsets of only a few microvolts. These effects can be neutralized by techniques such as measuring and subtracting the offset, or using an alternating current for I_X , to further improve on the accuracy of low resistance measurements.

Model 2001 has a feature called “offset compensated ohms” that reduces this effect. It takes two readings to give the compensated reading, one reading with the test current applied and one reading with no test current.

With no test current applied, the only voltage to be measured is the thermal EMFs in the circuit. With this measured, it can be algebraically subtracted from the first reading. This provides an “offset compensated” measurement.

Low Current Measurements

Full characterization of semiconductor devices requires a broad dynamic range (as many as 12 decades) of current stimuli and measurement. Leakage currents of FET gates and reverse biased junctions are well below 1nA. Insulation resistance of capacitors, PC boards, cables, and harnesses can also be determined using low current measurements. The measurement of these signals requires some precautions, even in a manual setup. In a system, the switching card becomes a critical element. It is advisable to keep the following points in mind when selecting a switch to make current measurements at levels below 1 μ A:

1. The current switching configuration should be capable of maintaining a complete path when the circuit is not being measured.
2. There must be very high isolation ($>10^{13}\Omega$ minimum) between adjacent channels and between the relay drive and the measurement channels. Such an arrangement minimizes extraneous current paths, which may introduce error currents into the measurement, especially noticeable below 1nA.
3. Provision for shielding is required, since the high impedance circuitry is susceptible to pickup of spurious radiated noise. Relay controls should be shielded from the coil to minimize induced noise from the relay drive power supply.

Presented in *Figure 8* is a generalized leakage test system in which a bias voltage, V_A , is applied across each test device and leakage currents are measured with an electrometer. The low current switching card introduces less than 1pA of current into

the measurement circuit. The devices could be transistors, diodes, or a multipin IC package where leakage currents into certain nodes must be determined with other nodes in a known state. DUT 1–10 may also represent a resistor network in which isolation between circuits must be determined. Capacitor leakages can be measured, as described in detail in Application Note #120.

Construction techniques, materials, and cleanliness are critical factors in the design of the low current interconnect. The major contributors to error currents above 1pA are:

- **Leakage currents.** Effects can be reduced by selection of proper insulating materials, guarding, and cleanliness.
- **Triboelectric currents.** This noise source can be reduced by using special low-noise cable and securing the interconnect to minimize movement.
- **Electrochemical current.** Thorough cleaning of joints and surfaces to remove electrolytic residue including PC etchants, body salts, and processing chemicals will minimize the effect of these parasitic batteries.

Other current sources, including piezoelectric, dielectric, photoelectric, and thermoelectric effects may also contribute to error in low current measurements. Additional information on these source problems and other related low current data are provided in Keithley's Catalog and Reference Guide and *Low Level Measurements Handbook*. The critical sources of current error are dependent on the levels and types of measurement being performed.

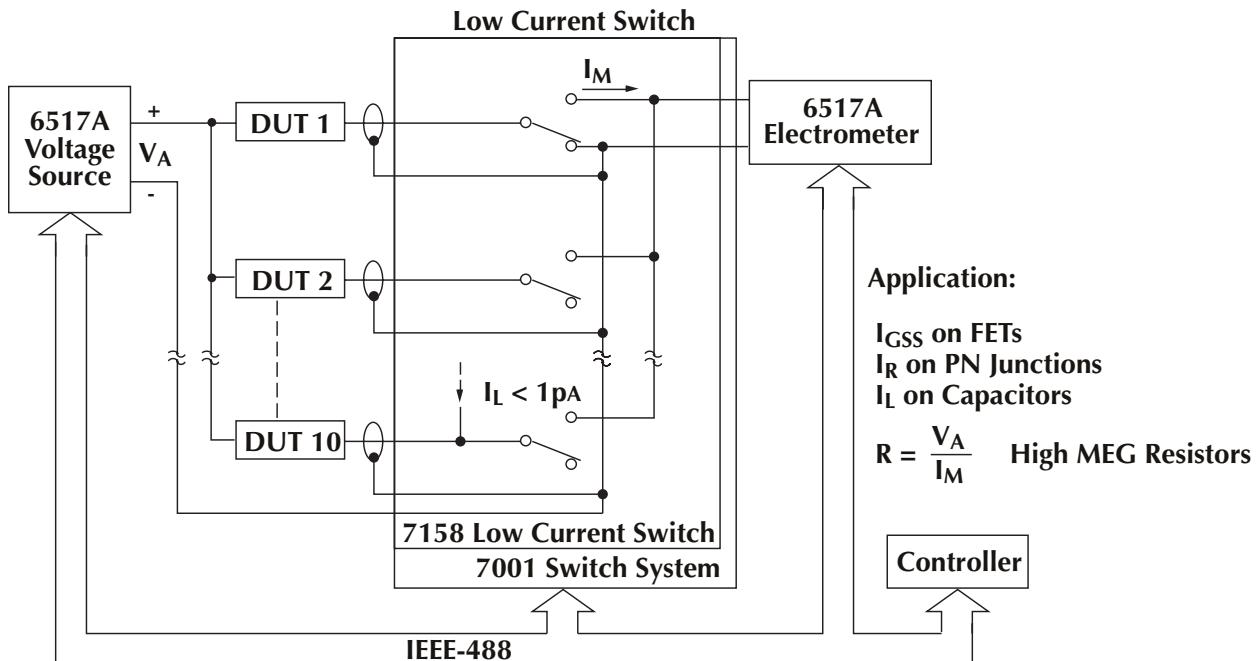


Figure 8: Automated Leakage or High Resistance Testing. The Model 6517A has an isolated voltage source that can be used to stimulate the device under test. The Model 6517A can then measure the developed current.

High Voltage Switching

Many procedures and parametric tests (such as insulation resistance testing on cables, harnesses, and PC boards, high-pot testing, and breakdown testing on semiconductors) require voltages from 500V to 1000V. Often these requirements are specified as part of a standardized test method such as MIL-STD-833C.

Since transients can be generated in the switching of high voltages, it is also generally required that the application of voltage be increased at a specified maximum rate. Because programmable high voltage supplies are not readily available, manual methods are often used to apply the test voltage in a controlled manner. Manual methods generally consist of adjusting a potentiometer or front panel control on the supply, a very loosely controlled situation. These methods are time consuming and can be hazardous to the operator unless safety interlocks are carefully designed.

An alternative is to approximate linear application of voltage, using a Model 7054 High Voltage Scanner Card and a constant voltage supply. The circuit illustrated in *Figure 9* charges capacitor C to voltages from taps on the divider networks. The charge rate is predictable and controlled. Maximum dV/dt at the DUT can be controlled through design selection of R and C, and system timing of the relay closures. Steps may be of any size, depending on the number of taps on the divider network.

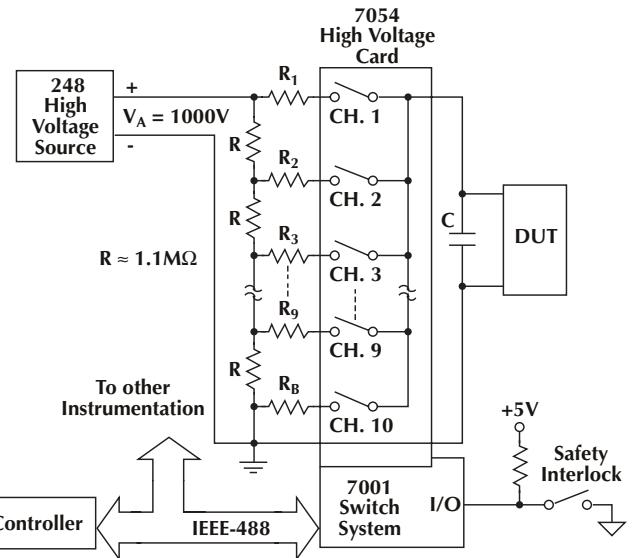


Figure 9: Uniform High Voltage Application for Breakdown and Isolation Testing

The controller can read the status of safety interlocks through the digital I/O port on the Model 7001 Switch System to assure safe testing. Values for R_1 through R_{10} are selected to approximately equalize the RC response between taps. R_B is a bleeder resistor selected to bleed charge safely from capacitor C at the completion of testing.

Matrix Switching

The matrix switch is commonly used in large systems. Its ability to connect any input to any output through only one set of contacts assures maximum flexibility in configuring system measurements. Using a matrix, connections and circuits can be completed at the test interface or within the matrix. System checks

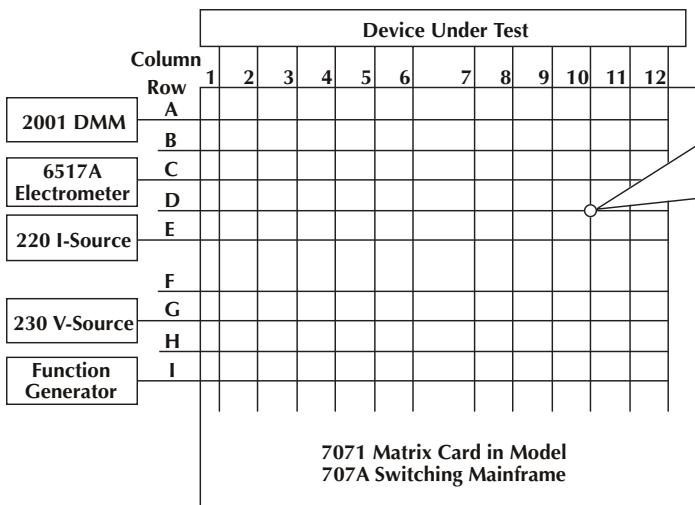
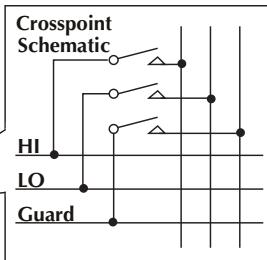


Figure 10: Uniform High Voltage Application for Breakdown and Isolation Testing

and validation can be performed in the matrix without external hardware. For example, the DMM in *Figure 10* can be used to monitor voltages at any test interface point in columns 1 through 12. The voltages' source can be measured by connecting it with the DMM via the same column inside the matrix. A matrix combines a complex set of switching applications into one array. The Model 707A is a matrix mainframe that has switching cards that

are 8×12 matrices. These cards can be cascaded to increase the number of rows and columns for an even more powerful array of switching capability.



Caution is advised in regard to matrix switching. Benefits gained through switching flexibility can be offset by catastrophic situations if care is not taken to verify all signal pathways. Closure of incorrect matrix crosspoints may produce internal shorts that can damage the relays, DUT, or system's instrumentation. It is therefore imperative that the test designer know and verify each cross-point configuration during test development before proceeding with "power up" testing.

The general case for system switching is illustrated in **Figure 11**. As implied by its position in the diagram, switching is central to good system design.

Careful consideration of switch characteristics is essential to optimize performance of the measurement system. Once the switch is selected, the application of basic measurement principles will assure reliable and accurate measurement of circuit parameters.

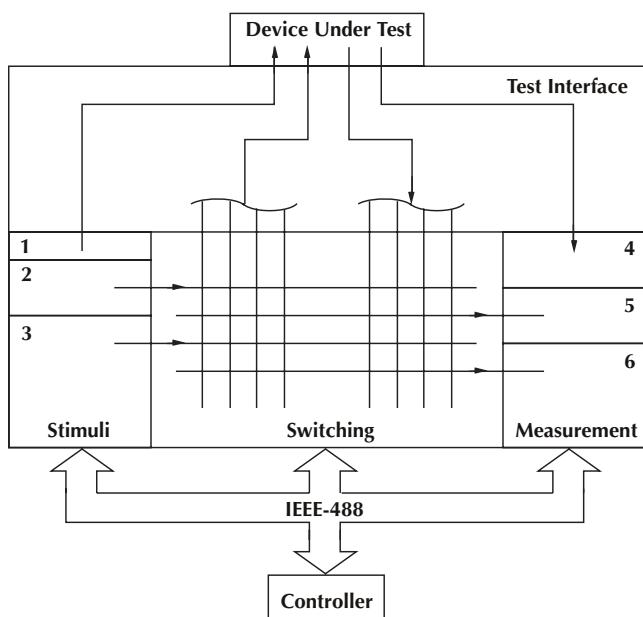


Figure 11: Application of Matrix Capability in a General Purpose Test System

Conclusion

When designing a measurement system, selection of the switch is as critical as the selection of system instrumentation or the design of the test interface. The intended application must be thoroughly considered and the switch selected must meet the requirements of the application. Careful attention to detail and to the basic principles of measurement can assure system accuracy and performance.

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